Evaluating Government's Policies on Promoting Smart Metering in Retail Electricity Markets via Agent Based Simulation

Tao Zhang *, William J. Nuttall
Judge Business School, University of Cambridge
Trumpington Street, Cambridge, CB2 1AG, UK
T.Zhang@jbs.cam.ac.uk

Abstract

In this paper, we develop an agent-based model of a market game in order to evaluate the effectiveness of the UK government's 2008-2010 policy on promoting smart metering. We also consider possible supplementary strategies. With the model, we test the effectiveness of four possible strategy options and suggest their policy implications. The context of the paper is a practical application of agent-based simulation to the retail electricity market in Britain. The contribution of the research are both in the areas of policy making for electricity markets and in the methodological use of agent-based simulation for studying social complex systems involving human behaviour.

Keywords

agent-based simulation, smart metering technology, the Theory of Planned Behaviour, retail electricity market

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1. Introduction

One of the UK government's most prominent recommendations for the energy market is the adoption of smart metering technology, which, in addition to offering a broad range of benefits to energy consumers, can substantially cut CO_2 emissions. As a novel technology, in the UK energy market smart metering is still in its infancy and its adoption appears as a long and slow process. The characteristic of uncertainty in technology diffusion raises the strategic issue of what policies the government should introduce to boost the roll-out of smart meters in the UK energy market. Lessons from international experience (e.g. Italy, Sweden and California) suggest that introducing smart metering in the context of monopoly provision can be a very successful strategy. However, the characteristics of competition and diversification of meter ownership in the UK metering market mean that the government faces a different context for policy. Therefore, in Feb 2006 the energy market regulatory agency in Britain (Ofgem) consulted different stakeholders and proposed six policy options. More recently (May 2007), the government (the Department for Business, Enterprise and Regulatory Reform (BERR)) has announced its policies on promoting smart metering technology in of its 2007 white paper on energy *Meeting the Energy Challenge*. However, how effective these policies are in terms of fostering smart metering and what other supplementary optimum strategies can be used to strengthen the effectiveness of these policies in the UK energy market still remain questionable. This paper is motivated by a desire to develop a methodological framework for studying these two inter-related research questions.

Traditionally, the adoption of a new technology as a particular form of collective behaviour of users occurring in markets or economies has been mainly studied from the perspective of management science, e.g. the "S-curve" model [1], the adopter heterogeneity model [2], learning or epidemic model [3] and real options model [4, 5]. However, recent studies (e.g. [6, 7]) show an individual user decision on choosing an innovative product is not only a function of the benefit and cost of the product, as described in economic theories, but also, and in some cases perhaps more so, a function of the factors from the user's psychology and the social networks the user involves. Yet, these factors in technology diffusion have received very little research. In order to bridge this gap, this paper follows up our previous study [8] and targets the aforementioned two inter-related research questions, i.e. how effective the government's proposed new smart metering policies would be and what supplementary optimum strategies can be adopted to enhance the effectiveness of these policies, via an agent-based model developed based on consumer psycho-behavioural theory.

The model in this paper is a market game developed based on the situation of the real retail electricity market in Britain. This market game represents the interaction between electricity suppliers and the residential electricity consumers. Essentially, we investigate the effectiveness of BERR's 2008-2010 policies on promoting smart metering and identify what supplementary optimum strategies can be used to enhance the effectiveness of BERR's new policies in the market game. The objective of the study is twofold. Firstly, we expect that the results of the study reported in this paper can potentially help stakeholders (especially government policy makers and energy suppliers) to take effective measures for boosting the roll-out of smart meters. Secondly, we aim to extend the application of agent-based computational simulation research method from theoretical to practical, i.e. using agent-based computational simulation method to analyse practical problems in the energy market.

The structure of the paper is as follows. The second section describes the metering market in Britain. The third section describes Ofgem's six policy options and BERR's new policies on promoting smart metering in Britain. The fourth section presents our agent-based simulation model of smart metering technology adoption (the market game) in detail. The fifth section shows the four scenarios of strategy options we simulated with the model. The sixth section focuses on the analysis of the simulation results and their policy implications. The seventh section concludes the study.

2. The Retail Electricity Metering Market in Britain

It is a legal requirement that all but a few exempted electricity consumers must have an appropriate meter when they use electricity. As a result, currently there are around 22.5 million domestic electricity meters installed in England and Wales: 3 million prepayment meters, 3.3 million multi-tariff meters and 16.2 million single rate credit meters [9]. Each year, about 2.2 million meters are installed (out of which 1.2 million are new and 1 million are replacement) [10]. Metering services have two core components: one is the provision of an accurate meter of an appropriate type, the other one is data services (taking meter readings periodically and processing the data). However, around 10% domestic electricity meters are prepayment meters. These meters allow customers to pre-pay for their electricity use via various means of payment such as electronic tokens, keys or payment cards.

Traditionally, the electricity Distribution Network Operators (DNOs) are the dominant meter operators for domestic meter points. They have a licence obligation to provide metering services to all meter points, upon the request of the relevant electricity suppliers. DNOs own and manage the meter assets. They also charge electricity suppliers for metering services. The prices they charge electricity suppliers are regulated by Ofgem. In March 2001, Ofgem published its metering strategy, aiming to introduce competition in the metering market. Following this, full electricity metering competition entered into force in 2003. The purpose of introducing competition in electricity metering services was to encourage supplier and metering service providers to lower prices, improve standards of service and innovate. A key principle of the policy of introducing competition in the electricity metering services is to make electricity suppliers, not DNOs, primarily responsible for purchasing metering services—the so-called "supplier hub" principle [11]. Since then, some electricity suppliers have appointed third-party commercial metering service providers, rather than automatically continuing to use existing providers, for providing electricity metering services to their domestic consumers. For example, Centrica has appointed United Utilities, OnStream and Siemens, three competing commercial metering service providers, for the provision of competitive electricity metering services to its domestic consumers [11].

Under the current regulatory framework, although domestic electricity consumers have the statutory right to make their own metering arrangements few have chosen to do so. Currently consumer demand for meter ownership and consumers making their own metering arrangements are virtually zero [12]. Moreover, DNOs are still responsible for (own and manage) over 90% of domestic electricity meters. The vast majority of domestic electricity meters are simple single-phase electro-mechanical or electronic meters with either a single register or multiple registers [9]. Therefore, these meters can only be read manually on an annual or bi-annual basis. In order to prevent fraud, they are generally backstopped so as to prevent them form running backwards.

