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The CEDSS Model of Direct Domestic Energy Demand

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***Abstract*—This paper describes the design, implementation and testing of the CEDSS model of direct domestic energy demand, and the first results of its use to produce estimates of future demand under a range of scenarios. CEDSS simulates direct domestic energy demand at within communities of approximately 200 households. The scenarios explored differ in the economic conditions assumed, and policy measures adopted at national level.**

Introduction

CEDSS (Community Energy Demand Social Simulator) is an agent-based model of direct domestic energy demand, created as part of the GILDED project (Governance, Infrastructure, Lifestyle Dynamics and Energy Demand) funded by the European Commission under the Socio-economic Sciences and Humanities Theme of the Framework 7 Programme (http://gildedeu.hutton.ac.uk) and written in NetLogo [1]. The project aim was to elucidate the socio-economic, cultural and political influences on individual and household energy consumption.

CEDSS models urban and rural communities, on the scale of around 200 households, in the area of Aberdeen and Aberdeenshire. The focus of CEDSS is on household purchasing decisions in the area of energy-using and energy-saving equipment related to space- and water-heating (boilers and insulation), and household appliances including cookers, refrigerators, freezers, washing machines, dryers, dishwashers and televisions. Its is designed for use in constructing policy-relevant scenarios of domestic energy use up to the middle of the current century, under a range of assumptions about economic and technological change, and policy choices.

This paper provides a description of CEDSS using the ODD protocol (section I), outlines the design process and the data used to parameterise the model (section II), and reports results from early scenario runs (section III). Finally, section IV discusses the model's strengths and limitations, and future work.

I. Description of the CEDSS model

We use an abbreviated version of the 'Overview, Design concepts and Details' (ODD) protocol [2], [3] to describe CEDSS. A full version is available along with model code, input files and explanatory text from the CoMSES OpenABM node: Network for Computational Modeling for SocioEcological Science (CoMSES Net), at http://www.openabm.org/model/3642/version/2/view.

A. Purpose

The purpose of CEDSS is to simulate the household energy demand of a small rural or urban community (e.g. a housing estate or village), with respect to energy used for space and water heating, and for household appliances, over the period 2000-2049.

B. Entities, State Variables and Scales

The agents in the model are households. Each household occupies a dwelling, and owns a set of appliances, some of which are regarded as essential (a heating system, cooker, washing machine and fridge), while others are not (freezers, dishwashers, dryers and TVs). The model does not cover lighting or computers because of limitations of the data sources used. A dwelling is of one of a range of types: bungalow, house or flat, with each of these categories subdivided according to situation and size.

The entities and relationships among them are summarised in Fig.1. Reified relationships (those having data stored about them) are shown in blue boxes. The most important state variables of the entities and reified relationships are summarised in the following tables.

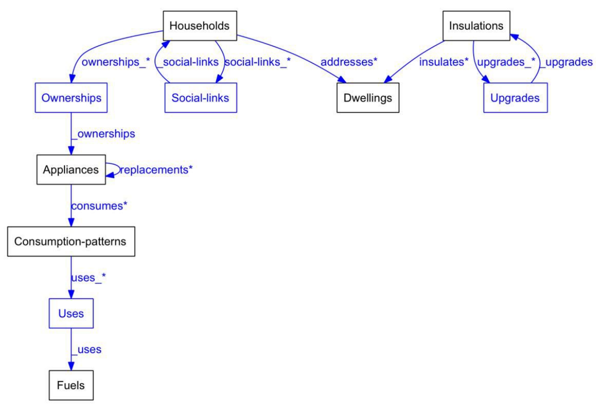

Fig.1 Entities and relationships in CEDSS

Table 1. Households

State variable	Type	Description
household-id	string	An identifier for the household
planning-horizon	integer	How far the household looks ahead when computing projected running and energy costs of appliances.
steply-net-income	double	How much income the household receives per step (one step represents a quarter here).
capital-reserve	double	How much money the household has in, e.g. savings.
goal-frame	string	The goal frame the household is currently using to make decisions.
gain-orientation	double	A representation of the household's egoistic value strength.
greenness	double	A representation of the household's biospheric value strength.
hedonism	double	A representation of the household's hedonic value strength.
steps-total-energy-use	double	How much energy the household has used in this step.
breakdown-list	Appliances	A record of the broken appliances that the household has not yet replaced.
wish-list	Appliances	A list of appliances that the household desires.

Table 2. Dwellings

State variable	Type	Description
dwelling-id	string	An identifier for the dwelling.
dwelling-type	string	A descriptor for the type of dwelling (e.g. 4-bedroom detached house, 1-bedroom flat).
tenure	string	The type of tenure – e.g. owner-occupied, or rented.

Table 3. Insulations

State variable	Type	Description
insulation-state	string	A descriptor for the state of the insulation (e.g. 270mm loft insulation, no double-glazing, cavity-wall insulation).
fuel-use-factor	double	How a dwelling's space/water heating fuel use is adjusted for this insulation, relative to a dwelling with minimal insulation.

