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An agent-based model for energy service companies

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ABSTRACT

The residential housing sector is a major consumer of energy accounting for approximately one third of carbon emissions in the United Kingdom. Achieving a sustainable, low-carbon infrastructure necessitates a reduced and more efficient use of domestic energy supplies. Energy service companies offer an alternative to traditional providers, which supply a single utility product to satisfy the unconstrained demand of end users, and have been identified as a potentially important actor in sustainable future economies. An agent-based model is developed to examine the potential of energy service companies to contribute to the large scale upgrading of household energy efficiency, which would ultimately lead to a more sustainable and secure energy infrastructure. The migration of households towards energy service companies is described by an attractiveness array, through which potential customers can evaluate the future benefits, in terms of household energy costs, of changing provider. It is shown that self-financing is a limiting factor to the widespread upgrading of residential energy efficiency. Greater reductions in household energy costs could be achieved by committing to longer term contracts, allowing upgrade costs to be distributed over greater time intervals. A steadily increasing cost of future energy usage lends an element of stability to the market, with energy service companies displaying the ability to retain customers on contract expiration. The model highlights how a greater focus on the provision of energy services, as opposed to consumable products, presents a viable approach to reducing future energy costs and usage.

1. Introduction

All households require energy to attain a desired level of comfort and a basic standard of heating, lighting and hot water. Individual requirements vary by house type (e.g. size, construction) and occupancy. Rising energy prices due to the depletion of natural resources and environmental policies have led to increased pressure to reduce and optimise consumption [1]. In addition, concerns about environmental sustainability have intensified efforts to reduce global carbon emissions. Globally, housing is a major consumer of energy and in the UK residential dwellings account for approximately 30% of CO_2 emissions [2] while the service sector, which incorporates all commercial and public buildings, accounts for only 11% [3]. Enhancing the energy efficiency of this housing stock could greatly contribute to the potential global energy reductions attainable in this sector [4], while also addressing the burden of rising energy prices by reducing annual utility costs.

Energy is supplied to end-users through an established physical network, which co-exists and operates in parallel with other utility networks (e.g. water, communications), collectively composing the national infrastructure [5]. Households achieve their desired level of comfort (e.g. temperature, hot water, personal device usage) by purchasing energy from utility companies that supply products such as electricity and gas. Traditionally, consumers receive each individual utility through a product specific infrastructure system and pay the relevant supplier for the quantity of product consumed. This system operates on the implicit assumption of continually meeting the unconstrained demand of the consumer. The responsibility for sourcing, installing and maintaining all appliances is assumed by the consumer, who also takes full responsibility for any energy saving activities, either by purchasing more energy efficient technologies or through individual actions. The need to reduce and optimise energy usage, while maintaining household requirements and minimising carbon outputs, has led to more integrated approaches being adopted for energy provision services. This need has seen the development of Energy Service Companies (ESCOs) [6], which have been promoted by legislative measures at both the national and European levels [7]. Such companies provide energy services to the end-user, with services varying from guaranteed savings on the cost of energy to the installation, operation and maintenance of electrical equipment [8].

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Improvements to energy efficiency must first overcome complex and interdependent barriers at consumer, manufacturer, financial and government levels [9]. In parallel, improvements can be accelerated by a better understanding of the drivers that push increased energy efficiency, such as consumer awareness, price and technology [10]. Improved building efficiency can be achieved through the installation of new technologies, such as improved heating, ventilation and air conditioning (HVAC) systems [11] or window alternatives [12], in addition to changing resident's attitudes and behaviours [13]. ESCOs, by offering an alternative to the traditional energy provider, could play an important role in promoting more efficient energy usage [6] by providing a service (e.g. thermal comfort) rather than an unconstrained quantity of a measurable resource (such as gas or electricity). As such, the needs of consumers can be satisfied at reduced costs, reduced levels of energy usage and in a more sustainable fashion. Overcoming the existing barriers will require technology and policy changes that recognise the interdependence and interconnectedness of existing infrastructure systems. At the domestic level, energy reductions at the scale of individual devices or appliances offer only incremental improvements in overall efficiency and a building level approach, in terms of both energy management and human behaviour, may provide greater opportunities for increased reductions [14]. In the UK, there is an aging household population, with more than 77% of current houses being built before 1980 [15]. The current housing stock numbers approximately 27.6 million and less than 180,000 new structures are built each year [16]. This indicates that upgrading the efficiency performance of existing households would be required to substantially reduce energy consumption in the near future.

Agent-based models are increasingly being used to model and analyse the complex nature of infrastructure systems [17], with energy efficiency receiving notable attention [18]. In such models, agents are independent entities (e.g. people, households, businesses) capable of interacting with each other and adapting to changes in their environment [19]. The concept of the economy as a complex system of interacting economic and human agents is well established [20] and has been applied to the emergence of technological innovations across the infrastructure domain, for example water-saving technologies [21] and hybrid electric vehicles [22]. Agent-based models applied to energy service innovations and the adoption of new technologies has also received attention in the literature [23]. Improvements in energy efficiency at the building level are influenced by both energy management and human behaviour [14], and the ability to represent individual actions and decisions provided by the agent framework is a valuable tool in modelling the evolving nature of consumer behaviour and its impact on energy systems. The impact of this individualistic behaviour is evident in the UK where, in the six years from 2007 to 2013, mean domestic electricity bills have increased by 39% and household gas bills by an astonishing 65% [24]. While rising energy costs undoubtedly contribute to this, consumer behaviour is also implicit, with the average number of electronic and computing devices per household increasing by a factor of 6 between 1980 and 2011 [2]. Therefore, improved household energy performance can only be achieved through a combination of technological improvements and behavioural changes. Agent based models are uniquely positioned to describe such heterogeneous populations. Individual level factors that may tempt consumers away from traditional energy providers would include reduced costs, removed risk of appliance failure and reduced energy consumption, which would particularly appeal to the more environmentally aware consumer. However, reduced costs are partially achieved by spreading the fixed cost of upgrading household energy efficiency over longer periods of time which necessitates long term contracts, typically 5–10 years [6]. Consumers could be hesitant to engage in such prolonged partnerships and may also reject the loss of control and/or ownership of their utility supplies and appliances.

This paper presents a model for the energy efficiency upgrading of the residential housing sector, through the introduction of energy service companies. An alternative arrangement to the traditional provider is considered, whereby all household energy needs are met by a single provider, the ESCO. An agent-based framework is implemented, in which household agents interact with energy provider agents. The ESCO agents supply all energy needs (e.g. electricity and gas) and are responsible for installing, maintaining and upgrading existing household energy technologies. The migration of households towards the ESCO providers is determined from an attractiveness array, from which the potential benefit of household upgrades can be weighed. The agent methodology and structure is presented in Section 2, where the economic actors (households and energy providers) are formulated and characterised. The model implementation and agent behaviours are also outlined. A market scenario, incorporating a single traditional energy provider and two distinct ESCO agents, is considered in Section 3. The market share achieved by each provider agent is adopted as the indicator of business success. The performance of the energy providers is analysed under varying market assumptions and business strategies. The model investigates the potential of the ESCO providers to create business models that compete with the traditional provider, while increasing the energy efficiency of the residential housing sector.

2. Agent-based model for the energy market

The market dynamics of the interactions between energy provider companies and the residential household population is modelled. Two distinct types of energy provider are considered. A traditional provider supplies energy to households through a single utility (e.g. gas or electricity) and offers no additional energy services. Households pay for the energy used and are not tied into a long term contract. Therefore, such households would assume sole responsibility for upgrades in energy efficiency, through the purchasing and installing of new appliances and insulation. The other type of energy provider considered, the ESCO, supplies multiple utilities (e.g. gas and electricity), in addition to managing and maintaining a customer's household energy systems. Furthermore, upgrades in household energy efficiency would be undertaken by the ECSO, with costs repaid by the customer over the duration of the contracted period. In the agent-based framework, three unique agents are defined to represent the traditional provider and two ESCO providers with potentially different business strategies, which are labelled ESCO A and ESCO B. Energy providers are indexed by k for $k \in [1, 2, 3]$, denoting the traditional provider, ESCO A and ESCO B, respectively.