3. Ofgem's Six Policy Options and BERR's New Policies on Promoting Smart Meters

Ofgem's Six Policy Options

Currently, reducing greenhouse gas emissions, maintaining security of energy supply and tackling fuel poverty are the three of the major challenges in the UK energy market. Smarter, more innovative electricity meters (smart metering) can potentially help tackle all the three issues [11]. Therefore, as an effective approach to energy efficiency, promoting smart metering is at the top of the government's energy agenda. Although competition has already been introduced in the electricity metering market, there is little evidence that electricity suppliers intend to introduce smart meters to their domestic electricity consumers on a large scale in the next few years [12]. In Feb 2006, Ofgem published a consultation document *Domestic Metering Innovation*, which marks the launch of a significant Ofgem initiative to work with the energy suppliers, the network operators, meter manufacturers, government and other stakeholders to help identify and unlock the potential of smart meters. In this consultation document, Ofgem proposed six policy options on promoting smart meters based on the consideration of the regulatory arrangements, i.e. should the introduction of smart meters be left to customers and energy suppliers to decide, or mandated, through some form of legislation and/or regulation by relevant authorities. The six policy options are as follows.

- Address barriers to innovation

This option emphasizes the effect of competition, leaving the final decision on whether to install smart meters to consumers, suppliers and the market. The advantages of this policy option is that the policy option can (i) “leave the technology choice in the hands of those best-placed to take the decisions (companies and customers)—this would reduce the risk of a “one size fits all” approach and/or picking the wrong technology”; (ii) “work with the existing arrangements without disturbing companies’ existing plans, contracts and investments and encourage those suppliers who are starting to consider innovative metering to continue down that road” [11].

- Enable the customer to contract for a smart meter

This is a more radical policy option emphasizing the role of the consumer in promoting smart metering. It puts the consumer, rather than the supplier, at the centre of the decision of what sort of smart meter they want to have. As consumers have the most to gain from smart metering, they might be best placed to choose whether to buy a smart meter. This policy option enables consumers to either own the meter, or contract directly with a meter provider for the meter or contract through the supplier with a meter operator.

- Impose an obligation on suppliers

This policy option highlights the role of the regulator and the government in promoting smart metering, based on the lessons learnt from international experience such as Sweden [11]. Under this policy option, an obligation could be placed on all energy suppliers to install meters with a minimum specification. This could be done via either amending suppliers’ licences to impose this requirement by Ofgem or legislating directly by the government.

- Re-bundle metering services into networks

This policy option involves re-bundling metering services into DNOs. Under this policy option, the DNOs would be re-positioned as monopoly providers for metering services. International experience in Italy shows that re-bundling could allow for a massive roll-out of smart meters to all domestic consumers [11]. However, monopoly DNOs may not be the best companies to deliver smart meters. The reason for introducing competition in metering market, at least in part, was that some energy suppliers complained of lack of choice, poor service, poor technology choice, high costs and high prices when the DNOs had monopoly on metering services [11].

- Await international evidence

This policy option assumes that currently there is not enough evidence on consumer response to justify the investing in smart meters. Policy makers (Ofgem and the government) should actively monitor the development of smart metering in countries where smart meters have been adopted to look at how consumers are responding. The international evidence could then be used to reappraise the case of smart metering in Britain.

- Instigate a trial

This policy option assumes that international evidence may not suitable to appraise the case of smart metering in Britain, because consumer response to smart metering varies according to the specific consumer characteristics, climate and culture of the country concerned. Thus, a policy option that Ofgem can make is to facilitate and support a large scale trial of smart meters in Britain to gather firm evidence of the consumer response. However, any trial would need to run for a minimum of one year, and it would also take time to analyse the results of the trial, so the conclusions arising from the trial may not be available for another two years. A range of practical issues such as "how can we geographically choose trial areas?", "how would the trial be funded?", "would consumers still be able to switch supplier during the trial?" would also appear in the trial. Research into these issues is of particular interest to policy makers. In our previous work [8], based on an agent-based model, we have already suggested that in a trial choosing initial participating households on a random and geographically dispersed basis would potentially be an effective strategy.

BERR's New Policies on Promoting Smart Meters

Ofgem's efforts have not been lost on the UK government who set promoting smart metering at the top of its energy agenda in order to comply with the EU Energy Services Directive, which states that "Member States shall ensure that, in so far as it is technically possible, financially reasonable and proportionate in relation to the potential energy savings, final customers for electricity, natural gas…are provided with competitively priced individual meters that accurately reflect the final customer's actual energy consumption and that provide information on actual time of use" [13]. In May 2007, BERR published its latest version of white paper on energy *Meeting the Energy Challenge*, which explicitly demonstrated the government's ambition in promoting smart metering in Britain (excluding Northern Ireland). In this energy white paper, BERR announced its new policies on promoting smart meters: (i) an expected 10-year plan to roll out smart meters with real-time visual display devices to all households and, between 2008-2010, as an interim measure and the first step to smart metering, real-time visual display devices will be available free of charge to any household that requests one; (ii) consultation on a government mandate for the implementation of a requirement for energy suppliers to roll out smart meters to all but the smallest business users in Britain and those larger businesses not already subject to half hourly metering, advanced and smart metering services, within the next five years.

4. Modelling Government Policies on Promoting Smart Metering in Domestic

Electricity Markets

4.1 Description of the Model

Since BERR has announced its policies on promoting smart metering in Britain, how effective these polices are and what other supplementary optimum strategies can be adopted to enhance the effectiveness of these policies still remain questionable. Under BERR's new policies, whilst Ofgem is in favour of "meter competition approach" to roll out smart meters, some other stakeholders (e.g. Energywatch), based on an analysis of limited evidence from the UK metering market, argue that re-bundling metering services to monopoly DNOs would be a more cost-effective approach [14]. As current regulatory framework (meter competition and diversified meter ownership) in the UK electricity metering market produces little quantitative evidence for economists and policy makers to assess the effectiveness of their smart metering policies via econometric models, a new research method for coping with this issue is helpful. We present research based on agent-based computational simulation method. The model targets the aforementioned two inter-related research questions in the paper, as an extension of our previous research [8], is an agent-based model developed based on psycho-behavioural theory.

The model is a market game involving two parties: residential electricity consumers and electricity suppliers. Each party is represented by a type of agent. Thus the model has two types of agents: residential consumer agents and electricity supplier agents. Similar to the real players in the real electricity market, these agents interact in a designed virtual environment in a computer. We formulise and code the policy options, carry out experiments in the virtual environment and then observe its system level emergent phenomena of the diffusion of real-time visual displays. The simulation results can be seen as inferences of the diffusion of real-time visual displays in the real retail electricity market. Through comparing different scenarios in the experiments and analysing the simulation parameters, we can assess the effectiveness of different policy options and identify the supplementary optimum strategies to support BERR's smart metering policies.