Table 4. Appliances

State variable	Type	Description
category	string	A high level category for the appliance (e.g. TV).
subcategory	string	A subcategory for the appliance (e.g. LCD TV, CRT TV, plasma TV).
name	string	Make and model of the appliance.
cost-list	double	List of purchase costs for the appliance in each step for which it is available.
breakdown-probability	double	Probability the appliance will break down in any step.
energy-rating	string	Energy rating for the appliance, if provided to buyers.
essential?	Boolean	Is the appliance essential for all households?
last-step-available	integer	Last step in which the appliance is available, if this is bounded.

Table 5. Consumption-patterns

State variable	Type	Description
for-dwelling-type	string	Dwelling type with which the consumption pattern is associated.
for-purpose	string	Purpose of consumption.
in-step	integer	Time of year with which the consumption pattern is associated (consumption for space-heating varies seasonally).

Table 6. Upgrades

State variable	Type	Description
upgrade-cost	double	Cost of making the insulation upgrade.

Table 7. Ownerships

State variable	Type	Description
age	integer	How many steps the household has owned the appliance.
broken?	Boolean	Whether the appliance is broken.

Table 8. Uses

State variable	Type	Description
units-per-use	double	How many units of the fuel the consumption pattern uses.

C. *Process Overview and Scheduling*

The model does the following in each time step:

1. Decide which owned appliances break down. All ownership links between households and appliances are checked against the appliances' breakdown probabilities.

2. Each household then does the following:

a. Choose goal frame. The goal-frame is chosen by choosing a random number R in the range 0 to the sum of the goal-frame value strength parameters (hedonism, gain-orientation and greenness): the probability of each goal-frame being selected is proportional to the current strength of the corresponding value.

b. Adjust goal-frame value strengths. This is done to implement a 'habit' component – the more a goal-frame is used, the more likely it is to be used in future. The habit-adjustment-factor parameter (H) is used to make this adjustment. If T is the sum of all goal frame parameters, then let A be the parameter corresponding to the selected goal frame, and B and C be the other two. $A$is increased by H, and B and C decreased by $H/2$. If the result causes A to be more than T, then adjustments are made to ensure that $A + B + C = T$, and that B and $C \geq 0$.

c. Compute the total energy use for this step from using appliances and space/water heating. For each appliance owned by the household, the step's fuel consumption and energy use is computed based on the consumption pattern associated with the household's type, the type of their dwelling, the usage mode, and the time of year.

d. Compute financial situation. The monetary cost of heating and running appliances is deducted from the capital-reserve of the household, and the income for that step is added (the income represents what is available to spend on direct domestic energy and related goods rather than total household income).

e. Replace broken appliances. If the appliance is essential and the household only had one of them before it broke, then a new item will be bought. If the home is rented the landlord is assumed to choose the cheapest replacement; otherwise the cost falls on the household and the choice criteria depend on the current goal-frame.

f. Update wish list (if goal-frame is 'hedonic' only). The wish list of the household is updated to contain items chosen in all of the following three ways (M, N and T are model parameters):

i. Up to M appliances (not to do with heating) each belonging to a different new subcategory introduced in the last N steps.

ii. One random item not already owned, seen on a visit to another household.

iii. One random replacement for an item more than T steps old.

g. Buy insulation (if goal-frame is not 'hedonic'). If the goal-frame is egoistic, then the household chooses an insulation state reachable from the current state that will save the most money and make a positive monetary saving over the planning horizon of the household. If the goal-frame is biospheric, then the household chooses an insulation state reachable from the current state that will leave a positive capital reserve and save the most energy.

h. Buy (non-essential) new appliances. If the current goal-frame is hedonic, then buy as many affordable appliances as possible from the union of the breakdown list and the wish list, but not more than one from the same category. An affordable appliance is one costing less than the capital reserve, plus the household's income this step multiplied by the credit-multiple-limit parameter. If the current goal-frame is egoistic, buy the cheapest possible replacement for one item on the breakdown list. If the current goal-frame is biospheric, buy the replacement for an item on the breakdown list, choosing that with the best energy rating (if supplied) or lowest breakdown probability (if not).

i. Visit social neighbours. Up to V (= visits-per-step) randomly chosen linked households may be visited each step (the number of *visits* will be less than V only if the household has no social links, but there may be multiple visits to a household). For each visit, the visiting household adjusts their goal-frame parameters; if the reciprocal-adjustment parameter is set to true, then the visited household also adjusts their parameters. Each goal-frame parameter G is adjusted in the following way: let G_i be the goal-frame parameter of the household making the adjustment; let G_j be that of the other household; then: $G_i = G_i + F(G_j - G_i)$ where F is the frame-adjustment parameter, set on the CEDSS interface. After this adjustment, if G_i is less than zero, G_i is reset to 0.

j. Update social links. With probability 0.5 either way, the household either loses a social link, if it has one, or gains a social link, if it currently has fewer than the maximum set by a model parameter. To lose a social-link, the household first determines the set of weak links – those with minimum appliance similarity (the number of appliances the two households have in common, minus the number of appliances that one has that the other does not). If this set has more than one member, then the set is reduced to those who have the maximum block distance from the household. If the set still has more than one member, then the link dropped will be randomly chosen from those the household has visited least. To gain a social link, the household determines the set of strong contacts – those with maximum appliance similarity. One of these is randomly chosen, and one of the households it is linked to (but the household updating its links is not) is selected, again at random.