A second agent type is defined to represent the heterogeneous household population. At any time t, a total of $H(t)$ household agents exist and each of the energy providers supply energy to $H^k(t)$ households, such that the total household population is given by

$$H(t) = \sum_{k=1}^{3} H^k(t).$$

The household agent population will grow due to construction at a rate of h new houses per year. The agent construct allows the heterogeneous characteristics of households to be incorporated into the market dynamics. A household agent describes the physical dwelling itself, in addition to the resident population. It is assumed that dwellings are homogeneous in all aspects (e.g. size, occupancy) and differ only in their unique energy efficiency rating. In the UK, all residential buildings are evaluated as part of the

Table 1
SAP ratings and bands. *Source:* [25].

Rating	Band
1–20	G
21–38	F
39–54	E
55–68	D
69–80	C
81–91	B
92–100	A

Standard Assessment Procedure (SAP) and assigned an energy performance rating [25]. This rating is expressed on a scale of 1–100, with higher values indicating better performance. Based on this rating houses are assigned to a band, Table 1. An Energy Performance Certificate (EPC) is issued for each dwelling documenting the SAP rating. The mean SAP rating in the UK is 58.5, with more than 75% of houses in the range 39–68 (bands D and E). For convenience, 11 levels of energy efficiency are constructed defined for $i \in [0, 10]$, which represent efficiency percentages of $[0\%, 10\%, 20\%, \ldots, 100\%]$. Thus, at any time t, the number of customers supplied by each company satisfies

$$H^k(t) = \sum_{i=0}^{10} H_i^k(t) \quad \text{for} \quad k = 1, 2, 3.$$

This structure is used for computational convenience and could be mapped to the official SAP energy bands given in Table 1.

Each agent type has a number of defining attributes. Energy providers are distinguished by the duration of the contract they offer to customers, c_k, and the number of staff they employ. Staff are further segregated into sales, $s_k(t)$, and service staff $p_k(t)$. The former interact with the household population to gain new customers for the company. The latter represents all other staff which could include the legal and marketing departments, in addition to the installation and maintenance crews. The business model of the ESCO, which oversees all customer energy systems, would, undoubtedly, necessitate a larger service staff than that required by the traditional provider. Companies gain and lose customers due to the interaction between household agents and sales staff from each of the energy providers. Sales are represented by households moving up efficiency levels but remaining with the same provider (*internal* sales), or signing up with a different company (*external* sales). Thus, the change in the number of customers signed to a particular company is solely determined from the external sales. A household agent choosing to upgrade or change energy provider will sign a contract for c_k years and, on expiration, may remain indefinitely with their current energy provider while becoming available as a potential customer for other providers. Therefore, all households are flagged as *off-market* or *on-market*, to represent houses currently under contract to an energy provider or available for recruitment, respectively. A household flagged as *off-market* is further classified by the duration of time remaining on the contracted period. Finally, each household is also designated a status, as *inert* or *active*. *Inert* households will always reject the possibility of changing their efficiency level or energy provider. These households could represent, for example, dwellings that cannot alter their status as a result of the construction characteristics. Furthermore, the inert population could be interpreted as representing socially or geographically isolated dwellings that would experience delays in exposure to new technologies or services. In this case, as the household take-up of ESCO services increases this isolated sub-population would become increasingly aware of the available services due to their network of social contacts and positive word-of-mouth. To describe such phenomena, it will be assumed that, as the proportion of the market captured by the ESCOs (A or B) increases, the number of inert households decreases, representing an increasing likelihood to purchase a contract with an ESCO provider as a greater number of social contacts migrate towards the ESCOs.

2.1. Model implementation

2.1.1. Agent initialisation

At time $t = 0$, each company agent for $k = 1, 2, 3$ is assigned a fixed contract length, c_k, which remains constant for the duration of the simulation. The traditional provider is initialised as the only energy provider in the market, such that the ESCO providers have zero customers at the outset. Furthermore, a contract with the traditional provider will be fixed as the duration of a single model iteration, such that customers are not removed from the market but also cannot change provider twice in a single time-step. Initial staff numbers, for both sales and services, must also be assigned to each agent and these properties evolve as the market dynamics evolve. Household agents are designated an energy efficiency, which is randomly assigned by a user-supplied probability distribution. All households are flagged as *on-market* and are thus immediately available for recruitment by the company agents. The initial *inert/active* status of agents is randomly assigned by declaring a fixed probability of a household being *inert*.

2.1.2. Market dynamics

In each time interval of duration Δt, representing one model iteration, each company makes contact with $s_k(t)Y_k\Delta t$ random households, where Y_k is the average number of customers each member of staff contacts per working day. The order in which companies approach households is randomised to prevent any one company form obtaining an advantage in the market. Households flagged as *off-market* or *inert* will always decline to upgrade efficiency and/or switch provider. If contacted by its current energy provider, a household can choose to remain at its current efficiency level or to move up the efficiency scale to a higher level. If contacted by another company, a household can choose to remain with its current company, move to the new company and remain at its current efficiency level, or move to the new company and move up the efficiency scale to a higher level, Fig. 1. This decision is determined from an *Attractiveness* array. Switching company or upgrading efficiency all evoke new contract periods.

To describe the *Attractiveness* array, it is first noted that, for a household to ascend the energy efficiency scale, more efficient insulation and appliances must be installed. An ESCO will absorb the initial cost of this upgrade, which would subsequently be repaid by the customer over the contract period. However, the traditional provider will not absorb this cost and it would thus fall to the customer to self-finance the full upgrade cost during a single model iteration. A potential customer will weigh the benefits of energy costs saved over the duration of the contract period against the cost of an efficiency upgrade. The cost of a household increasing its efficiency from level j to level i is denoted by $U_{j,i}$. It is assumed that an ESCO can purchase identical appliances or insulation products at a reduced wholesale cost. The cost of upgrading can thus be written as $\delta_k U_{ji}$, with $\delta_1 = 1$ and $\delta_{2,3} < 1$. The benefit to households of increasing efficiency level from j to i, while remaining with the same provider, will satisfy

$$B_{j,i}^{k,k} = c_k\left[P_k\left(1 - \frac{j}{10}\right) - P_k\left(1 - \frac{i}{10}\right)\right] - \frac{\delta_k U_{j,i}}{c_k}.$$

The mean annual household energy bill with provider k is given by P_k. ESCOs could sell energy at a fraction, $\mu_{k=2,3} < 1$, of the price available from the traditional provider, such that $P_{2,3} < P_1$. The benefit of moving company from provider n to m and upgrading efficiency from j to i is similarly calculated following

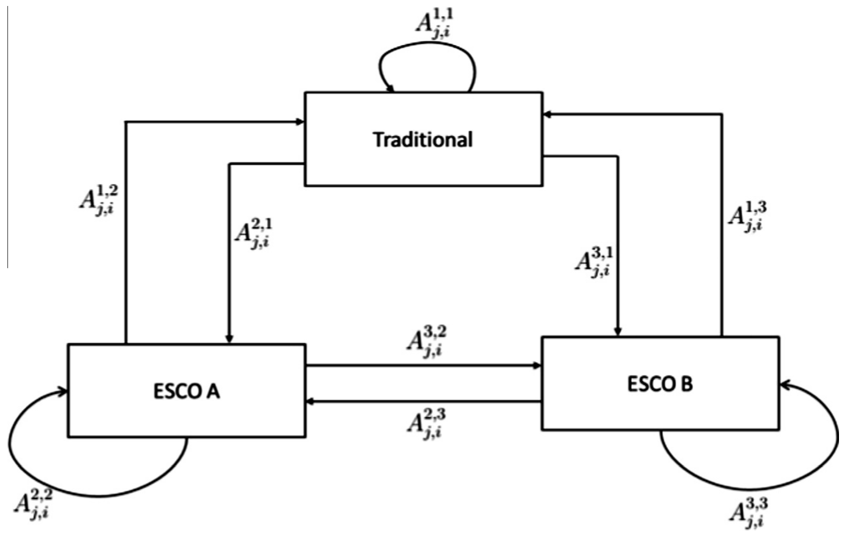

Fig. 1. Flowchart of household transitions.

