Understanding and Improving Household Energy Consumption and Carbon Emissions Policies – A System Dynamics Approach

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Abstract:
The purpose of this paper is to propose and demonstrate the application of system dynamics modeling approach to analyze and study the behavior the complex interrelationships among the different policies/interventions aimed at reducing household energy consumption and CO_2 emissions (HECCE) based on the Climate Change Act of 2008 of the UK government. The paper uses the system dynamics as both the methodology and tool to model the policies/interventions regarding HECCE. The model so developed shows the complex interrelationships among the different policies/interventions variables and presents the basis for simulating the different scenarios of household energy consumption reduction strategies. The paper concludes that the model is capable of adding to the understanding of the complex system under which HECCE operate and improve it accordingly by studying the behavior of each policy/intervention over time. The outcomes of the research will help decision makers draw more realistic policies/interventions for household energy consumption which is critical to the CO_2 emissions reductions agenda of the government.

Keywords:
CO_2 emissions, domestic buildings, household energy consumption, government policies, system dynamics.

1. Introduction

There have been concerns over sustainability issues around the world, especially when it comes to the way energy is used and the corresponding environmental impacts in the form of climate change, global warming, etc. The effects of climate change, due to carbon dioxide and other greenhouse gas emissions for example, could see the global temperatures rise by up to 6^{o}C (UNDESA, 2010) thereby causing extremes in weather systems. Reduction in energy consumption patterns in dwellings is, therefore, seen as one of the breakthroughs to curtail this threat. According to the Office of National Statistics (2009), total energy consumption in buildings in the UK accounts for 42.3% in relation to the UK total energy consumption. 27.5% of this amount was consumed in domestic buildings in the year 2008. Presently, CO_2 emissions attributed to domestic buildings alone is around 26% of the total UK's carbon emissions (Natarajan *et al.*, 2011). For this reason, the domestic sector of the UK's economy is then chosen as the centre of focus for both mitigation and adaptation agendas (Natarajan *et al.*, 2011) with a view to meeting the CO_2 emissions reductions target of 80% by 2050 based on 1990 levels as laid down by the Climate Change Act of 2008.

To have this target met, the UK's government has initiated a number of policies/strategies like fabric insulation improvement, energy tariffs, alternative energy sources e.g. micro-generation, energy subsidy for uptake of technology like micro-generation, behavioral change, initiatives on fuel poverty, *e.t.c.* to serve as measures against this menace. Oladokun *et al.* (2012) argues that the issue of sustainability in terms of HECCE is a complex socio-technical system that must be acknowledged as such and appropriately understood as a system because the characteristics of the parts making up this system cannot be viewed individually. Prior now, there have been a plethora of approaches used in analyzing the HECCE. The reality on ground suggests that there still remains debate on how best energy consumption and carbon emissions reductions in dwellings can be achieved when there are different policies evolving on a daily basis! It is against this backdrop that this paper intends to propose and demonstrate a methodology that is capable of modeling the complex system of different policies regarding HECCE. This study will contribute to the body of knowledge by adding to the understanding of the complex nature of HECCE and providing a model of interrelationships/dependencies among different variables that need consideration when analyzing and formulating policies regarding HECCE. Further, the study would contribute to the body of knowledge by providing a reliable tool that may even serve as learning laboratory for policy/decision makers to test different policies and answer the question of “what if” of carbon reductions strategies.

2. The Epistemology of Household Energy Consumption and CO_2 Emissions Models

In energy studies literature, there has been a superfluity of frameworks serving as theoretical knowledge-base to conceptualize HECCE and these have contributed in no small measure to the tools for the analysis and policy formulation regarding HECCE. Keirstead (2006) argues that these frameworks fall within two domains – disciplinary and integrated domains.

2.1. Disciplinary Frameworks

For years, “disciplinary” frameworks have been the dominant guiding approach for explanation and policy making regarding HECCE. For example, these frameworks are developed from four major disciplines with each discipline illustrating its own approach/framework for solving HECCE problems. These disciplines are engineering, economics, psychology, and sociology and anthropology. Engineering frameworks, for example, illustrates mainly the technology of HECCE by estimating HECCE based on the physical laws with little or no attention to economic, sociology, or even behavioral aspects of HECCE (*i.e.* the studies of Anderson, 1985; Stokes *et al.*, 2004; Hart and Dear, 2004). The economic framework as one of the disciplinary frameworks conceptualizes HECCE when it comes to understanding HECCE due to the effects of income levels, energy prices and taxes, *etc* (Ruffell, 1977; Baker, 1991; Greening *et al.,* 1995; Ironmonger *et al.,* 1995). As a social science based framework, however, it introduces some behavioral aspects.