4.2 Behaviour of Residential Consumer Agents

As residential consumer agents represent residential electricity consumers (households), they are "smart agents" [15] with human intelligent behaviour in terms of decision-making in choosing both energy suppliers and smart meters. In the real electricity market, an residential electricity consumer gains information about electricity suppliers and metering technologies from both its social network (e.g. neighbours, friends or colleagues) and energy suppliers (through advertising such as TV, the Internet and news reports), processes the information and then makes decisions. We have studied the related psycho-social literature (e.g. [16, 17]) and empirical investigations (e.g. [18]). The characteristic features of consumers' decision-making can be summarized as follows: (i) intention is the immediate antecedent of an actual behaviour (choose an option); (ii) a persuasive message will (both positively or negatively) influence a consumer's intention to choose an option only if it affects either his/her attitude towards the option or his/her perceived social pressure to choose the option from important referent individuals or groups such as the person's spouse, family, friends or colleagues; (iii) when facing a range of options, a consumer is most likely to choose the one that gives him/her the largest intention, given that the consumer perceives he/she has the ability to choose the option. These points lead us to formulize residential consumer agents' behaviour based on the Theory of Planned Behaviour (the TpB model) [19], which is the most influential theory in psycho-behavioural science and particularly suited to modelling consumer behaviour.

We assume, in the virtual environment, two kinds of interactions can influence an ordinary residential consumer agent *i* to choose option *α* (whether choosing a real-time visual display device or not with a particular electricity supplier agent). One kind, in the form of price information of electricity and benefits of smart metering, is the interaction between residential consumer agent *i* and electricity supplier agents. The other kind, in the form of word-of-mouth effects and personal influences, is the interaction between residential consumer agent *i* and other residential consumer agents. Based on the TpB model , firstly, the interaction between residential consumer agent *i* and a particular electricity supplier agent such as information about electricity prices $P^{\alpha}{}_{E}$ sent to residential consumer agent *i* from the electricity supplier agent, can influence residential consumer agent *i*'s attitude towards choosing option α, but its influential power is calibrated by residential consumer agent *i*'s personality trait "price sensitivity". Therefore, residential consumer agent *i*'s attitude towards choosing option *α* can be formulated as follows:

$$A_i^{\alpha} = W_{iP} * P_E^{\alpha} \qquad (1)$$

Where: A_i^{α} = residential consumer agent *i*'s attitude towards choosing option *α*

W_{iP} = residential consumer agent *i*'s personality trait "price sensitivity"

Secondly, the interaction between residential consumer agent *i* and other residential consumer agents, such as a persuasive message or personal influence about option *α* from an important referent residential consumer agent *j*, can influence residential consumer agent *i*'s subjective norm towards choosing option *α*, but its influential power is calibrated by residential consumer agent *i*'s motivation to comply with residential consumer agent *j*. Therefore, residential consumer agent *i*'s subjective norm towards choosing option *α* can be formulated as follows:

$$SN_i^{\alpha} = \sum_{j=1}^{n} (W_{ij} * Inf_{ji}^{\alpha}) \qquad (2)$$

Where: SN_i^α = residential consumer agent i's subjective norm toward choosing option α

Inf_{ji}^α = influence from residential consumer agent j to residential consumer agent i on choosing option α

W_{ij} = residential consumer agent i's motivation to comply with residential consumer agent j

n = the number of other residential consumer agents interacting with residential consumer agent i

Thirdly, a range of residential consumer agent i's demographic attributes or environmental factors such as residential consumer agent i's income, education level, government legislations or unexpected events can influence residential consumer agent i's perception of his/her ability (the perceived behavioural control) to choose option α. Therefore, these factors can be regarded as control beliefs in the TpB. Analogously, the influential power of a control belief about option α, C^α_{ki} , is calibrated by residential consumer agent i's related perceived power of the control factor PC_{ik}. Residential consumer agent i's perceived behavioural control towards choosing option α can be formulated as follows:

$$PBC_i^\alpha = \sum_{k=1}^{m}(PC_{ik} * C_{ki}^\alpha) \qquad (3)$$

Where: PBC_i^α = residential consumer agent i's perceived behavioural control towards choosing option α

m = the number of control factors

Finally, combining residential consumer agent i's attitude (equation 1), subjective norm (equation 2) and perceived behavioural control (equation 3) towards choosing option α, residential consumer agent i's intention to choose option α can be expressed as follows:

$$I_i^\alpha = \sum_{j=1}^{n}(W_{ij} * Inf_{ji}^\alpha) + \sum_{k=1}^{m}(PC_{ik} * C_{ki}^\alpha) + W_{iP} * P_E^\alpha \qquad (4)$$

Where: I_i^α = residential consumer agent i's intention to choose option α

When facing a number of options, the one that can give residential consumer agent i the greatest intention is his/her preferred one, i.e. his/her final decision on with which energy supplier and whether to choose a real-time visual display device or not. The decision-making can be formulated as follows:

$$D_i = \max \{\mathrm{I}^1, \mathrm{I}^2, \mathrm{I}^3, \ldots \mathrm{I}^\alpha \}$$

Where: D_i = residential consumer agent i's final decision

4.3 Behaviour of Electricity Supplier Agents

Electricity supplier agents are business organizations who are competing in the electricity market under the economic regulations set by relevant authorities. Market reports based on empirical investigations [12] suggest that currently the competition between electricity suppliers in the GB electricity market is based primarily on price comparison. Hence in our model of market game, the behaviour of an electricity supplier agent includes: (i) disseminating its electricity price information to residential consumer agents in the virtual environment; (ii) adjusting electricity price each three months, based on the variation of its overall market share. The behaviour can be formulated as follows:

$$P_{E\ (t)}^{\alpha} = \begin{cases} P_{E\ (t-1)}^{\alpha} & \text{if } t \bmod 3 \neq 0 \\ d * P_{E\ (t-1)}^{\alpha} & \text{if } t \bmod 3 = 0 \end{cases}$$

Where: t = time steps in the simulation

d = a parameter for adjusting the electricity price

4.4 The Environment Design

The environment in our model is a virtual system where agents behave and interact in a computer. The virtual system in our model of market game is a square lattice of 62500 cells (250*250) with periodic boundary conditions. Cells can be either blank or occupied by residential consumer agents, as shown in Figure 1. The population density in the environment can be controlled by a relevant parameter.