D. Design Concepts

1) Basic Principles

The model is based on the psychological theory of 'goal-frames' [4], [5], discussed in section IV, in which households make decisions in one of three modes: 'hedonic', 'egoistic' and 'biospheric'; which mode they choose depends on the current relative strength of the corresponding 'values': stored parameters representing the household's 'hedonism', 'gain-orientation' and 'greenness'.

2) Emergence

Emergent properties of the model are the community-level consumption of energy from various sources, and the numbers of different appliances owned.

3) Objectives

Households must ensure they keep essential equipment running, otherwise, households' objectives depend on their dominant goal-frame. Hedonists aim to buy as many of their desired appliances as they can afford, egoists aim to save as much money as they can, whilst biospherics aim to minimise their energy consumption.

4) Prediction

Households may compute the expected running costs and space heating costs when buying appliances and considering insulation options, depending on the mode in which they are making decisions.

5) Sensing

Households are aware of appliances owned by their friends when they visit them.

6) Interaction

Households visit each other, according to their social links. They adapt their social links according to how similar their profile of appliances is with that of the people they visit. The profile of appliances is used as a proxy for lifestyle characteristics in the model, and the assumption is made that people are more likely to be friends with those having similar lifestyles. Visits result in guests wanting to acquire appliances that hosts have and they do not; and in some convergence of host and guest value strengths.

7) Stochasticity

Stochasticity is used initially in setting up social links, and may also be used in setting households' initial value strength parameters. It is used during a run in updating social links, arranging visits, selecting items to buy, determining the current goal-frame, and determining appliance breakdowns.

8) Observation

The model collects data on energy use (broken down by fuel), how much money households have, how many social links they have, how many of each category of appliance are owned by households in the community, how many of each category of appliances have been thrown away by the community, goal-frames used to make decisions, goal-frame parameters, and numbers of visits made per social link.

II. Design and Parameterisation

Model design was determined jointly by the purpose of the model (constructing policy-relevant scenarios of future direct domestic energy demand); the environmental psychology literature; the peer-reviewed, grey and commercial literature on domestic energy and appliances; public domain datasets, related to domestic energy use in the UK (from the UK Department of Energy and Climate Change and Office for National Statistics); a series of "ontology-elicitation workshops"; and the results of a questionnaire-based survey of 397 households – 197 of them urban, 200 rural.

The model's key social-psychological assumptions are that households make domestic energy-related decisions under the influence of competing top-level goals [4], [5] which express individual or group values, often conflict, and vary in strength over time and with context; and that such decisions and such values have a habitual component [6]-[8], but are also subject to social influence [9]. "Hedonic" goals concern immediate good or bad feelings, "egoistic" goals access to resources, and "normative" goals, social norms. We found, however, no detailed work on how such goal/value conflicts are resolved, or on networks of social interaction in relation to domestic energy use, so the specific algorithms used in these aspects of the model are chosen for simplicity and computational convenience. The sources related to domestic energy use provided information on household demand for space- and water-heating; the availability, prices, energy requirements and other and properties of domestic appliances and energy-related equipment; time series of fuel prices, household income, capital and energy-related spending and percentages of households owning specific equipment. The workshops, with members of a project stakeholder advisory group and non-modelling members of the project team, produced informal ontologies that influenced the model structure, particularly in relation to electrical appliances.

The survey of households provided data on their dwellings, equipment and equipment use, energy demand (use of electricity, gas and oil is modelled – data from the few households primarily using other fuels was excluded), finances, and values as expressed in the answers to questions about energy use and environmental issues, as of 2010. To model changing energy demand over a future period of decades with any confidence at all, however, we needed to show that the model could reproduce to an acceptable level the past trajectory of such demand. We therefore needed to "retrodict" plausible states for the sampled households at some time in the past. If running the model forward to mid-2010 then gave energy demands close to the figures derived from the survey, we could have sufficient confidence in the model to extend such runs to mid-century with the expectation of getting meaningful and useful results. 2000 was the earliest "retrodiction date" for which we could collect adequate data.

A wide range of public domain sources was consulted, but the most important of those used directly in constructing the CEDSS parameter files were as follows:

- UK Department of Energy and Climate Change (DECC) time series of prices for domestic electricity, gas and heating oil (taken from files qep413.xls, qep551.xls and qep591.xls).
- DECC's *Great Britain's Housing Energy Fact File 2011* [10].
- DECC's calculations of the energy requirements of household heating systems and domestic appliances [11].
- UK Office for National Statistics (ONS) "Family Spending" series, used for 2000-2010 time-series estimates of spending on fuels, household appliances, and household maintenance and repair, by each gross income decile of the UK household income distribution; and the percentage of households with washing machines, tumble dryers and dishwashers in 2000 and 2010 [12].
- An Institute for Fiscal Studies Working Paper [13] provided figures on the net wealth of the UK population, stratified by income quintile, in 2000.
- Argos catalogues, 2000-2010. Argos is a UK retailer, selling a wide variety of household appliances. CEDSS requires a list of appliances offered for sale, with prices and (where they exist) energy efficiency ratings, for each quarter-year covered by a run. Those used in the model were sampled from these catalogues. The catalogues contained little computer equipment, so this could not be included in the model.