$$B_{j,i}^{n,m} = c_m\left[P_n\left(1-\frac{j}{10}\right) - P_m\left(1-\frac{i}{10}\right)\right] - \frac{\delta_m U_{j,i}}{c_m},$$

and it is assumed that ESCOs sell energy to customers at the averaged priced of $P_{2,3} = P_1(1+\mu_{2,3})/2$. Finally the benefit of moving and/or upgrading is converted to the attractiveness of each option via $A_{j,i}^{n,m} = \exp(rB_{j,i}^{n,m})$ where r represents the relative attractiveness to a customer of each possibility based on the corresponding financial benefit. Each household views the attractiveness of the possible options available to it and makes its decision with a probability determined from the relative magnitudes of the attractiveness of each option. Finally, the price of energy P_1, is implemented as an external forcing effect, such that it is assumed to be independent of market dynamics and grows exponentially at a rate ε.

At the end of each market iteration, companies adjust their sales and service staff to account for changes in the market. Each company possesses predefined staff parameters ρ_k and γ_k, which represent the service staff required to supply 1 million customers and the idealised number of households that a single sales person would be assigned in order to capture the available market, respectively. The available market is defined as the number of households not currently under contract, and thus flagged as *on-market*. Service staff numbers are adjusted, to account for the increased/decreased service demand due to an increase/decrease in customer numbers, as follows

$$p_k(t+\Delta t) = p_k(t) + \rho_k\left[H^k(t+\Delta t) - H^k(t)\right]10^{-6}.$$

Sales staff are updated based on the magnitude of the available market. Ideally, and without financial limits, companies would adjust their sales staff so as to have the ability to contact all potential customers. However, the number of sales staff that a company may acquire will be limited by its available funds. This is implemented by assuming that the ability to adjust sales staff numbers is limited by the company's share in the market, which yields

$$s_k(t+\Delta t) = s_k(t) + \Delta_{\text{market}}\left(1 - \frac{H^k(t+\Delta t)}{H(t)}\right)\frac{H^k(t+\Delta t)}{H(t)},$$

where $\Delta_{\text{market}} = H_{\text{on-market}}(t+\Delta t) - H_{\text{on-market}}(t)$. A minimum number of sales staff, $s_k^{\min}$ is always maintained.

The percentage of *inert* households is assumed to decrease exponentially, as the fraction of the market captured by the ESCOs increases, at a rate of $R = -\ln(I_a/I_0)$, where I_a is the percentage of households that will always remain *inert* and cannot upgrade their energy efficiency due to, for example, their construction, Fig. 2. In addition, a percentage, I_0, of households are designated as *inert* when the total ESCO market share is identically zero, which is assumed to be the initial market structure at time $t = 0$. Thus, at each iteration, the number of houses that become *active* is

$$I_0\left[e^{-R\frac{\sum_{k=2}^{3}H^k(t)}{H(t)}} - e^{-R\frac{\sum_{k=2}^{3}H^k(t+\Delta t)}{H(t)}}\right]\frac{H(t)}{100}, \tag{1}$$

and the newly *active* status is applied to randomly selected formerly *inert* houses. Once activated, a household remains in this state forever. Finally, the household population grows by $h/\Delta t$ in each iteration. By default, all newly created houses are assigned to the traditional energy provider with an efficiency level uniformly distributed in the range 4 to 7, flagged as *on-market* and have a probability of $\frac{I_0}{100}$ of being *inert*.

3. Market scenario

The model applied to a hypothetical household population of $H(0) = 28\times10^6$ houses is considered. For computational efficiency, a scaling factor of 10^3 is adopted, so that each household agent represents 10^3 physical households. Initially, all household energy is supplied by the traditional provider, $H^1(0) = H(0)$. In addition, each household is randomly assigned an energy efficiency level, distributed as in Fig. 3. Furthermore, all houses are flagged as *on-market* and have a probability of $I_a/100 = 0.6$ to be flagged as *inert*. A minimum of $I_0 = 2\%$ of all households will always remain *inert*. The household population will grow by $h = 10^5$ houses per year.

At time $t = 0$, the mean cost of a household's annual energy usage with the traditional provider is assumed to be $P_1(0) = £2400$. This is allowed to grow exponentially over time following

$$P_1(t) = P_1(0)e^{\varepsilon t},$$

where $\varepsilon = 0.02$ is the annual rate of growth in the mean household energy bill and represents a 100% increase in the cost of household energy costs over a period of approximately 35 years. It is assumed that the ESCOs could sell energy to their customers at 30% less than the traditional provider ($\mu_{2,3} = 0.7$), so that the average annual

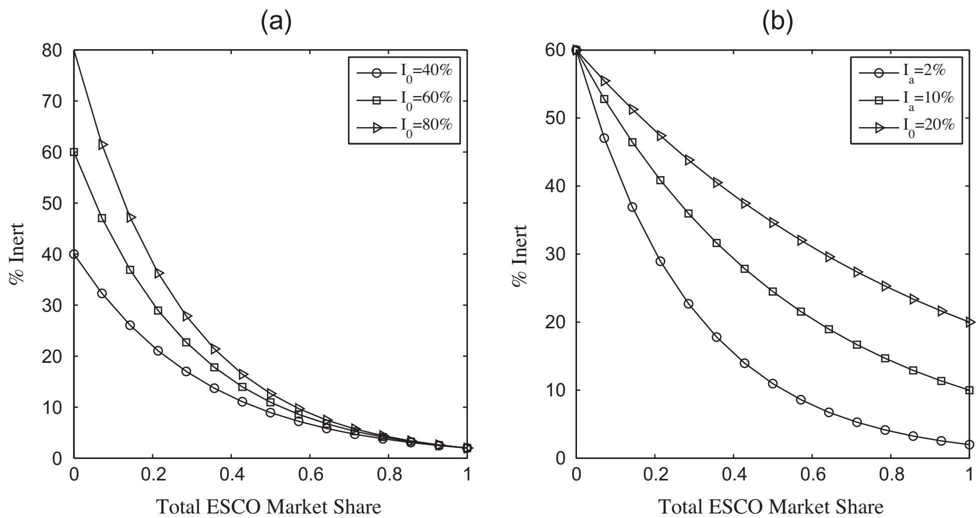

Fig. 2. The change in the percentage of inert households as a function of the total ESCO market share (ESCO A + ESCO B). (a) Percentage of households always inert is fixed at 2%. (b) Percentage of households inert when the ESCO market share is identically zero is fixed at 60%.

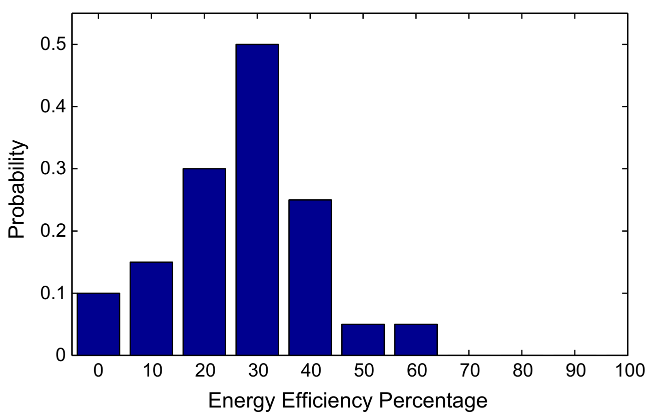

Fig. 3. Initial energy efficiency probability distribution of households.

Table 2
Parameters and values used in the numerical simulations.