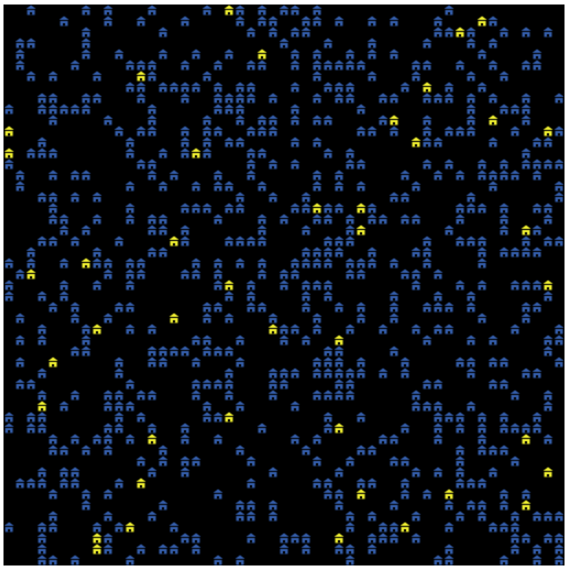

Figure 1: The Environment

Note: In the virtual community, residential consumer agents are randomly populated in the cells (blue or yellow houses), and the black areas are unpopulated cells (non-residential areas). Each populated cell just has one residential consumer agents, and the number of total residential consumer agents is control by the parameter called “population-density”. The blue houses are the residential consumer agents with conventional meters, while yellow houses are the residential consumer agents with smart meters. In order to eliminate edge effects, the square lattice has periodic boundary conditions.

Based on related literature in sociology and networking [20, 21, 22, 23] we can consider two types of interactions between an residential consumer agent with other residential consumer agents: regular interactions and random interactions, as shown in Figure 2. This design enables the social networks in the environment to have the characteristic features of both “small-world” effect and scale-free power-law distribution.

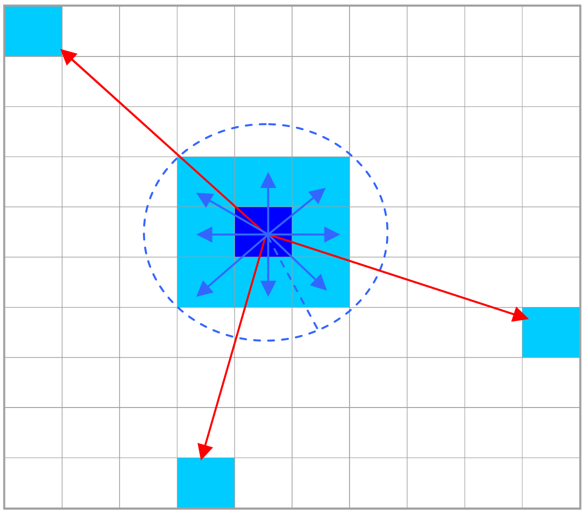

Figure 2: A residential consumer agent's regular (blue) and random interactions (red) with other residential consumer agents

Note: In the virtual environment, for example, the dark blue residential consumer agent on the one hand can regularly receive influences from and exert influences on its neighbouring residential consumer agents through regular interactions (blue arrows in Figure 2) with them, and the number of regular interactions is controlled by a parameter called "radius". If we make the parameter "radius" greater (a longer dashed radius in Figure 2), the dark blue residential consumer agent will have more regular interactions. On the other hand, the dark blue residential consumer agent can randomly receive influences from and exert influence on other residential consumer agents through random interactions with them (red arrows in Figure 2) and the number of random interactions it has is controlled by a parameter called "random-interaction".

5. The Simulation

BERR's new policies for promoting smart metering state that between 2008 and 2010 any household requesting a real-time visual display device can get one free of charge. The key issue raised from this policy is that who pays for this device. Based on this issue, we further break down the policy into three dimensions: (i) the government subsidizes; (ii) electricity suppliers pay for real-time visual displays; (iii) DNOs pay for real-time visual displays. Under the three strategies, the next issue is how best to roll out real-time visual displays. If the government subsidizes real-time visual display devices, these devices can be rolled out in either the context of monopoly (by DNOs) or the context of competition (by electricity suppliers); if electricity suppliers pay for real-time visual displays devices and are responsible for rolling them out, they will be rolled out in the context of competition; if DNOs pay for real-time visual display devices and are responsible for rolling them out, they will be rolled out in the context of monopoly. Therefore, our model of market game will simulate the scenarios of these strategies, as shown in Figure 3.

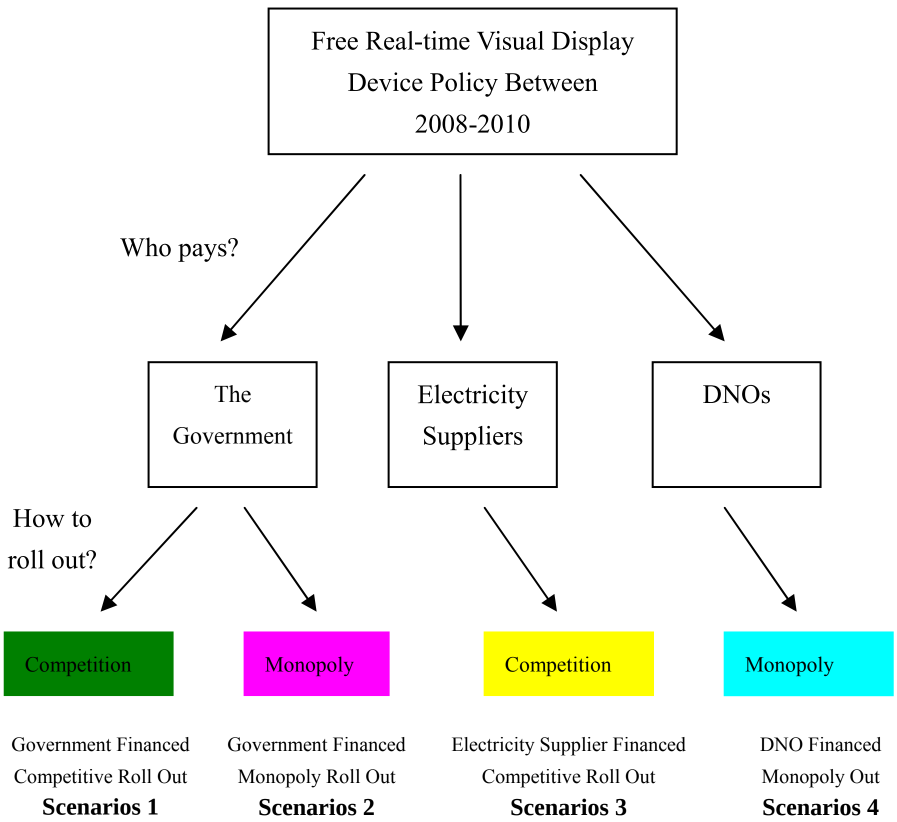

Figure 3: Scenarios of strategies in the simulation

We develop six electricity supplier agents representing six main competitors in the UK electricity market with the initial market share of each electricity supplier agent the same as its counterpart's market share in the real UK electricity market (Figure 4).