Interestingly, Wheelock and Oughton (1994) argue based on the available evidence that the concept depicts by economic approach is not complete in aiding the understanding of HECCE. It is against this background that the studies in the area of psychology took up this challenge and contribute to the understanding of household energy consumption behavior. Notably in this circle is the Theory of Planned Behavior (TPB) of Ajzen (1991), which immensely contributed to the behavioral aspect of HECCE by serving as theoretical knowledge-base to many studies. However, the TPB framework cannot be used as a standalone framework for explaining HECCE because the theory only used personal constructs like attitudes and beliefs without any recourse to other aspects like social and cultural contexts. This then led to studies in the field of sociology and anthropology in a bid to conceptualize energy and society.

Reflecting on all these approaches, it is evident that they are unlikely to capture the kind of complex problems plaguing energy sector now and hence the need for a more robust approach capable of integrating a number of disciplinary approaches together. It is on the basis of this that a small number of literatures suggest “integrated” frameworks that cut across many disciplines.

2.2. Integrated Frameworks

A number of “integrated” frameworks have been used to conceptualize HECCE in order to aid a better understanding of energy issue and proffer adequate solutions. The study of van Raaij and Verhallan (1983) provided a novel approach to conceptualizing energy behavior. His framework made use of both physical parameters of the dwellings and behavioral characteristics of the households. The research of Lutzenhiser (1992) proposes a cultural framework of HECCE and the work of Wilk (2002) gives the global consumption framework of household energy consumption. The study of Hitchcock (1993) uses the systems theory to provide an integrated framework of energy use and behavior in domestic buildings and argues that energy consumption patterns in domestic buildings needs to be fully understood from systems perspective. The study used the concept of socio-technical systems to conceptualize HECCE and came up with a framework. However, no modeling technique was proposed to capture these socio-technical systems. It is then pertinent to look at the modeling approaches of these “integrated” frameworks.

2.3. Bottom-Up and Top-Down Modeling Approaches

Over the years, there have been a number of studies on modeling approaches to capture domestic energy consumption (Strachan and Kannan, 2008; Bohringer and Rutherford, 2009; Tuladhar *et al.*, 2009; Swan and Ugursal, 2009); Kavgic *et al.*, 2010). Based on Kavgic (2010), these approaches vary tremendously in terms of requirements, assumptions made, and the predictive abilities of the models. Majority of the studies (Kavgic *et al.*, 2010; Kelly, 2011) argue that there are basically two epistemic approaches to modeling HECCE. According to Kavgic *et al.* (2010) and Kelly (2011), these approaches are either top-down approach or bottom-up approach. They acknowledged that there have been some cases where a hybrid of the two approaches have been made which combined them together to form more robust models.

These approaches have received one form of criticism or the other when it comes to modeling HECCE. Among those that have offered criticism is Natarajan et al. (2011). This came from the point of view that the issue of energy consumption is a complex one which needs to be acknowledged as such by looking at it from the non-deterministic perspective rather than the deterministic approach being currently in use. Also, majority of these modeling approaches find it difficult to model a combination of quantitative and qualitative variables together. This difficulty stems from the fact that the issue of energy consumption and carbon emissions in general involves a web of interaction between householders and the technology put in place in the dwellings and the wider socio-economic environment. This then calls for an approach that is able to cope with this kind of difficulty. The next section then discusses system dynamics as an alternative approach to model complex systems.

3. System Dynamics – An Approach to Model Complex Systems

System dynamics (SD) has been depicted as an emerging field in the study and analysis of complex systems. It is, indeed, a multi-disciplinary subject that deals with the study of any dynamic system. Motawa and Banfill (2010) argue that SD is both a methodological approach and set of analytical tool capable of palliating the deficiencies of traditional analytical approach and the justification for this modeling paradigm has been covered elsewhere by the authors (Oladokun *et al.*, 2012). There are quite a number of definitions of SD, but the one given by Coyle (1997) offers a more robust definition as an approach that "deals with the time-dependent behavior of managed systems with the aim of describing the system and understanding, through qualitative and quantitative models, how information feedback governs its behavior, and designing robust information feedback structures and control policies through simulation and optimization". Fundamentally, SD deals with 'feedback' processes (as given in the definition) and built on 'cause and effect' relations among different variables influencing the system under investigation (Ranganath and Rodrigues, 2008). According to Sterman (2000), SD is a "method to enhance learning in complex systems" as it is grounded in the theory of modern feedback control and nonlinear dynamics. This has now been applied to numerous fields of study. Sterman (2000) argues that SD has found application in modeling human behavior as well as physical and technical systems, which is capable of solving important real life problems mainly because it draws on cognitive and social psychology, economics, and other social sciences.