These and other data sources were used, together with the survey results, to construct a version of the survey households as they might have been in material terms most relevant to direct domestic energy use: dwelling type (assumed to be the same as in the 2010 survey) heating system, home insulation, domestic appliances (lighting was not surveyed in enough detail for modelling), income and liquid capital.

The 397 "millennium households" were divided into urban (Aberdeen, 197 households) and rural (Aberdeenshire, 200 households) subsets, and these were used to populate separate imagined communities – conceived of as an urban estate or a village respectively, and embedded in a grid of streets and junctions. CEDSS has the capacity to simulate demographic change, but this has yet to be used; instead, all households were given a "size" equal to the mean number of people in their subset (urban or rural) of households in the 2010 survey. (The model uses this number only in calculating energy used in water-heating: space-heating and domestic appliance demand are not affected.)

The households were assigned an initial set of value strengths. These were not drawn from data, since results from the survey did not indicate any clear relationship between values *as expressed in the answers to survey questions* and domestic energy demand. Instead, the value strengths (representing values that affect the purchase decisions being modelled), were assigned to households at random from distributions treated as free model parameters.

At the start of some model runs, households were also assigned initial social links, in ways that made closer neighbours more likely to be linked, but allowed the possibility of linkage for any pair of households.

The model readily reproduced qualitative features of domestic energy demand over the period 2000-2010, known from national statistics: the reduction in energy used for heating due to the installation of more efficient boilers and better insulation, and the partial offsetting of this improvement by the increase in the number of electrical appliances bought for and used in the home. The model was calibrated on the urban community, then the chosen version was validated by applying the same parameter settings to its rural counterpart, thus following the procedure of using half the available data to calibrate a model, then testing it on the other half. The calibration process involved two stages. The variants of the model were assessed primarily on the *sum* of the absolute differences in eight categories of all-household energy demand (electricity, gas and oil used for space-heating and water-heating, and electricity and gas used for domestic appliances) and the corresponding model results for 2010. The first stage varied parameter settings affecting the income, planning horizon (how far ahead the household looked in certain decisions), tendency to act habitually, ability to access credit, and values of the households, and whether social interaction was present or absent. The selected model variant from this phase was used as the basis for the second phase, in which income, and settings influencing the "wish-list" of desired appliances were varied. The variant selected from this second phase (henceforth, the "calibrated model") was then tested on the rural "community", with reasonably satisfactory results: the only areas in which there were errors (i.e. absolute differences between survey and model results in 2010) of more than 10% were gas used for appliances, and electricity for space heating, both minor contributors to total energy demand.

The collection and use of empirical data, their integration into the model, and the processes of calibration and validation, are described in more detail elsewhere [14].

III. Results

The calibrated model has now been used to explore a range of possible scenarios for the period to the end of 2049. In a scenario run, the calibrated model is run from 2000-2010, using past data about household incomes and spending, energy prices, and the availability and prices of domestic heating and domestic appliance technology; it then continues using data constructed to represent a scenario: a possible future set of conditions for domestic energy use. Our initial investigations have focused on four variable features of possible domestic energy futures: two are economic factors, the others directly concern policy options:

1. Economic factors:

a. Household incomes. We have examined scenarios where these are stable (in relation to appliances prices), and where they are rising at 2% per annum.

b. Fuel prices. We have examined scenarios where these are stable (relative to appliance prices), or increase at either 2% or 4% per annum. (Fuel prices are of course affected by policy decisions, and policies on taxation and/or subsidy may be aimed at reducing or increasing energy demand; but these prices are also affected by factors beyond the control of policy makers.)

The different trajectories for incomes and fuel prices, combined, define six families of "income-fuel-price scenarios".

2. Policy options:

a. Regulation of the energy efficiency of appliances. By default, we have assumed no such regulation. Alternatively, we have assumed that once sufficient choice is available of a particular type of appliance at or above a particular energy-rating, appliances with lower ratings are no longer allowed to be sold.

b. Subsidisation of boiler replacement and insulation measures. By default, we have assumed that prices of boilers and insulation measures remain the same. Alternatively, we have assumed that these prices are subsidised from 2015, falling by 30% at that date.

Regulation and subsidisation together define four clusters of “policy scenarios”.

In total, we thus have 24 scenarios, grouped in four policy-defined clusters, which cut across six income-fuel-price defined families. We report results from using the urban millennium community (those from the rural millennium community appear similar). Each of the scenarios has been run 256 times, for a total of 6,144 runs. Statistical analyses undertaken so far are based on the energy demand, summed across the simulated community, for all uses, for space heating, for water heating, and for domestic appliances, recorded for each of the years 2009, 2019, 2029, 2039 and 2049.

Overall, the differences between scenarios were quite small (less than 5% for total demand and space-heating demand, even less for water-heating, although in some cases over 10% for domestic appliance demand). Total, water-heating and space-heating energy demand decline steadily over the whole period, although fastest before 2010, and increasingly slowly thereafter. Appliance energy seems first to grow, then from around the 2030s decline, in a jerky fashion, which awaits further investigation.