Group	Dec-02	Jun-03	Dec-03	Jun-04	Dec-04	Jun-05	Mar-06	Mar-07
BGT	22%	23%	24%	24%	23%	22%	22%	22%
Powergen	22%	22%	21%	21%	21%	21%	20%	19%
SSE	13%	14%	14%	15%	15%	16%	16%	18%
npower	16%	16%	15%	15%	15%	15%	15%	16%
EDF Energy	15%	15%	14%	14%	13%	13%	13%	14%
ScottishPowe	10%	10%	11%	12%	13%	13%	13%	12%
Others	0%	1%	1%	0%	0%	1%	0%	0%

Electricity Supplier Agent
A
B
C
D
E
F

National market share in electricity (Source: Domestic Retail Market Report, Ofgem, June 2007)

Figure 4: Electricity supplier agents in the model of market game

We simulate four scenarios of strategies shown in Figure 3. Each time step in the model is designed as one month. In all the four scenarios, a residential consumer agent cannot switch electricity supplier agent within two time steps (complying with the 28-day rule in real electricity market [12]). Each residential consumer agent has been assigned a parameter "enthusiasm" ranging from 0 to 1 to signify the degree to which the residential consumer agent is interested in having a real-time visual display. In order to assess the effectiveness of different strategies, the four scenarios are under the same initial condition shown in Table 1. Because currently competition between electricity suppliers in the UK electricity market is based primarily on price comparison [12] and, as a result empirical observations from the real UK electricity market show a declining trend of annual electricity bills (Figure 5), we adopt a declining pattern of electricity prices in our model, i.e. each three month, an electricity supplier agent checks its overall market share. If its overall market share is declining, it will slightly lower its electricity price in order to attract residential consumer agents.

parameter	value	comments
number of electricity supplier agents	6	There are six electricity supplier agents in the virtual community
population-density	0.40	40% of the cells in the virtual community is populated, i.e. there are 25000 (62500*0.4 = 25000) residential consumer agents in the virtual community
market-share-A	0.22	Initially electricity supplier agent A has 22% market share
market-share-B	0.19	Initially electricity supplier agent B has 19% market share
market-share-C	0.17	Initially electricity supplier agent C has 17% market share
market-share-D	0.16	Initially electricity supplier agent D has 16% market share
market-share-E	0.14	Initially electricity supplier agent E has 14% market share
market-share-F	0.12	Initially electricity supplier agent F has 12% market share
random-interaction	10	Each residential consumer agent has less than 10 random interactions in the virtual community
radius	2	Each residential consumer agent regularly interacts with other residential consumer agents within 2 unit radius

Table 1: The initial conditions of the four scenarios

Scenario 1 (Government Financed-Competitive Roll Out) simulates the strategy that the government subsidizes real-time visual display devices and electricity suppliers are primarily responsible for rolling out these devices. The simulation in this scenario is based on the following principles: (i) the electricity supplier agents are competing to gain market share; (ii) as they do not have to undertake the cost of real-time visual display devices, they disseminate the information of the free real-time visual display device policy throughout the whole virtual environment and initially residential consumer agents with enthusiasm greater than 0.9 will consider requesting these devices; (iii) meter competition enables electricity supplier agents to deliver real-time visual display devices of different types/functions to residential consumer agents, thus residential consumer agents have many options on real-time visual display devices.

Scenario 2 (Government Financed-Monopoly Roll Out) simulates the strategy that the government subsidizes real-time visual display devices and DNOs are responsible for rolling out these devices. The simulation in Scenario 2 is based on the following principles: (i) the electricity supplier agents are competing to gain market share; (ii) as they do not have to undertake the cost of real-time visual display devices, they disseminate the information of free real-time visual display device policy throughout the whole virtual environment and initially residential consumer agents with enthusiasm greater than 0.9 will consider requesting these devices; (iii) there is a DNO of monopolistic power in the virtual environment; (iv) electricity supplier agents instruct the DNO to deploy real-time visual display devices to residential consumer agents upon the requests from residential consumer agents; (v) the DNO only delivers **one selected type** of real-time visual display device to residential consumer agents, thus residential consumer agents only have one option on real-time visual display devices.

Scenario 3 (Electricity Supplier Financed-Competitive Roll Out) simulates the strategy that electricity suppliers pay for real-time visual display devices and they are also responsible for deploying these devices. The simulation in Scenario 3 is based on the following principles: (i) the electricity supplier agents are competing to gain market share; (ii) as they have to absorb the cost of real-time visual display devices, **they are not keen to disseminate the information of the free real-time visual display device policy to residential consumer agents,[1] thus initially only residential consumer agents with enthusiasm greater than 0.98 (i.e. every enthusiastic consumers) will consider requesting these devices**; (iii) meter competition enables electricity supplier agents to deliver real-time visual display devices of different types/functions to residential consumer agents, thus residential consumer agents have many options on real-time visual display devices..

[1] This organisational behaviour has already been witnessed in the wireless telecommunication market. In the wireless telecommunication market, one competition policy is that mobile phone customers can retain their existing mobile numbers when switching between network operators, the so-called Mobile Number Portability (MNP) policy. Although this policy was introduced to the wireless telecommunication market by the Office of Communications (Ofcom) in 1999, up to date only a small number of customers know it because network operators are not keen to publicise the policy. One of the key reasons for their unwillingness to publicise the MNP policy is that if a customer switches from one network to another network and keeps his/her existing mobile number, the recipient network operator will have to pay a charge to the donating network operator for the routing of a parted call. This is the so-called the Donor Conveyance Charge (DCC) in the wireless telecommunication market. For further information, please see [26].