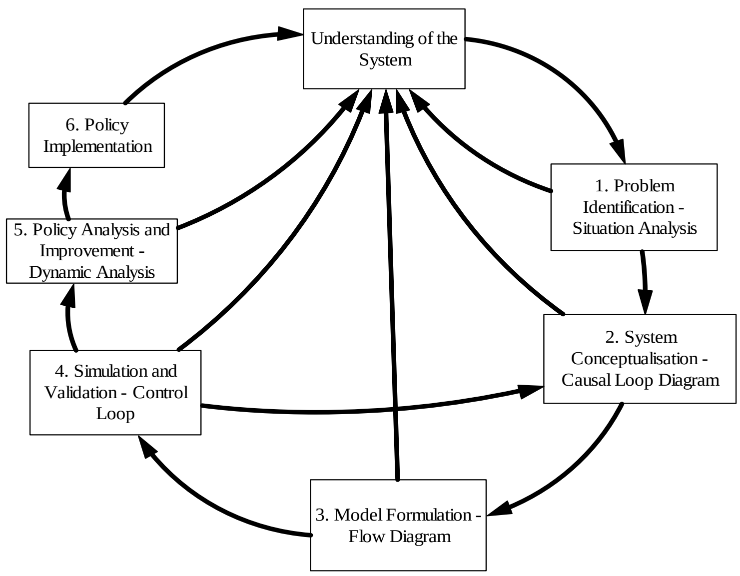

Fig. 1. System Dynamics Methodology (Adapted from Ranganath and Rodrigues, 2008)

The diagram shown in Figure 1 depicts the system dynamics methodology in a general sense as adapted from the work of Ranganath and Rodrigues (2008). This shows the method used in solving any system dynamics problem. The stages involved are interrelated and linked together as all the steps are directed towards the 'understanding of the system'. This reveals that at any point in time in each stage of system dynamics, a better insight into the problem is gotten, which eventually leads into the better understanding of the system under study. The methodology indicates that the first stage it to identify the problem in question and properly define it through the situation analysis. This involves identifying the variables in the problem and relates them to one another in order to find out the causal relationships and feedbacks in the system. Based on Ranganath and Rodrigues (2008), the most important aspect of problem identification is to identify the time-based policy parameters, which influence the dynamics of the system under study.

The second stage as shown in Figure 1 is the system conceptualization. This involves representing the ‘cause and effect’ relationship between the variables in the system pictorially and this is called causal loop diagram (CLD). It is worth mentioning that at this stage the diagram does not indicate the stock or the flow but merely indicates the influence of one variable on the other. Stage three involves formulating the model by representing the model using the stock and flow diagram (SFD). This diagram is a pictorial representation of the behavior of the system in the form of accumulation (stock) and flow (rate). This automatically leads to stage four where the SFD is turned into a simulation model. It must be emphasized that mere CLD or SFD do not constitute the system dynamics. It is when the variables in the model are related together in terms of equations before it can be said that it forms the simulation model. Once the model is validated accordingly, the simulation is then run and the output of the simulation is presented in the form of graphs. These graphs reveal the pattern exhibit by the variables under study over a period of time. Based on these outputs, policy analysis and improvement is carried out by the decision makers and this is stage five of the methodology. Implementation of the policy improvement (stage six) then concludes the system dynamics methodology.

This method demonstrates system dynamics as a powerful analysis tool for use by decision makers. It is worth mentioning that system dynamics has the ability to be used as a learning laboratory tool (Rodrigues and Bowers, 1996) and in conjunction with other traditional decision making techniques. The following section presents the application of system dynamics methodology to model the impact of different UK government policies on HECCE.

4. Application of System Dynamics Methodology to the Impact of Different Policies on Household Energy Consumption and CO_2 Emissions

Based on the system dynamics methodology discussed above, the following sub-sections then discuss the system dynamics steps that are covered so far in this paper.