Parameter	Description	Value
$H(0)$	Initial number of houses	28×10^6
I_0	Initial percentage of inert houses	60%
I_a	Percentage of houses always inert	2%
h	Household growth rate	10^5 year^{-1}
$P_1(0)$	Initial annual energy costs	£2400
ε	Annual energy cost growth rate	0.02 year^{-1}
μ_k	Proportion of energy costs	$[1,\ 0.7,\ 0.7]$
δ_k	Proportion of upgrade costs	$[1,\ 0.7,\ 0.7]$
c_k	Contract length in years	$[0.25,\ 5,\ 10]$
$s_k(0)$	Initial sales staff	$[10,\ 200,\ 200]$
$p_k(0)$	Initial service staff	$[250,\ 1000,\ 1000]$
ρ_k	Service staff to supply 10^6 houses	$[10,\ 100,\ 100]$
γ_k	Idealised houses per sales person	$[10^4,\ 10^4,\ 10^4]$
Y_k	Households contacted per sales person	$[20,\ 20,\ 20]$ day^{-1}
U_0	Cost of first 10% efficiency upgrade	£400
r	Relative attractiveness of upgrades	10^{-4}

energy costs of ESCO customers is $P_{2,3} = 0.85P_1$. It is further assumed that ESCOs can upgrade household energy efficiency at 70% the cost of self-financing ($\delta_{2,3} = 0.7$). The cost of upgrading to more efficient insulation and appliances will be calculated using the function

$$U_{ji} = U_0 \frac{91(j-i)}{(10-j)(10-i)+1}, \tag{2}$$

where $U_0 = £400$ is the cost of attaining the first 10% improvement. This ad hoc choice of function yields a relatively slow increase in cost to attain the lower efficiency levels but displays rapidly increasing costs in order to attain the highest energy efficiency levels. The attractiveness of all options is then calculated with $r = 10^{-4}$.

As a base case scenario, a market where both ESCO A and ESCO B adopt identical business strategies and differ only in the duration of the contract they offer to customers is first considered. As previously stated, the traditional provider does not impose a long term contract and households are only retained under contract for a single model iteration, taken as 3 months, such that $c_1 = \Delta t = 3$ months. Contract lengths of $c_2 = 5$ years and $c_3 = 10$ years are imposed by ESCO A and B, respectively. At the outset, ESCOs have no customers, however, they require an established service staff to facilitate potential customers. The business model of the ESCO, whereby they install and maintain appliances and insulation, requires a larger service staff than the traditional provider. In addition, the traditional provider requires a minimal sales staff team as it already has 100% of the market and initially aims to retain its customer base rather than attract new customers. Therefore, staff numbers are initialised as $s_k(0) = [10,\ 200,\ 200]$ and $p_k(0) = [250,\ 1000,\ 1000]$. We set $\rho_k = [10,\ 10^3,\ 10^3]$ and $\gamma_k = 10^4,\ \forall k$, and a minimum of $s_k^{\min} = 1$ sales staff is maintained by all companies. Finally, each sales person contacts $Y_k = [20,\ 20,\ 20]$ households per day. All parameter values used in the simulations are summarised in Table 2 and the model is run over a period of 40 years. The probabilistic nature of agent behaviour yields a unique output for each distinct simulation of the model and the mean of 100 stochastic realisations is calculated to describe the averaged market behaviour over time. Confidence intervals are then determined to indicate how the mean behaviour of the market can fluctuate between model realisations.

4. Results

4.1. Fixed ESCO business model

The energy needs of the total household population is initially, at time $t = 0$, supplied by the traditional provider. However,

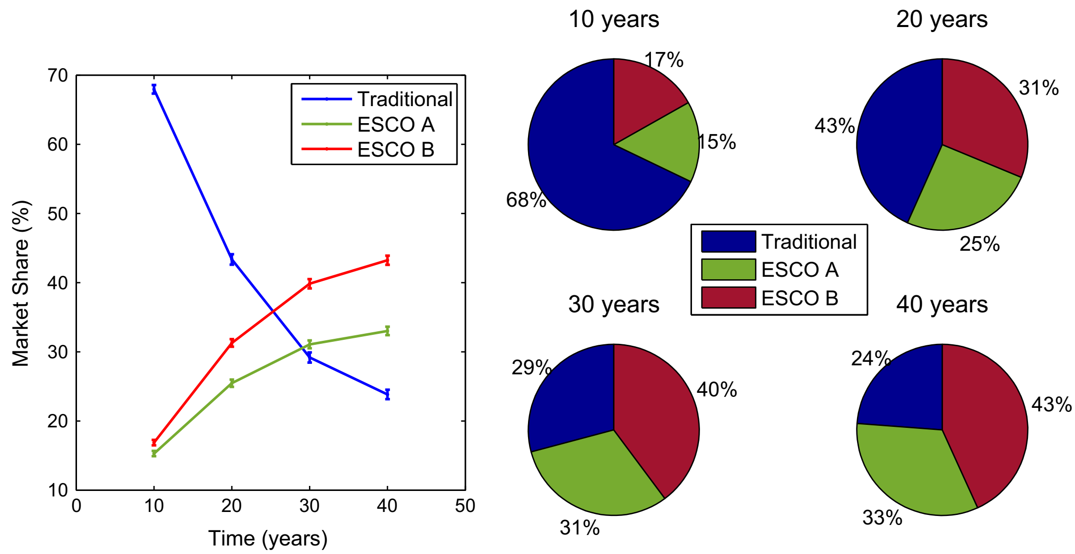

Fig. 4. Base case model scenario. The mean percentage of the household market captured by each energy provider at 10 year increments, averaged over 100 realisations. The error bars represent the 95% confidence interval.

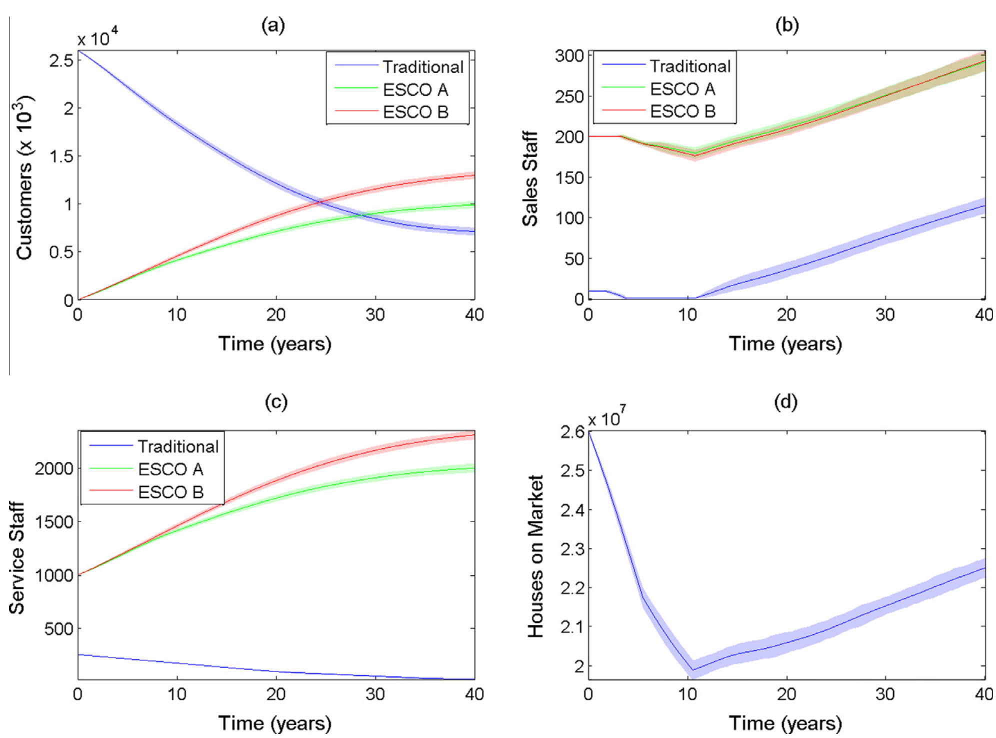

Fig. 5. Base case model scenario. Time series of energy provider performance, averaged over 100 realisations. The shaded areas denotes the 95% confidence interval.