Scenario 4 (DNO Financed-Monopoly Roll Out) simulates the strategy that DNOs pay for real-time visual display devices and they are also responsible for deploying these devices. The simulation in Scenario 4 is based on the following principles: (i) the electricity supplier agents are competing to gain market share; (ii) as they do not have to absorb the cost of real-time visual display devices, they disseminate the information of the free real-time visual display device policy throughout the whole virtual environment and initially residential consumer agents with enthusiasm greater than 0.9 will consider requesting these devices; (iii) there is a DNO of monopolistic power in the virtual environment; (iv) electricity supplier agents instruct the DNO to deploy real-time visual display devices to residential consumer agents upon the requests from residential consumer agents; (v) the DNO only delivers real-time visual display devices of **minimum specifications** (the cheapest type of real-time visual display devices) to residential consumer agents, thus residential consumer agents only have one option on real-time visual display devices.

6. Simulation Results

As the free real-time visual display device policy lasts only for two years, in the simulation we focus on the first 24 months. Through the four simulation experiments we observe three interesting emergent phenomena, which may give us phenomenological information for assessing the effectiveness of BERR's new policies on promoting smart metering in the real UK electricity market.

Firstly and most importantly, an "S-curve" pattern of technology adoption [1] has been reproduced in our model of market game. Figure 6 shows the trends of real-time visual display device adoption in the four scenarios all have a common pattern of "S-curve", which complies with our empirical observation from the Telegestore Project of promoting smart meters carried out by Enel in Italy (see Figure 7). Figure 6 can also help us evaluate the effectiveness of the four strategies. From Figure 6 we can see that smart metering can be most quickly adopted in Scenario 1 (Government Financed-Competitive Roll Out), followed by the adoptions in Scenario 2 (Government Financed-Monopoly Roll Out), Scenario 4 (DNO Financed-Monopoly Roll Out) and Scenario 3 (Electricity Supplier Financed-Competitive Roll Out). Thus policy implications from this are: (i) under the free real-time visual display device policy, the government subsidizes real-time visual display device is a more effective way than that electricity suppliers and DNOs undertake the cost of these devices; (ii) if the government subsidizes real-time visual display devices, imposing an obligation on electricity suppliers so as to force them roll out these devices through competition is a more effective way than rolling out smart meters in the context of monopoly through re-bundling metering services to DNOs; (iii) if the government is unable to subsidize real-time visual display devices and the cost of these devices has to been undertaken by electricity suppliers or DNOs, rolling out these devices in the context of monopoly through re-bundling metering services to DNOs is a more effective way than rolling out these devices in the context of competition through imposing an obligation to electricity suppliers.

Secondly, a typical "lock-in" effect [24] appears as an emergent phenomenon in the simulation. The "lock-in" effect is a very interesting phenomenon in market, referring to a state of an evolving market in which consumers prefer one of two or more competing products and this preference persists for a long time beyond what would be economically rational [25]. The evolutions of electricity supplier agent's market shares in all the four scenarios (Figure 8, Figure 9, Figure 10, and Figure 11) are in line with the "lock-in" effect. In the model, although the incumbent initially can take a large market share based on its market power, other competitors will soon fight back and finally a relatively stable state will appear in the market (see Figure 8, Figure 9, Figure 10, and Figure 11). Our empirical observation from the real UK electricity market shows that a real "lock-in" effect does indeed exist between the major competitors (see Figure 12).

Thirdly, our simulation shows a dynamically unstable state of consumer switching: after the introduction of real-time visual display devices, in the early stage a large number of residential consumer agents switch electricity supplier agent seeking a preferred real-time visual display device; later although a stable state in market share (the "lock-in" effect) appears, as a result of competition every month there are still a considerable number of residential consumer agents switching electricity supplier agents, as shown in Figure 13. This emergent phenomenon precisely complies with our empirical observations of consumer switching from the real UK electricity market (see Figure 14).

7. Conclusions

The issue of what policies and strategies the government and Ofgem should make in terms of promoting smart metering in the UK is still an open research question and thus a better understanding of the evolutionary process in technology diffusion should have important implications on policy making. The latest consultation document published by BERR on 29th April 2008 stated that the government will "hold urgent discussions with electricity suppliers to assess how displays could best be made available to consumers in the short-medium term" [27]. Therefore, at the moment it is still not clear that what strategies the UK government will make to promote smart metering. An agent-based model of market game is described in this paper and it has provided some initial insights for evaluating the government's new policies on promoting smart metering. Our model shows that the government's free real-time visual display device policy in 2008-2010 will be an effective policy on promoting smart metering. This policy can be accompanied by some supplementary optimum strategies and based on the key issue "who pays for the smart meters" we test the effectiveness of four possible strategy options in four scenarios. The policy implications from our simulation results can help policy makers figure out the best policies and strategies for promoting smart meters under different conditions. Based on the research, the best strategy we would like to suggest is that under the free real-time visual display device policy, the government subsidizes the promotion of these devices and meanwhile imposing an obligation on electricity suppliers so as to force them roll out these devices through competition.

As an extension to our previous research [8], the model of market game presented in this paper makes agent-based simulation approach one important step forward from theoretical development to practical application. A methodological contribution of this model is that it successfully incorporates human psycho-behavioural theory into agent-based simulation. Because the behaviour of residential consumer agents in the model are based on well-established psycho-behavioural theory and the whole model is developed based on empirical observations (e.g. competition results in declining electricity prices), the simulation results from our model bear resemblance to the phenomena (e.g. the "S-curve" pattern of technology adoption, the "lock-in" effect and the dynamically unstable state of consumer switching) as widely observed in the real world. This also signifies the validity and robustness of our model. Moreover, this model can be seen as a generic reference multi-agent framework for modeling any complex social system involving human behaviour.