4.1.1. Problem Identification

In system dynamics modeling process, the first step, as advocated in Section 3 above is to identify the problem that necessitates the model. The problem under study has, therefore, been explicitly discussed in Section 1 of this paper.

4.1.2. System Conceptualization

As previously highlighted, the government of the UK is taking a number of pragmatic steps in order to meet the energy consumption and carbon emission reductions targets. Among the measures on ground are: improving household fabric energy efficiency, encouragement of micro-generation of energy at household level, provision of subsidy/financial incentives for uptake of this micro-generation technology by householders, householders behavioral change, and the likes. After the review of relevant literature including government documentations was carried out in order to identify the variables to be included in the model, the system conceptualization was conducted that involves identifying the sub-systems, the model boundary, the reference modes, and the main CLD for the model. The following sub-sections then discuss these steps.

4.1.2.1. Model Sub-systems

The system under study has a number of sub-systems and each of them is controlled by a number of variables as identified from the literature. The sub-systems in this model are discussed as follows.

1. Energy efficiency of dwellings is one of the sub-systems under consideration by this model. It needs to state that the government policy on dwellings' energy efficiency aims at providing zero carbon homes which is a step towards the carbon reductions targets. This policy targets dwellings in general. Householders are required to increase the energy efficiency of their homes by improving on fabrics insulation. This may mean taking the step of cavity wall, loft, and floor insulation, drought proofing and an uptake of double glazing. This will allow the householders to spend little in heating up their homes without being in fuel poverty. Fuel poverty means "being unable to afford to keep warm". According to Department of Energy and Climate Change (DECC) (2012a), a household is considered to be in fuel poverty if it spends more than 10% of its income on fuel in order to adequately heat its home. Fuel poverty negatively affects people's health especially the elderly, children and those with a prolonged illness or disability. Poor home energy efficiency, high energy tariff and low household income have been attributed to the cause of fuel poverty.

2. Uptake of alternative energy source, in the form of micro-generation, is another sub-system that is worth discussing. Micro-generation is defined under the Energy Act 2004 and according to DECC (2012b) to be "a term used for the generation of low, zero carbon or renewable energy at a 'micro' scale". This covers any energy generation that is decentralized. Micro-generation technologies may take the form of solar photovoltaic (PV), micro-wind turbines, micro-hydro or even micro-combined heat and power (CHP). Micro-generation provides energy security by increasing household energy flow and by tackling the issue of increase in energy tariff and attracts subsidy/financial incentives to the consumers with further reduction in tax for uptake of this technology.

3. Another sub-system in the model is subsidy/financial incentives to consumers for uptake of technology like micro-generation. This sub-system is another important policy of the government in making sure that energy security is guaranteed at all times by increasing the uptake of alternative energy source *i.e.* micro-generation and helps in reducing energy tariff. However, availability of energy subsidy may have rebound effects on energy consumption by spending the savings accrued on increased energy consumption. The energy subsidy sub-system has a number of variables and feedback loops that control the behavior of the system under study.

4. Household energy consumption behavior is another sub-system that worth discussing. Dietz et al. (2009) argue that behavior is influenced by a complex blend of demographics, values, intentions, situational characteristics and psychological factors. In this sub-system, behavioral intention to consume energy reinforces household energy consumption and invariably leads to increment in CO_2 emissions. While energy tariff as one of government policies and the cost expended on energy try to

stabilize the household behavioral intention to consume energy, increase in household income reinforces their consumption pattern.

4.1.2.2. Model Boundary

This section discusses the boundary for the model. As highlighted in section 3 previously, one of the strengths of SD is in its ability to deal with feedback structure. It is well known that every feedback structure has a closed boundary. As one of the modeling process in SD, it needs to clearly define the model boundary since it is practically impossible to include all the variables in the model. In this research, the variables to be used for the model are extracted from the relevant literature including government documents. Table 1 then shows the variables included in the model and the ones that are not considered in the present version of the model. The variables included in the model are divided into two namely: (1) endogenous – dynamics variables involved in the feedback loops of the system; and (2) exogenous – variables whose values are not directly affected by the system.