households gradually migrate towards ESCO energy providers, Fig. 4. The invasion of ESCOs into the energy supply market occurs quite rapidly during the first 20 years and the rate at which the traditional provider loses customers begins to decline thereafter, with the performance of ESCO A and B displaying greater divergence at later times. The slower growth rate in ESCO customer numbers at later years is the result of households being tied into long term contracts, thus limiting the potential customer pool. The number of customers with the traditional provider decreases monotonically over the 40 year period, while those of the ESCO providers increase, Fig. 5(a). ESCO B is the more successful of the two by attaining a larger share of the market. This can be attributed to the longer contract period (10 years) and the resultant lower annual energy costs incurred by households as a result of spreading the costs of energy efficiency upgrades over this longer time period, which makes ESCO B a more attractive option to potential customers. Sales staff numbers mirror the available pool of customers, determined from the number of households flagged as *on-market*, Fig. 5(b). All providers initially decrease sales staff due to the reduction in potential customers, Fig. 5(d), as households sign long term contracts with the ESCOs which takes them off the market. This reduction is initially negligible due to the limitation imposed on the ability to increase/decrease sales staff numbers due to the size of a company's market share. Therefore, while ESCOs have a large potential customer base, they do not modify sales staff numbers due to their insufficient market share.

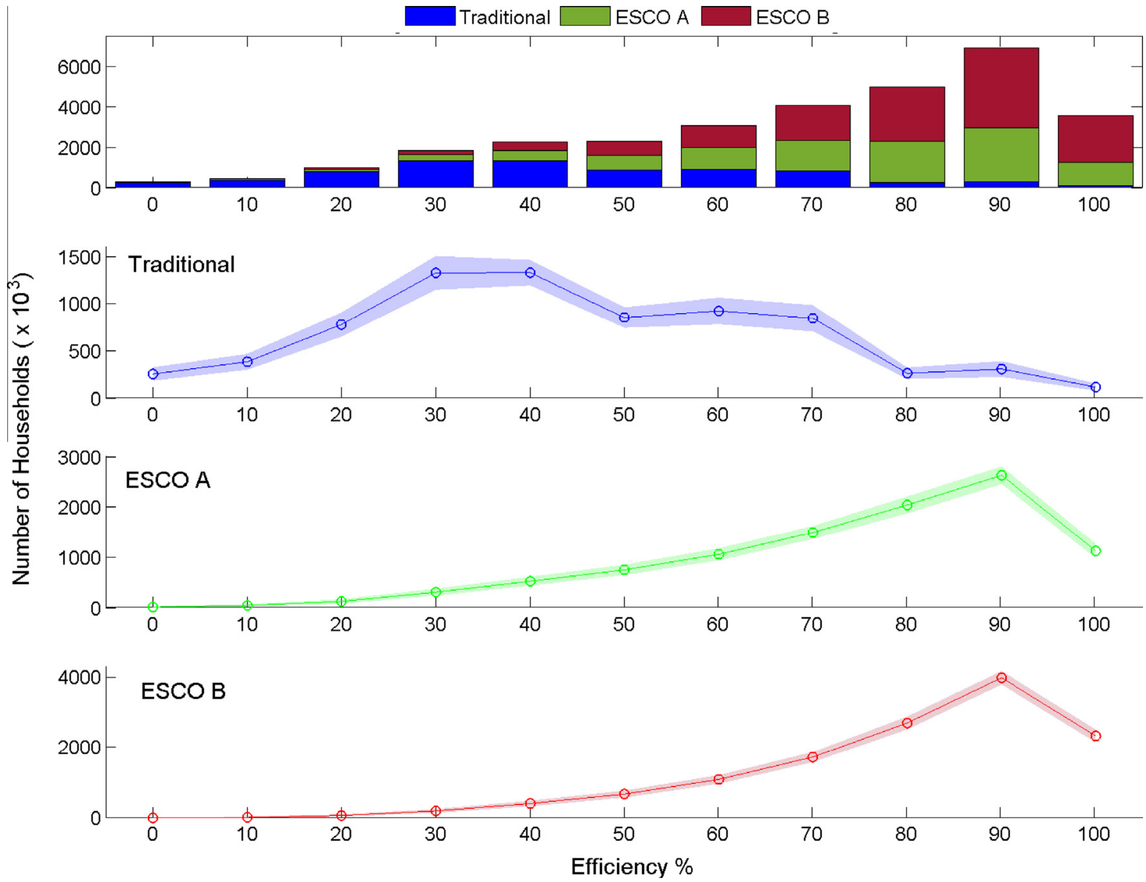

Fig. 6. Base case model scenario. Distribution of the energy efficiency of households signed with the traditional provider, ESCO A and ESCO B after a 40 year period of time and averaged over 100 realisations. The shaded areas denote the 95% confidence interval.

Similarly, the traditional provider does not alter sales staff numbers as it already has the majority of the market. Service staff are seen to increase in line with customer numbers, with the traditional company maintaining minimum staff numbers once ESCOs start to dominate the market, Fig. 5(c). Finally, the number of houses flagged as *on-market* decreases during the initial 10 year period, as customers sign contracts with the ESCO providers, Fig. 5(d). Following this initial period of decline, numbers start to increase again as contracts begin to expire.

The energy efficiency distribution of households contracted to each of the three providers after 40 years is shown in Fig. 6. The traditional provider customer base exhibits a slow migration towards the higher efficiency levels, with the middle levels of 50–70% being more attractive (compare with the initial distribution seen in Fig. 3). The ESCO customer base displays a markedly different pattern with households migrating towards higher efficiency levels, peaking at 90% efficiency. The prohibitively high cost of attaining 100% efficiency, assumed in Eq. (2), restricts the movement of households towards the 100% level. Some traditional households always stay in the lowest efficiency levels, representing the *inert* houses that are unable or unwilling to upgrade their energy efficiency. The number of times each household changes energy provider is also recorded, Fig. 7. The majority of households switch provider once and only a small minority switch 4 times over the 40 year period. No households were found to switch more than 4 times. A small portion of the households that never change provider is accounted for by the 2% of households that always remain inert (I_0), however, the majority of households that did not switch did, nevertheless, upgraded their efficiency level with the same energy provider, Fig. 6.

Once a contract period expires with an ESCO, a household has the possibility of once again changing provider, either to the other ESCO or to the traditional provider. However, it is found that many households choose to remain with the ESCOs beyond the initial contract period. The majority of households signed to the ESCOs spend between 0 and 20 years flagged as *on-market*, Fig. 8(a). This implies some level of stability within the market whereby ESCOs retain customers and households do not immediately switch provider when contracts expire. This is similarly reflected when the time households spend *off-market* is considered, Fig. 8(b). In this

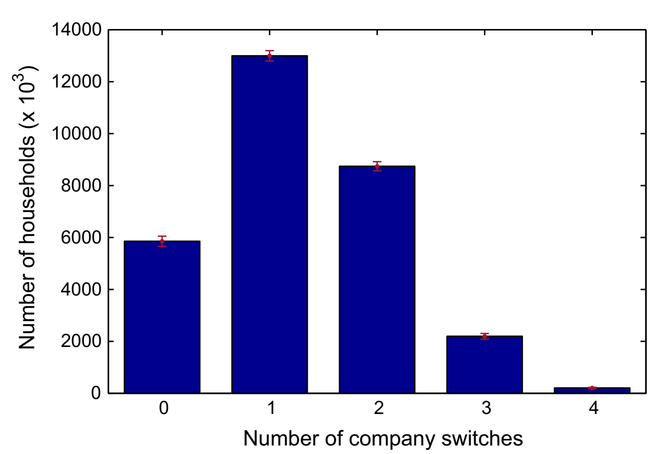

Fig. 7. Base case model scenario. Bar chart displaying the number of times households change energy provider during a 40 year period, averaged over 100 realisations. The error bars indicate the 95% confidence interval.