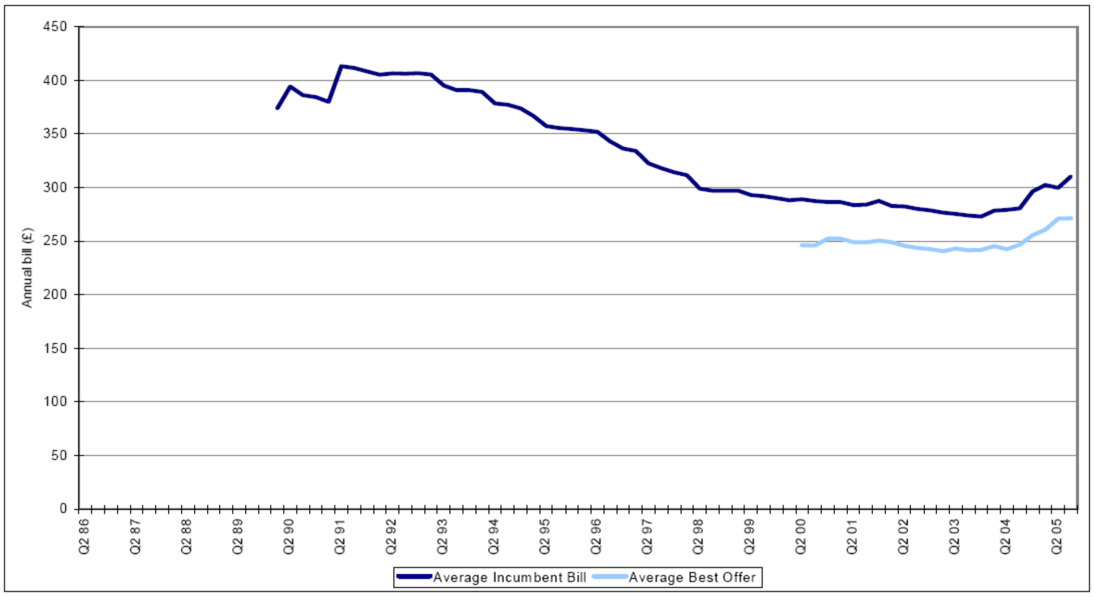

Figure 5: Real annual domestic electricity bill in GB (Source: Ofgem)

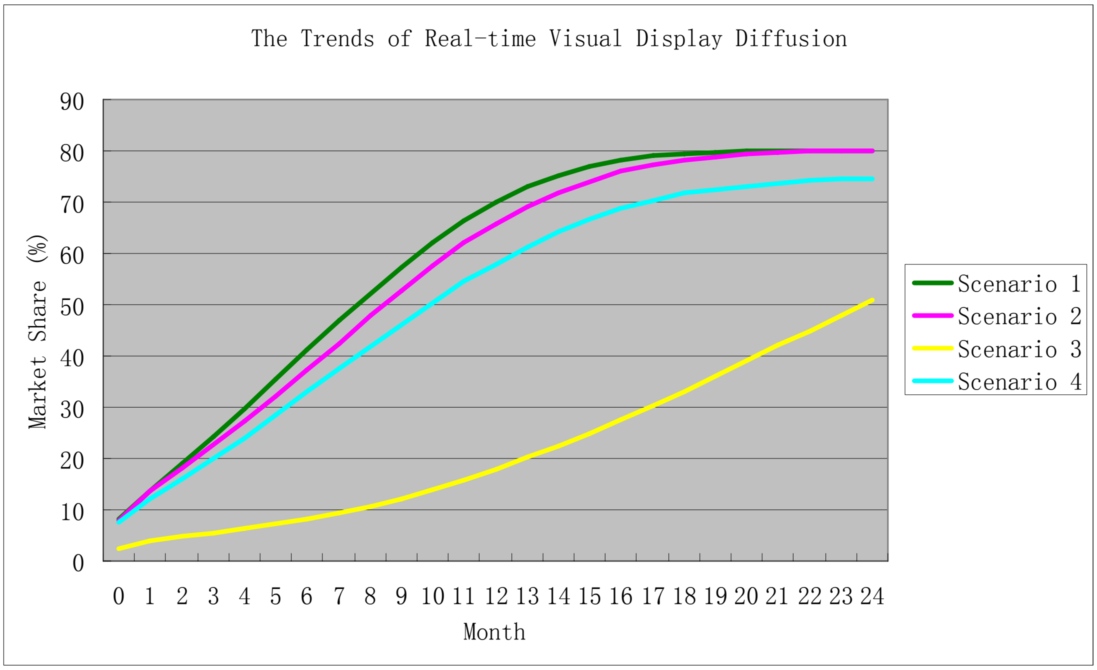

Figure 6: The trends of real-time visual display diffusion

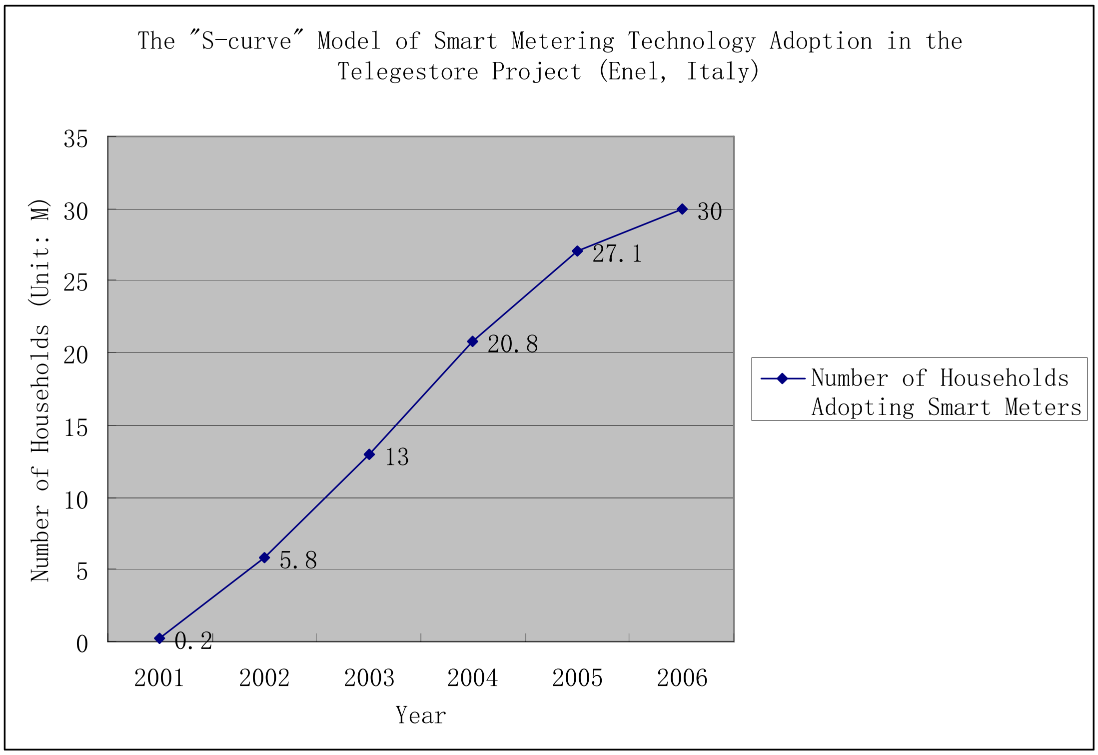

Figure 7: The "S-curve" pattern of smart Metering technology adoption in the Telegestore Project (Data Source: Enel, Italy)