Table1. Model Boundary

Endogenous variables	Exogenous variables	Excluded variables
Climatic effects	Surface temperature	Factors influencing international fuel price like war, etc
International fuel price	Rainfall	Other factors that can cause catastrophic climatic effects
Government policy change	Snowfall	
Alternative energy sources i.e. micro-generation	Sea level	
Energy subsidy on alternative energy sources	Householders health	
Energy tax		
Energy tariff		
Energy expenses		
Fuel poverty		
Fabric insulation improvement		
Energy efficiency in dwellings		
Household income		
Household behavioral intention to consume energy		
Household energy flow		
Household energy consumption		
CO2 emissions		

4.1.2.3. Reference Modes for the Model

The next step under the system conceptualization in SD is to give a plot of the behavior of key variables in the model over time. This is referred to as reference mode or behavior chart. The reference mode depicts historical data and/or mental models in graphical form and forms the basis for comparison once the model is built. Figures 2 and 3 illustrate examples of some of the main reference modes for the model.

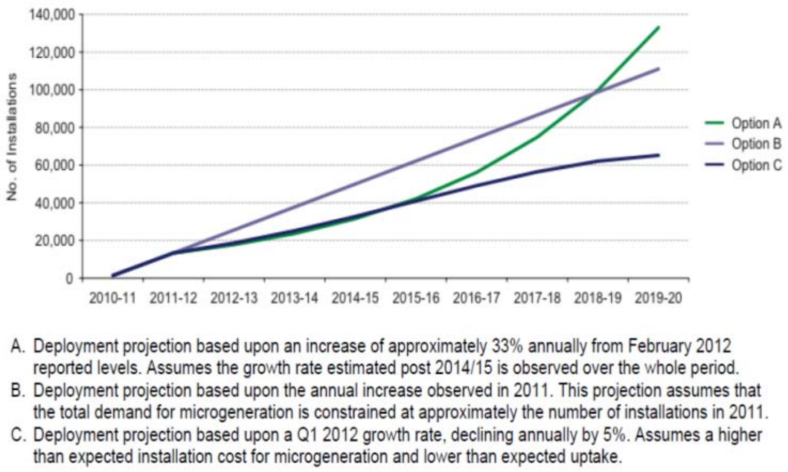

Fig. 2. Uptake of micro-generation (The Scottish Government, 2012)

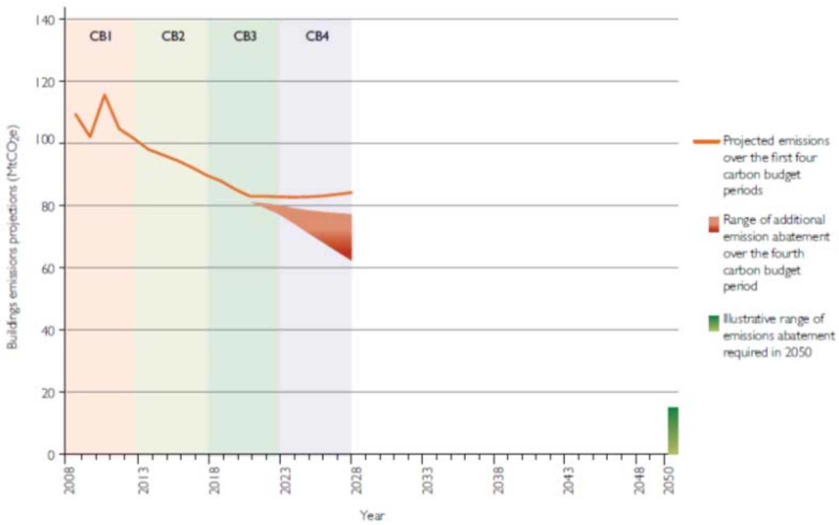

Fig. 3. Carbon emissions projections (DECC, 2012c)

4.1.2.4. The Main Causal Loop Diagram

Achieving CO_2 emissions reductions target is critical to the UK government based on the Climate Change Act of 2008. Fig. 4 illustrates the main CLD developed for the problem under investigation. The key variables and their relationships are shown in the diagram which demonstrates the use of SD in adding to the understanding of this complex system. The CLD so developed indicates that there are many feedback loops. The polarity attached to a given feedback loop is achieved by summing up the negative polarity of each of the variables within such a loop. Loops with an even number of negative relationships among the variables are regarded as positive (self-reinforcing loops), whereas, the ones with an odd number are negative (self-balancing loops). It is necessary to mention that loops with zero negative relationship are taken as being even. Also, it is worth mentioning that variables within the self-balancing loops will stabilize over time, whereas variables within self-reinforcing loops will continue to increase indefinitely.