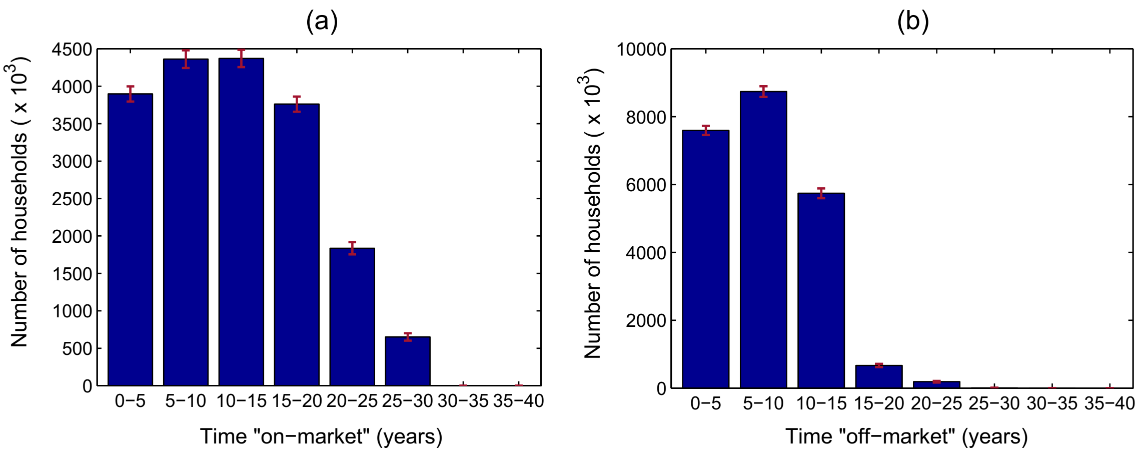

Fig. 8. Base case model scenario. Bar charts displaying (a) the number of years that households spend *on-market* while signed to an ESCO (i.e. not under contract) and (b) the number of years that households spend *off-market*. The error bars indicate the 95% confidence interval.

case, it is found that a negligible number of households are under contracts with ESCOs for more than 15 years of the 40 year simulation period. This indicates that only a minority of households sign new contracts in immediate succession.

4.2. Variable ESCO business model

On consideration of the parameters listed in Table 2, it is evident that they can be separated into two distinct classes: market specific parameters and company specific parameters. The former directly impact the behaviour and properties of the household population and the latter represent the business strategies of the different providers. For example, the market parameters form the subset $[I_a, I_0, \varepsilon, P_1(0), r, U_0]$ and they inform the model about inert households, annual household energy costs and household views on efficiency upgrades. In contrast, the company parameters form the subset $[\delta_k, \mu_k, \gamma_k, s_k(0), p_k(0), \rho_k, Y_k]$ and these directly impact the staffing policies and business operations of the different energy providers for $k \in [1, 2, 3]$. Considering both of these parameter subsets, a sensitivity analysis of the model was conducted. The company market share was adopted as the quantitative indicator of business success and the impact of variations in input parameters on the final market shares was investigated. Individual parameters were varied by ±20% and the resultant change in market share from the base case scenario was recorded.

Firstly, with all company specific parameters fixed at the values given in Table 2, the market parameters were varied in order to ascertain the possible consequences of different market properties and to identify the parameter variations to which the model is most sensitive. The market share achieved by each energy provider after 25 years was recorded, with this time interval chosen to reduce computational time. Fig. 9 displays the market share achieved by each of the providers, where the bar charts are centred around the base case scenario. The model is clearly most sensitive to variations in the initial number of inert households, I_0. A 20% increase or decrease in this parameter results in the ESCO providers capturing significantly more or less of the market respectively. This outcome is the result of the assumed household activation rate (see Eq. (1)) and can be interpreted as follows. If the initial proportion of inert households is decreased, the rate at which households become active also decreases (Fig. 2) which reduces the potential ESCO customer pool and would inevitably slow the migration of the market towards the ESCO providers and ultimately result in a smaller market share being achieved. Similarly, when the initial proportion of inert households is increased the rate at which households become active increases which has the effect of creating a larger market of potential customers for the ESCO providers more rapidly which results in a greater market share being achieved. Variations in the other market parameters have little impact on the final provider's market share, with 20% parameter variations resulting in less than 1% market variation.

A further sensitivity analysis was conducted to investigate the effect of ESCO providers altering their business strategies. First, the impact of ESCO A altering its defining parameter set was considered, Fig. 10. The majority of company parameters were found to exert little influence in the final market shares. However, variations in the sales strategy yielded a different market structure. ESCO A achieved a larger market share by either increasing its initial sales staff, $s_2(0)$, or the staff daily household contact rate, Y_2. This increased market share came at the expense of the other providers, which had quantitatively similar decreases in their respective market shares. Conversely, decreasing the sales specific parameters yielded a lower market share for ESCO A, as would be expected. However, the quantitatively similar resultant increase in the other providers market share indicates that, despite the more attractive energy bills available to the customers of ESCO B, the traditional provider is still able to compete for customers and maintain a substantial share of the market. Qualitatively similar results are obtained by varying the business strategy of ESCO B, Fig. 11. Perhaps surprisingly, variations in the proportionate costs of energy and efficiency upgrades (μ_k and δ_k) did not have a significant impact on the ESCO performance. Thus, it would seem that the household energy bill reductions achieved by spreading the cost of upgrades over the contract period has more of an impact on customer choice than the reduced price that ESCOs can offer for energy supplies. In summary, the optimal business model for ESCOs, under the current model assumptions, would be to adopt more aggressive sales and/or marketing strategies.

5. Discussion

In this paper an agent-based model for the establishment of energy service companies in the household market has been presented. The more service orientated business model adopted by these companies can help to improve household energy efficiencies, thus reducing overall energy usage and carbon emissions in this sector. The agent construct allows the model to be structured around a heterogeneous household population composing the consumer market, which have unique characteristics and decision making abilities achieved through a probabilistic framework. In