Both 2-way ANOVA (economy*policy) and 4-way ANOVA (incomes*fuel-price*regulation*subsidisation) were undertaken for each of the 20 combinations of year (2009, 2019, 2029, 2039, 2049) with type of demand (total, space, water, appliances), together with non-parametric Kruskal-Wallis tests. The last were added because the sample of runs did not fully meet the usual criteria for an ANOVA: in some scenarios, distributions of the some of the 20 demand measures showed significant deviations from normality, and for some measures, variances differed by more than a factor of 2 between some pairs of scenarios. We focus here on the 4-way ANOVAs; results from the other procedures were fully consistent with the 4-way ANOVAs, but less informative. The main results are fairly clear.

- In 2009, none of the main effects are significant for any of the 4 types of demand, as expected.
- For total demand, income and fuel-price both have effects significant at the .001 level from 2019 onwards (growth in income raised demand, increases in fuelprice reduced it by a greater amount) and both the interaction of these two factors (income:fuelprice) and regulation, have significant effect at the .001 level from 2029 (regulation reduces demand).
- For appliance demand, income, fuelprice, regulation and income:fuelprice have significant effects at the .001 level from 2019 onward (regulation and fuelprice increases reduce demand, income growth increases it; fuelprice has the greatest effect, followed by income and regulation). Subsidy also has effects (slightly increasing demand) significant at varying levels from 2019. It’s interesting that this shows up here but nowhere else: if the effect is real, it is presumably a result of subsidies freeing up money to be spent on appliances.
- For space-heating, among main factors in the 4-way ANOVA only fuel-price has a significant effect, (at .001 level, with rising prices depressing demand).
- For water-heating, there are no significant effects.

Figure 2 shows heating demand (space- and water-heating combined) and appliance demand for those scenario runs without either regulation of inefficient appliances, or subsidies for new boilers and insulation. The difference made by both income and fuel-price factors to the appliance energy demand are evident. Effects of these factors on heating demand are less apparent, but it is clear that almost all the runs with heating demand below 3,150,000 kWh belong to scenarios in which fuel prices increase faster than income. Figure 3 illustrates the effects of regulation and subsidisation, in the case where fuel prices are increasing at 4% per year

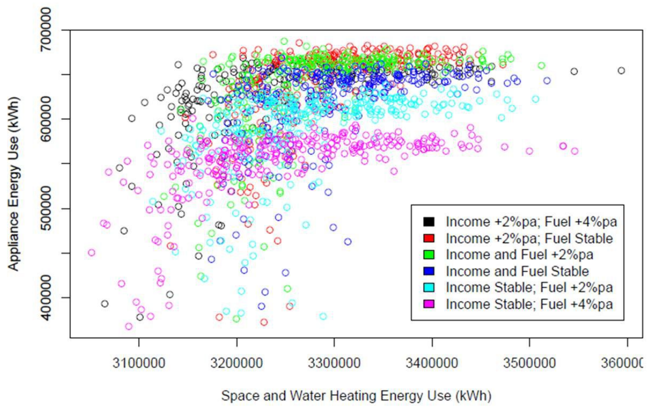

Fig. 2: Heating and appliance energy use 2049, no regulation or subsidisation

while incomes are stable. The effect of the regulation of inefficient appliances on appliance energy demand is reasonably apparent, in the clustering of black and green circles, representing those runs without such regulation, toward the top of the figure. The effect of subsidisation is less obvious, but among runs with the lowest appliance energy demand, most are those with regulation but without subsidy (blue).

The scatter plots of figures 2 and 3 also show a common spatial pattern, with most of the runs grouped toward the top of the figure (high appliance energy use), and a small number in the lower left quadrant (low appliance and heating energy use), but none with high heating energy use and low appliance energy use. Investigation indicates that this pattern is probably due to the dynamics of value strengths in CEDSS. The calibrated model has value strengths assigned to the households which were drawn once-for-all from distributions designed to favour hedonic and egoistic values over biospheric values; but by chance the average initial strength of hedonism is slightly greater than that of egotism, and most runs appear to end up with hedonism predominant in the community: the runs in the lower left quadrant are those

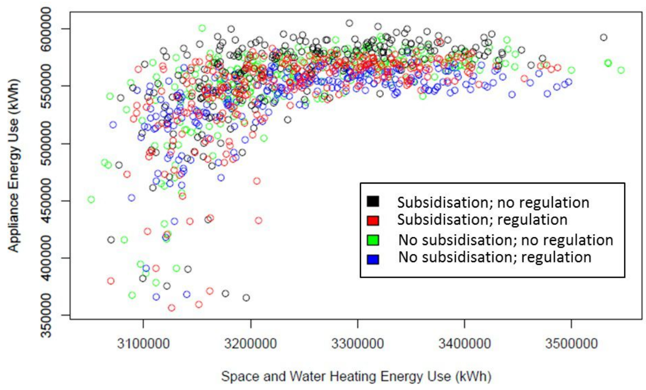

Fig. 3: Heating and appliance energy use 2049: incomes stable, fuel prices rising 4% p.a.

where this has not happened: a positive correlation between level of hedonism and total, space-heating and above all appliance energy demand is found in all scenarios.