As earlier noted that the CLD presented in Fig. 4 shows many self-reinforcing feedback loops causing instability in the system, only some of these loops will be taken for demonstration purpose only. Indicated in Fig. 4 are three self-reinforcing loops (R1 – R3). R1 is consumption loop and contains variables like [Household energy consumption – CO_2 emissions – Climatic effects – International fuel price – Household energy flow]. R2 is subsidy loop, which is provision of subsidy for uptake of alternative energy like micro-generation which increases household energy flow and therefore encourages more energy consumption by householders. This loop contains the following variables: [Energy subsidy on alternative energy sources – Household energy consumption – CO_2 emissions – Climatic effects – Government policy change]. Further, energy tariff loop (R3) is causing instability in the system and contains the following variables [Energy tariff – Energy expenses – Energy tax].

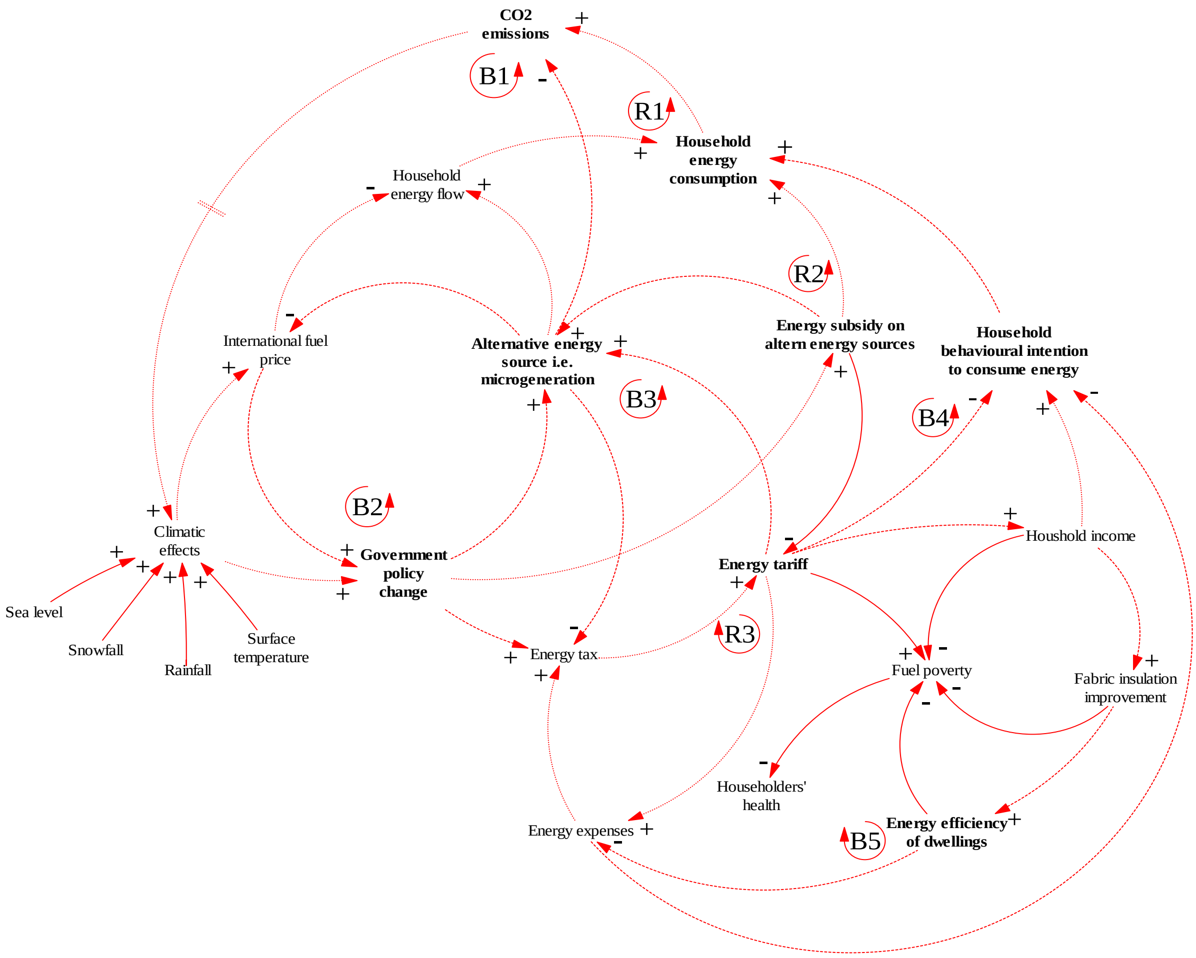

Fig. 4. Main Causal Loop Diagram

In order to counter the instability caused in the system as a result of the self-reinforcing loops, the self-balancing loops are created. Five of the self-balancing loops (B1 – B5) in the model are as indicated in Fig. 4. B1 is termed the emission loop. CO_2 emissions is been reduced based on the policy of government on provision of alternative energy that is cleaner and renewable. This loop contains [CO_2 emissions – Climatic effects – Government policy change – Alternative energy source *i.e.* micro-generation]. Also, the instability in the system is calmed down by different policies of the government (B2 - government policy loop) which contains variables like [Government policy change – Alternative energy source *i.e.* micro-generation – International fuel price]. B3 is alternative energy source loop [Alternative energy source *i.e.* micro-generation – Energy tax – Energy tariff]. Loop B4 is consumption behavior loop [Household behavioral intention to consume energy – Household energy consumption – CO_2 emissions – Climatic effects – Government policy change – Energy tax – Energy tariff]. An attempt to carry out fabric insulation improvement, which undoubtedly improves the energy efficiency of dwellings, is reflected in loop B5 (energy efficiency loop) [Energy efficiency of dwellings – Energy expenses – Energy tax – Energy tariff – Household income – Fabric insulation improvement].

Once the model is set-up, it will mean that there will be needs to pay special attention to some of the variables in the loops causing instability in the system (especially the time – dependent ones).

5. Conclusion and Further Work