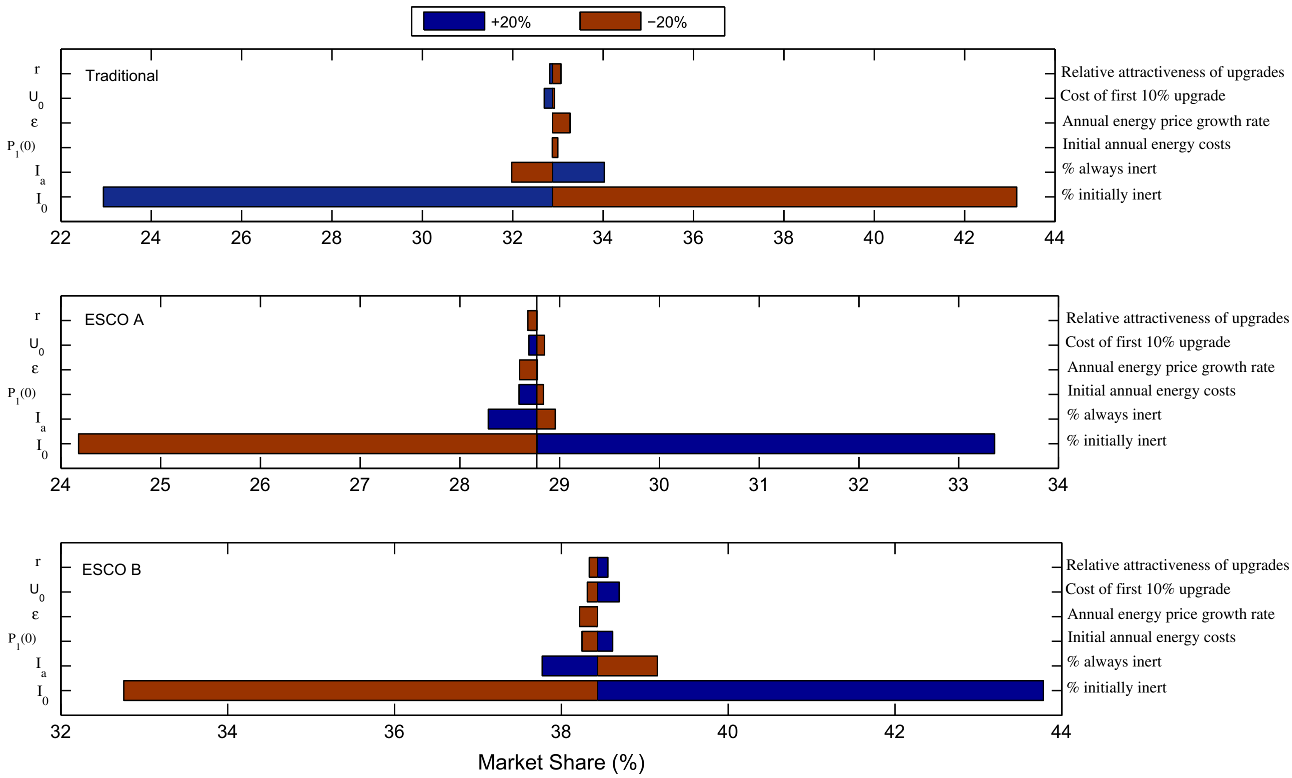

Fig. 9. Results of sensitivity analysis. The diagram shows the degree to which a 20% variation in the market parameters, $[I_a, I_0, \varepsilon, P_1(0), r, U_0]$, affects the base case market share after 25 years. Each bar is a representation of how uncertainty in that particular parameter affects the results.

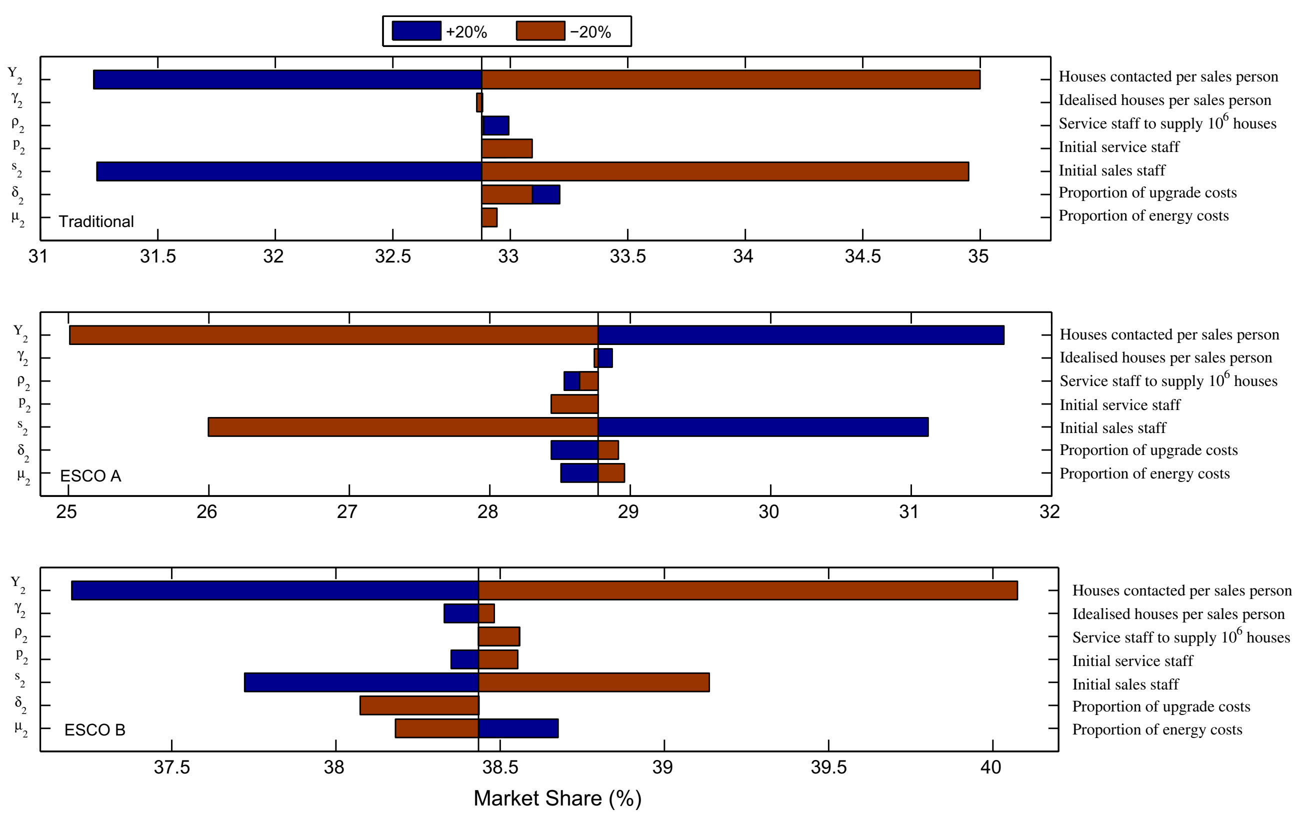

Fig. 10. Results of sensitivity analysis. The diagram shows the degree to which a 20% variation in ESCO A's defining parameter set, $[\delta_2, \mu_2, \gamma_2, s_2(0), p_2(0), \rho_2, Y_2]$, affects the base case market share after 25 years. Each bar is a representation of how uncertainty in that particular parameter affects the results.

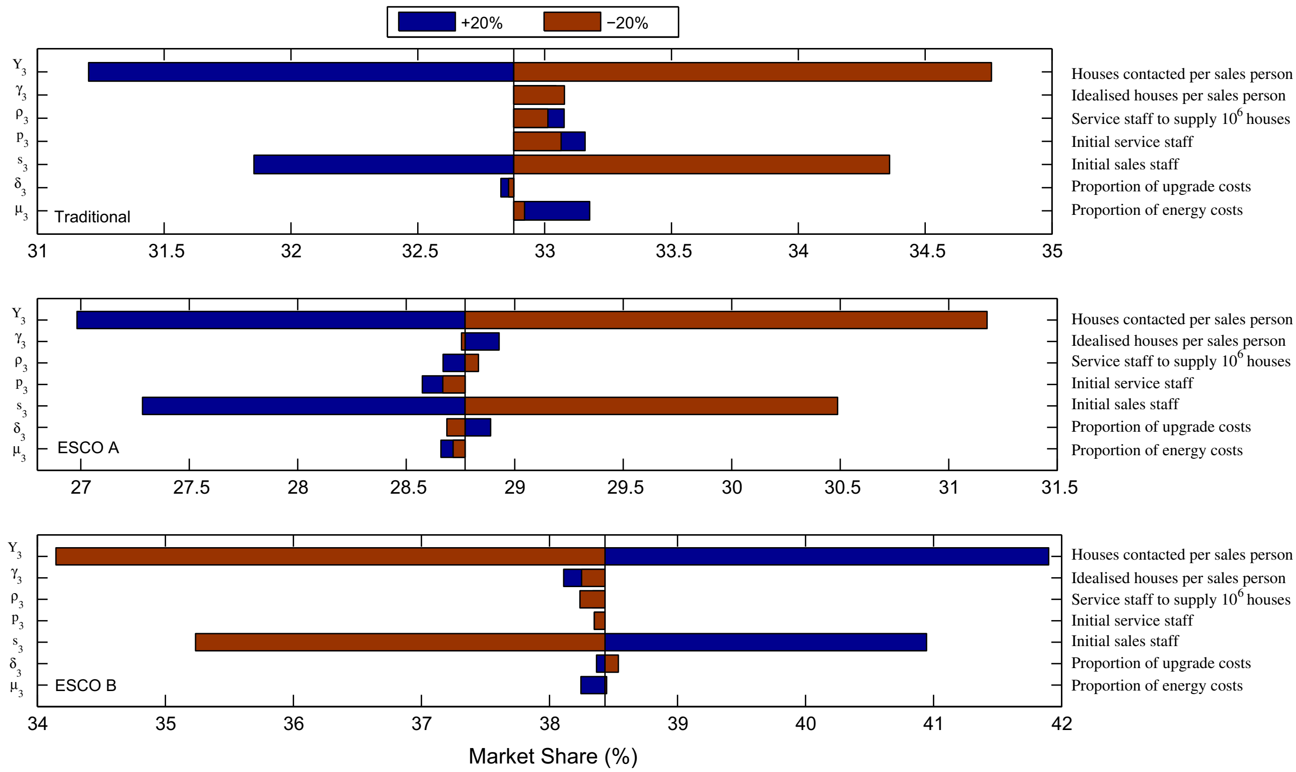

Fig. 11. Results of sensitivity analysis. The diagram shows the degree to which a 20% variation in ESCO B's defining parameter set, $[\delta_3, \mu_3, \gamma_3, s_3(0), p_3(0), \rho_3, Y_3]$, affects the base case market share after 25 years. Each bar is a representation of how uncertainty in that particular parameter affects the results.