It is also interesting to examine the changes in energy demand over time. Looking first at total energy demand, there is a common pattern across all conditions, of a relatively sharp drop during the first decade – the period up to the 2010 survey – followed by a markedly slower and nonmonotonic decline throughout the period to 2049. Fig. 4 illustrates this for the condition in which neither regulation nor subsidisation was applied, and both income and fuelprice were stable. Comparing this with the picture for space-heating alone (the largest component of demand), shown in Fig. 5, we see that the overall pattern is similar, but the decline is smoother in three respects: there is no longer an obvious kink in the curve at around 2010, the decline thereafter continues to slow, although more gently, and the “wobbles” in the curve disappear. The picture for water-heating (Fig. 6) is similar, but that for appliance demand (Fig. 7) has a completely different appearance: an initial rise and fall during the first decade, followed by an initially sharp then slowing rise, turning to a fall around 2040, and with a superimposed “saw-tooth” pattern of smaller but sharper rises and falls.

The patterns found in the space-heating and water-heating demands are due to a combination of the replacement of old, non-condensing boilers by more efficient condensing ones – something that would be expected to slow down as the proportion of households with a non-condensing boiler falls towards zero – and the addition of new insulation measures –

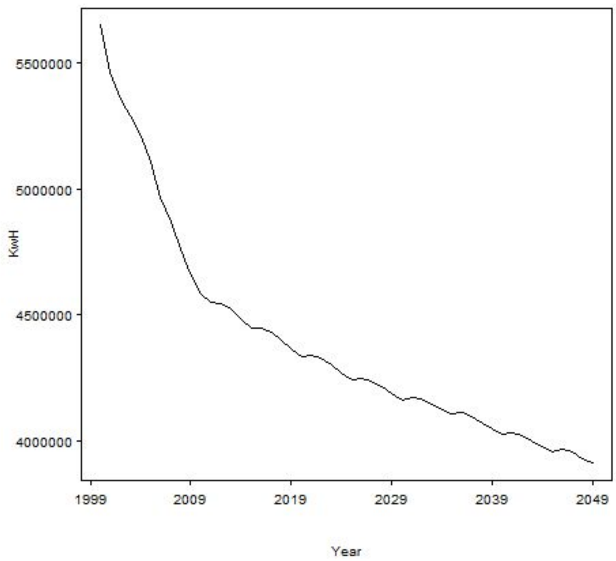

Fig. 4: Total energy demand over time, no regulation or subsidisation, incomes and fuel prices stable

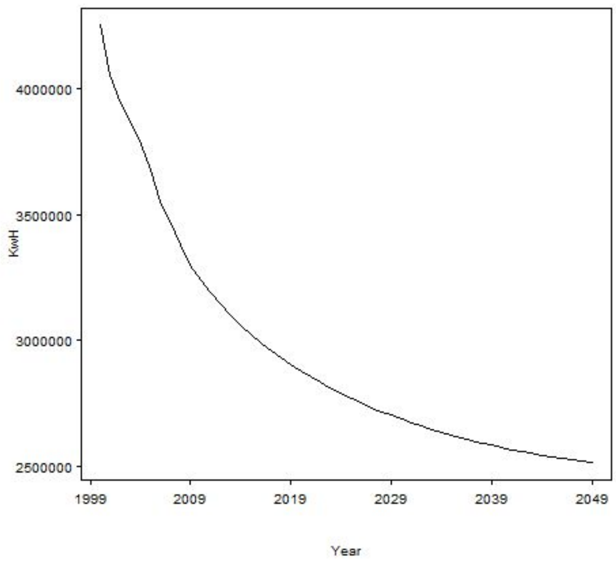

Fig. 5: Space-heating energy demand over time, no regulation or subsidisation, incomes and fuel prices stable

which might also slow down as the cheaper measures, such as double glazing and loft insulation are completed, leaving only the more expensive wall insulation as a possible heat-loss reduction measure. The pattern found in appliance energy demand is less readily accounted for, although the jerkiness may be a result of the schedule on which new, generally more energy-efficient appliances were introduced during the

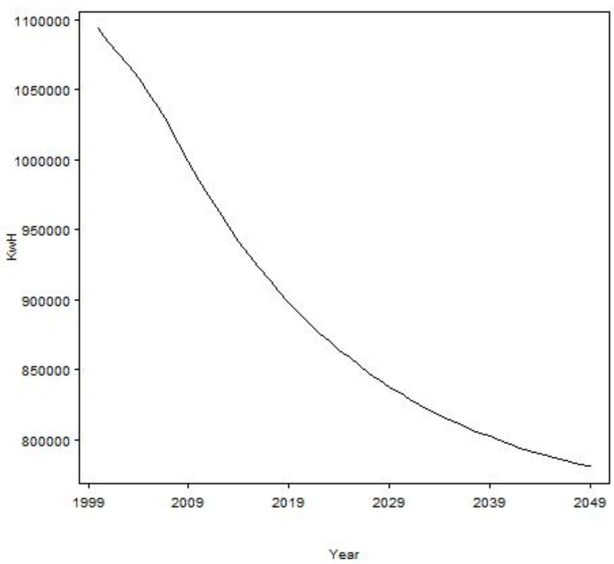

Fig. 6: Water-heating energy demand over time, no regulation or subsidisation, incomes and fuel prices stable