This paper has demonstrated the efficacy of system dynamics tool in adding to the understanding of policies regarding household energy consumption and CO_2 emissions. Authors advocate that there are many interrelated variables in play, the analysis of which will further help in relieving the pressure being mounted by the need to significantly reduce household energy consumption and meet up with the CO_2 emissions reductions targets. The CLD developed illustrates the importance of SD as a methodology to simulate various policies regarding CO_2 emissions reductions target. Feedback loops are shown that need close monitoring in order to stabilize the system performance under consideration. The next stage of the research is to translate the CLD to SFD and relate all the variables in the model together with algebraic equations. The simulation will be run and the output of the simulation is presented in the form of graphs. Validation of the model will then be carried out accordingly. Based on these outputs, policy analysis and improvement can then be conducted and correct policy improvement is implemented.

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References:

Ajzen, I. (1991), *The theory of planned behavior*, Organizational Behavior and Human Decision Processes, **50** (2), 179-211.

Anderson, B. R. (1985), *BREDEM: BRE Domestic Energy Model: Background, Philosophy and Description B2 - BREDEM: BRE Domestic Energy Model: Background, Philosophy and Description*, Building Research Establishment, Watford.

Baker, P. (1991), *A Model of Household Gas and Electricity Expenditures for the UK: the IFS Simulation Program for Energy Demand (SPEND)*, Institute for Fiscal Studies, London.

Böhringer, C. and Rutherford, T. F. (2009), *Integrated assessment of energy policies: decomposing top-down and bottom-up*, Journal of Economic Dynamics and Control, **33** (9), 1648-1661.

Coyle, R. G. (1997), *System dynamics modeling: a practical approach*, Chapman and Hall, UK.

Greening, L. A. (1995), *Use of region, life-cycle and role variables in the short-run estimation of the demand for gasoline and miles travelled*, Applied Economics, **27** (7), 643-656.

Department of Energy and Climate Change (DECC) (2012a), *Fuel poverty*, available at http://www.decc.gov.uk/en/content/cms/funding/fuel_poverty/fuel_poverty.aspx, accessed on 18th April 2012.

DECC (2012b), *Micro-generation*, available at http://www.decc.gov.uk/en/content/cms/meeting_energy/microgen/microgen.aspx, accessed on 18th April 2012.

DECC (2012c), *The future of heating: A strategic framework for low carbon heat in the UK*, Whitehall Place, London, May.

Dietz, T., Gardner, G. T., Gilligan, J., Stern, P. C. and Vandenbergh, M. P. (2009), *Household actions can provide a behavioral wedge to rapidly reduce U.S. carbon emissions*, Proceedings of the National Academy of Sciences.

Hart, M. and de Dear, R. (2004), *Weather sensitivity in household appliance energy end-use,* Energy and Buildings, **36**, 161-174.