addition, distinct business strategies can be defined for each energy provider to investigate competition in the market. The interactions between energy providers and customers (i.e. households) is primarily defined by a company's sales strategy, which in turn is determined by the company-specific staff mechanisms and dynamics.

There are many business models and strategies that energy providers could adopt which greatly influence market performance and success. In the agent framework, such strategies are expressed as rules, unpinning the mechanisms by which companies react to changes in the market and interact with other agent entities. A base case market scenario was established, in which all providers adopt identical business operations and differ only in the length of the initial contract period. This is a fundamental property for businesses as defined in the model, as it determines the duration of time over which household energy efficiency upgrades must be repaid, which in turn directly determines annual household energy costs. This scenario displays a market behaviour in which households migrate toward the ESCOs while also upgrading their energy efficiencies. Households that choose to remain with the traditional provider, or indeed return after an ECSO contract, demonstrate an aversion to the upper efficiency levels due to the high costs associated with self-financed improvements. In a global economy, determined to reduce carbon emissions, self-financing is a limiting factor in improving the energy efficiency and usage in the residential housing sector. The model does not account for household income and financial status, with the underlying assumption being that the attractiveness of upgrading is determined from the cost of upgrading. Therefore, an *attractive upgrade* can be undertaken without regard to the household ability to pay for that upgrade. The impact of this assumption would be more pronounced in the traditional provider's customers as the total upgrade cost must be paid immediately (in a single model iteration). The definition of the ESCO contract, where upgrade costs are dispersed over long periods of time, dampens this effect. Therefore, the impact of the self-financing limitation would undoubtedly be more pronounced in the traditional customer efficiency distribution when household income is considered. The model could be adapted to include national data on household income, essentially creating an agent-specific attractiveness array scaled by the household ability to finance efficiency upgrades. Another factor to be considered is consumer aversion to long-term contracts, which could bias the market towards companies offering shorter contract periods. It was found that a larger market share was attained by ECSO B, which imposed a contract period exactly double that of ESCO A. Both ESCO providers purchase energy at the same price and the ability to sell energy to customers at reduced costs is determined by the repayment period for efficiency upgrades. ECSO B allows customers to repay over a 10 year period which reduces short term energy costs and establishes ECSO B as a more attractive financial option. However, a household's decision to purchase would be jointly influenced by cost savings and contract duration. For example, first time buyers may be hesitant to get locked into a 10 year energy provision contract. Similar aversions would apply to other social groups such as pensioners, tenants and landlords. The agent-specific attractiveness array could again be modified to account for individual customer preferences regarding contract durations, which could be implemented from suitable data or using a scaling factor to incorporate an increasing aversion with increasing contract duration. Finally, cost alone is not the sole factor that influences household attractiveness to more efficient energy usage. Environmental awareness and a desire to reduce individual carbon footprints is an important element that could drive the invasion of ESCOs, as described here, into the energy provision market. The versatility of the attractiveness array structure would allow such influences to be incorporated at the agent level by assigning an *environmental awareness* scaling factor to individual household agents.

An element of stability was observed in the market dynamics, with the majority of households changing energy provider less than twice during the 40 year simulated period. In addition, a large portion of households spent over 15 years as ESCO customers but not locked into a contract. This demonstrates the ESCO's ability to retain customers on contract expiration and also reflects the apathetic nature of many consumers who choose the convenience of inaction and do not seek more competitive options. An important element that may influence the observed stability may be the external forcing provided by the annual mean household energy costs. A conveniently simplistic model was adopted to describe the evolution of energy costs over time, which was implemented as an exponentially increasing market-extraneous variable. Indeed, this variable is a complex function of individual demand, resource availability, market dynamics, government policies and taxes, in addition to highly involved interconnections with other infrastructure systems, such as transportation and water. A monotonically increasing cost, as assumed herein, may not reflect the persistent fluctuations on shorter time scales or future trends which may emerge due to stricter controls on carbon emissions, depletion of natural resources, emerging economies or the increasing demands for personal electronic devices. An additional consideration in this context is the simulated model time frame, chosen as 40 years, over which the annual household energy costs steadily increase. Increasing global temperatures may result in reduced future demand for household heating. However, economic markets operate on time scales infinitely shorter than those of the earth's climate. The financial consequences of curbing carbon emissions in the short term, through improving energy efficiency, may not be immediately realised in energy costs due to the phenomenon of *committed warming* resulting from the long time scales associated with the thermal inertia of the oceans and ice sheets [26]. Moreover, future reductions in the widespread availability of oil and gas may shift the economy towards costly alternatives [27], necessitating large injections of capital to provide energy security which could result in periods of rapid cost inflation. Acknowledging the substantial uncertainties associated with future energy costs, we conclude that a steadily increasing energy cost over a maximum simulation time of 40 years is adequate for the scope of this work and, with a lack of definitive knowledge on future energy costs, we adopted this elementary approach to capture the market response to the, seemingly inevitable, future increasing costs of household energy requirements.

An important component absent from the model is the economic performance of the energy providers. In its absence, business success is based on customer numbers achieved. The model investigates the role of ESCOs in the migration towards a more energy efficient residential sector and the complexities of business competition in a real work economy are beyond the scope of the present work. However, with detailed data on ESCO business practices, such as realistic work force size, employee salaries, services offered and operational costs, the dynamics of the energy provider agents could be modified to operate on a monetary basis. In the absence of such data, business performance is evaluated on market share, which is assumed to directly influence a company's ability to restructure its work force to adapt to the evolving energy market. Another issue compounding the integration of economics into the present model is the evolving technological and regulatory character of the energy production sector. To accurately capture this dynamic business domain the provider agents would need to adapt to newly emerging technologies, in terms of both production costs and work force (e.g. provide training to service staff on new technologies). Business operations (i.e. agent rules) would also need to adapt to changes in legislation and governmental policies or taxes.

The model presented in this work represents a preliminary foundation on which to evaluate the migration of the residential sector to a more energy efficient performance. The model is versatile and can be improved and adapted, incorporating other effects into the attractiveness array structure. Future developments could include the addition of multi-utility service companies providing additional services to households, such as water and communications.

6. Conclusions

An agent-based model was developed to examine the potential of energy service companies (ESCOs) to contribute to the large scale upgrading of household energy efficiency. The attractiveness of this service model is influenced by the duration of the contract offered, which enables households to spread the costs of upgrades over longer periods of time. It could also enable the ESCO to recover the initial cost of service contract set up and to negotiate lower rates with domestic technology providers for efficient equipment. Self-financing of energy upgrades, necessitated by customers of traditional utility providers, is a limiting factor to widespread efficiency improvements. Future rises in energy costs favour the ESCO business model, with customers achieving greater cost savings with increasing energy prices. This could also encourage demand side management behaviours for domestic consumers in order not to be penalised for use outside contracted consumption rates. A greater focus on providing energy services, as opposed to consumable products, presents a viable approach to reducing future energy costs and consumption.

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