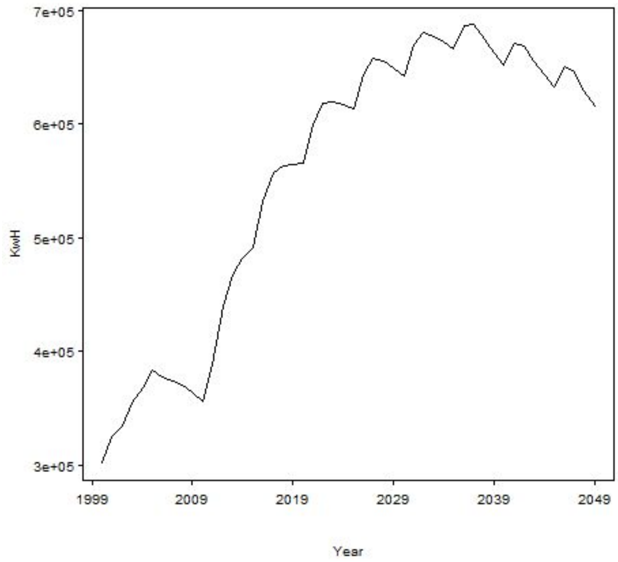

Fig. 7: Appliance energy demand over time, no regulation or subsidisation, incomes and fuel prices stable

post-survey scenario era: there does appear to be a roughly 5-year periodicity in the oscillations.

The overall pattern of usage does continue a key feature of that known to have occurred at a national level over the past decade, at least until the late 2030s,: reduction in demand for space-heating (after a long period when this demand rose as households became accustomed to warmer rooms) and water-heating, as more efficient boilers and better insulation have been adopted, while the demand for appliance use has increased considerably [12], because although there have been efficiency gains in this area too, they have been outweighed by increases in the number of appliances owned by households, and also the size of refrigerators, freezers and televisions – as described in [15], and reflected in the contents of the Argos catalogues we used. The transition to a fall in appliance demand toward the end of the scenarios probably reflects the fact that we have not yet attempted to extrapolate the trends to larger appliances, and to a greater variety of appliances in the scenarios. We have allowed the number of appliances per household to continue to rise, but this trend may have reached saturation point (reflected in the limits we set on the number of appliances of each category a household could possess) by around 2040.

IV. Discussion

Household energy use and personal transport account for a considerable proportion of total energy use, and greenhouse gas emissions, in rich countries. In Europe, about 35% of all primary energy use and 40% of all greenhouse gas emissions come from private households—with regional differences

[16], [17]. Home energy, personal travel, and food and beverages are the most important sets of activities. US studies find similar results [18]. Given the vital importance of reducing greenhouse gas emissions from energy use, it is surprising how little attention has been given to the dynamics of household energy demand; and in particular to the interactions between technological change – which can act both to reduce energy use through greater efficiency, and to increase it by producing an unending supply of new household appliances – economic conditions, policy, and socio-cultural forces. CEDSS goes some way toward filling that gap in the area of agent-based modelling.

We are not aware of any previous agent-based model that has investigated household decision-making processes in this area. Perhaps the most relevant previous studies have concerned water usage in the UK [19], [20]. The process of designing and implementing such a model in itself has revealed many of the complexities of how people think about their domestic energy use, and energy using and energy saving equipment. It has also perhaps clarified how agent-based modelling can complement more established approaches to social science, which in this area tend to focus on what people say about their energy use and its relationship to their values, as opposed to hard data about the decisions they make and their medium to long-term consequences.

Reference [21], surveying ABMs described in the literature between 2000 and 2008, distinguished three segments of a continuum with regard to a model's purpose: as a "Generator", "Mediator" or "Predictor", differing primarily in how well the system modelled is understood before the ABM is designed. When the real-world system is very well understood, the model is used "like a calculator to provide clear and concise predictions about the system": a "Predictor". When the state of understanding is intermediate, it "provides insight into the system, but is not a complete representation of how that system actually behaves" – acting as a "Mediator". When the system is little understood, the model is used as a "Generator", i.e. to generate hypotheses about it. In these terms, CEDSS is a "Mediator" (the definition of a "Predictor" is so strict that [19] found no "Predictors" among the 279 models surveyed. Even the assembly of data sufficient to inform the construction of a "Mediator" was a considerable task.

Another dimension on which ABMs can be classified is the relative importance of theoretical and empirical constraints in determining model design. CEDSS is near to the empirically-constrained end of this spectrum (as for most ABMs, and as has been made clear in this paper, there are also aspects of the model design that are constrained by neither theory nor empirical evidence). However, the theory of goal-frames has been a significant influence on our work, so we take the opportunity of this discussion section to outline it in a little more detail, and reflect on how far CEDSS captures its main features, and, in the context of future work, how we might expand or modify the model to improve this match.