Hitchcock, G. (1993), *An integrated framework for energy use and behavior in the domestic sector*, Energy and Building, **20**, 151-157.

Ironmonger, D. S., Aitken, C. K. and Erbas, B. (1995), *Economies of scale in energy use in adult-only households*, In P. Stevens (Ed.), The Economics of Energy, Volume 1 (pp. 318-327): Elgar Reference Collection. International Library of Critical Writings in Economics, **119**.

Kavgic, M., Mavrogianni, A., Mumovic, D., Summerfield, A., Stevanovic, Z. and Djurovic-Petrovic, M. (2010), *A review of bottom-up building stock models for energy consumption in the residential sector*, Building and Environment, **45**, 1683-1697.

Keirstead, J. (2006), *Evaluating the applicability of integrated domestic energy consumption frameworks in the UK*, Energy Policy, **34** (17), 3065-3077.

Kelly, S. (2011), *Do homes that are more energy efficient consume less energy?: A structural equation model for England's residential sector*, EPRG Working Paper, Electricity Policy Research Group, University of Cambridge.

Lutzenhiser, L. and Hackett, B. (1993), *Social stratification and environmental degradation: understanding household CO2 production*, Social Problems, **40** (1), 50-73.

Motawa, I.A. and Banfill, P.F. (2010), *Energy-efficient practices in housing – A system dynamics approach*, In Proceedings of 18th CIB World Building Congress: TG62 – Built Environment Complexity, Salford, United Kingdom, 44-56, May.

Natarajan, S., Padget, J. and Elliott, L. (2011), *Modeling UK domestic energy and carbon emissions: an agent-based approach*, Energy and Buildings, **43**, 2602-2612.

Office for National Statistics (2009), *Digest of UK energy statistics 2009*, TSO, London.

Oladokun, M.G., Motawa, I.A. and Banfill, P.F.G. (2012), *Modeling techniques for capturing the socio-technical aspects of sustainability in post-occupancy stage of buildings*, In Proceedings of Retrofit 2012 Academic Conference, University of Salford, Greater Manchester, United Kingdom, 24th – 26th January.

Ranganath, B. J. and Rodrigues, L.L.R. (2008), *System dynamics: Theory and case studies*, I.K. International Publishing House Pvt. Limited, New Delhi.

Rodrigues, A. and Bowers, J. (1996), *The role of system dynamics in project management*, International Journal of Project Management, **14** (4), 213-220.

Ruffell. (1977), *An econometric analysis of the household demand for electricity in Great Britain* , Scottish Academic P.

Sterman, J.D. (2000), *Business dynamics: Systems thinking and modeling for a complex world*, McGraw-Hill, New York.

Stokes, M., Rylatt, M. and Lomas, K. J. (2004), *A simple model of domestic lighting demand*, Energy and Buildings, **36**, 103-116.

Strachan, N. and Kannan, R. (2008), *Hybrid modeling of long-term carbon reduction scenarios for the UK*, Energy Economics, **30**, 2947-2963.

Swan, L. G. and Ugursal, V. I. (2009), *Modeling of end-use energy consumption in the residential sector: A review of modeling techniques*, Renewable and Sustainable Energy Reviews, **13**, 1819-1835.

The Scottish Government (2012), *Micro-generation strategy for Scotland*, APS Group, Scotland, June.

Tuladhar, S. D., Yuan, M., Bernstein, P., Montgomery, W. D. and Smith, A. (2009), *A top–down bottom–up modeling approach to climate change policy analysis*, Energy Economics, **31**, S223-S234.

Van Raaij, W. F. and Verhallen, T. M. (1983), *A behavioral model of residential energy use*, Journal of Economic Psychology, **3** (1), 39-63.

United Nations Department of Economic and Social Affairs (UNDESA) (2010), *Buildings and construction as tools for promoting more sustainable patterns of consumption and production*, Sustainable Development: Innovation Briefs, Issue **9**, http://www.un.org/esa/sustdev/publications/innovationbriefs/index.htm, viewed: 23/05/2011.

Wheelock, J. and Oughton, E. (1994), *The household as a focus for comparative research*, Newcastle: Centre for Rural Economy, Department of Agricultural Economics and Food Marketing, University of Newcastle upon Tyne.

Wilk, R. (2002), *Consumption, human needs, and global environmental change*, [Short Survey], Global Environmental Change, **12**, 5-13.