Goal-framing theory [4], [5] proposes that human perception and decision-making are organized in a broadly modular way (broadly, in that the "modules" are not impervious to each others' influence), with the top-level modules corresponding to three overarching goals, each including and organizing a large number of subgoals and ways of achieving those subgoals. As already mentioned, these high-levels goals can be termed "hedonic" (feeling good), "egoistic" (protecting and improving resources) and "normative" (acting appropriately, in terms of social norms). At any one time, one of these top-level goals will be focal, establishing a "goal-frame" that directs attention and steers decision-making – although the non-focal top-level goals will still in general have some influence. The hedonic and egoistic overarching goals are considered, in general, to be stronger than their normative counterpart. It was noted in section II that the best match between CEDSS and the survey results on direct domestic energy use were found when the strength of biospheric values was assumed to be low relative to hedonic and egoistic values.

Within goal-framing theory , situational cues are considered capable of triggering goal-frame switches on the short timescales explored in psychology experiments [22], [23], but within CEDSS, changes in goal-frame occur only once per time step (monthly in the runs reported here). It would be possible to alter the model code to allow switches of goal-frame within a time step, but it is not clear that this would actually improve model performance. Intuitively, it seems likely that there are fluctuations on multiple timescales in the proportion of the time each of the three overarching goals is focal, depending on multiple factors, including the influence of social contacts [9], and habit [6]-[8], as currently implemented in CEDSS; but also factors which do not affect the choice of goal-frame in CEDSS, such as household financial situation (which does nevertheless affect purchasing decisions when the goal-frame is hedonic – this can be seen as an example of the influence of non-focal goals referred to above), and exposure to advertising, news items and publicity campaigns, which are not currently modelled.

Returning to empirical constraints on CEDSS, while the survey data has been essential to our modelling work, in order to implement a model that could plausibly tell us something about the future, we needed to be able to model the recent past, and change over that period; and in order to do that, we needed a wide range of quantitative data about the recent past: energy prices, household incomes, heating systems, insulation measures, the prices and properties of household appliances. This information is not readily available in convenient forms and formats, and we needed to make more assumptions than we would have liked. Where we were unable to access any relevant data – as in the case of the influence of social contacts on purchase decisions – we have been obliged to experiment with different parameter settings to calibrate those aspects of our model. The fact that we were nevertheless able to construct a version of the model that reproduced trends known from national datasets, and produced outcomes in the present that were quite close to those indicated by the survey, we regard as a vindication of the agent-based modelling approach. The main results from the future scenarios reported in the preceding section appear plausible.

Nevertheless, the model does show some anomalous or questionable behaviours. Some of these have been mentioned in the results section. The predominance of hedonism in most scenario runs is another, for which further investigation is planned. If this outcome is the result of the small initial imbalance mentioned, it could indicate that our value strength adjustment algorithms, which are admittedly not empirically based, are too sensitive to initial conditions; if it is due to some other cause, we need to understand it. Another anomaly uncovered in the scenario output is that the households tend to accumulate too many televisions, while seldom replacing other non-essential items such as dishwashers and dryers. The calibration and validation procedures could also be criticized as insufficiently thorough, since they did not detect these anomalies.

Our future work on CEDSS will involve a survey of the model's behaviour over its parameter space that is both broader and more detailed (measuring more aspects of the output from runs) than that briefly described here; and the selection of a range of model variants rather than a single variant for use in future scenarios, thus allowing us to determine which parameters make the most difference to outcomes, and to provide policy-makers with appropriately qualified forecasts of likely direct domestic energy demand under a range of assumptions both about exogenous influences (economic conditions and policy decisions, which we have already begun to explore as described), and also about intra-household and intra-community dynamics, and socio-cultural trends, such as external influences on the strength of biospheric values, which we have not.

It is difficult to envisage domestic energy use being reduced as much as emission reduction targets require over the period of the CEDSS scenarios, without considerable behavioural change. Here, goal-framing theory can help us to devise appropriate scenarios, and where necessary, extensions to CEDSS itself. In goal-framing theory terms, such behavioural change would require increasing the proportion of decisions for which the normative goal-frame is focal, and [5] discusses possible ways in which this could come or be brought about: strengthening of the underlying normative (and specifically biospheric) values by "moralization" (in this context; explicit social disapproval of excessive energy use), exposure to good examples both of directly relevant behaviour ([24] showed that learning that neighbours used less energy than themselves prompted people to reduce their own energy use), and of prosocial behaviour in general [25]; and increasing capacity for "self-regulation". This is the ability people have to increase the likelihood they will act in ways they wish to act in order to satisfy long-term goals, despite temptations not to do so. In the context of encouraging proenvironmental behaviour, self-regulation capacity can be augmented by improving feedback, reducing conflict of the normative goals with hedonic and egoistic goals, and communicating concrete, low-level norms (specific behavioural rules) that are clearly linked to the targeted higher-level norm – in this case, reducing domestic energy use. We intend to explore ways to implement these mechanisms within CEDSS. "Moralization" can be explored by providing exogenous boosts to the strength of households' biospheric values, representing government publicity campaigns; the effect of good examples by providing households with information about the average energy use in their neighbourhood; and making self-regulation easier by providing more detailed information about the household's own energy use, as can be done in the real world using smart metering. Finally, we also intend to implement the demographic functions of the model, and extend it to deal with travel and food consumption, once we have adequate data.

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