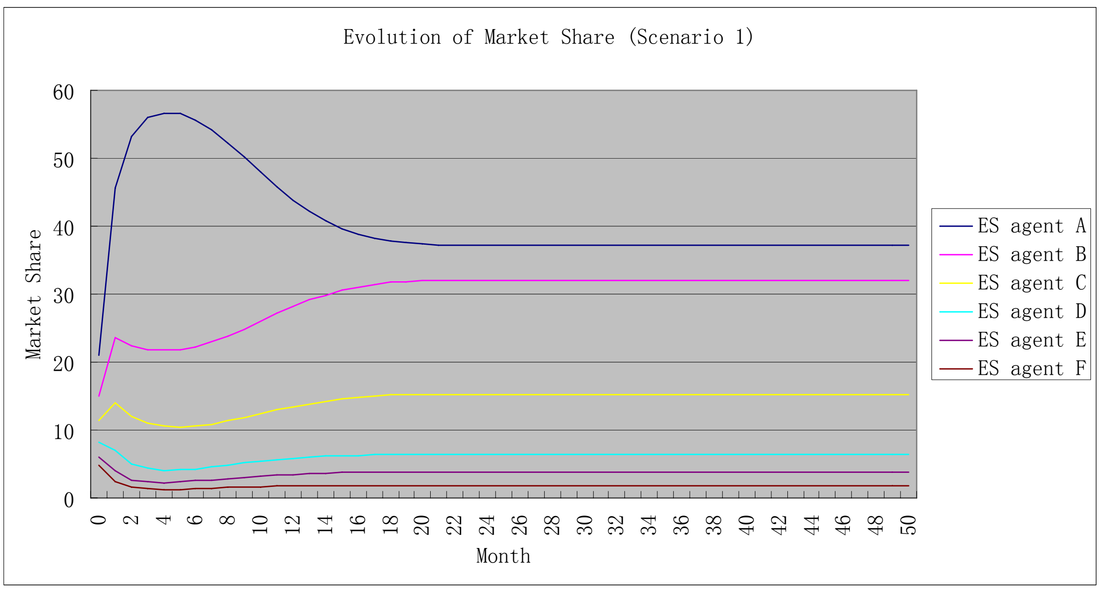

Figure 8: Evolution of electricity supplier agent's market shares in Scenario 1 (Government Financed-Competitive Roll Out)

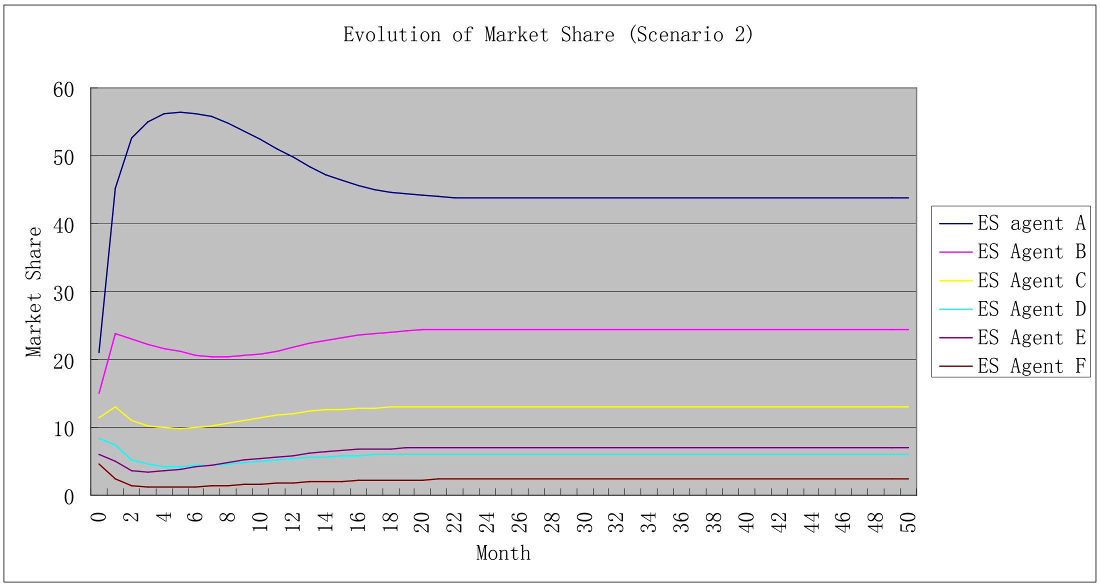

Figure 9: Evolution of electricity supplier agents' market shares in Scenario 2 (Government Financed-Monopoly Roll Out)

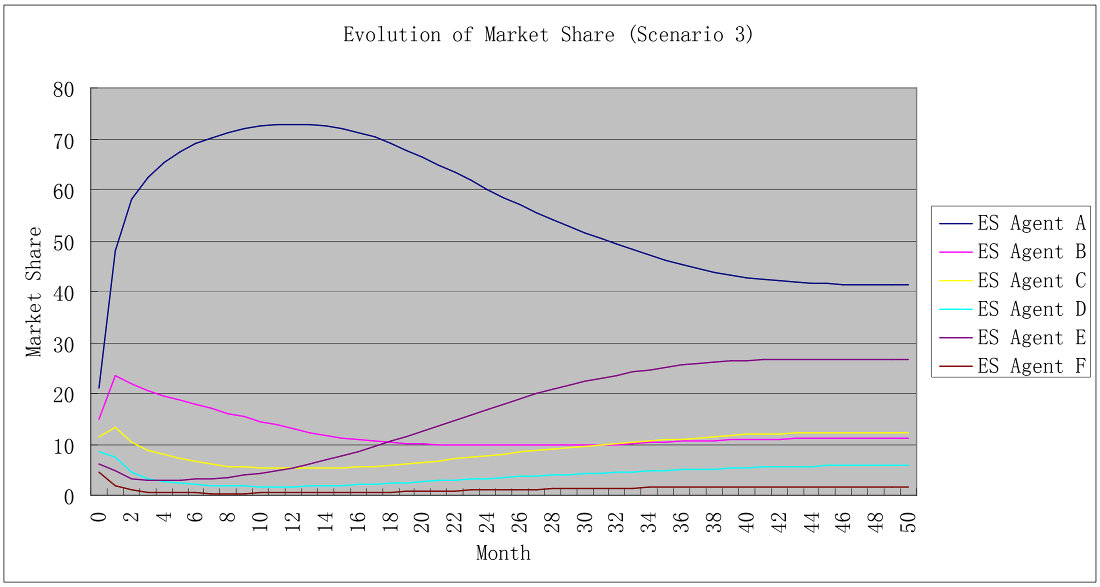

Figure 10: Evolution of electricity supplier agents' market shares in Scenario 3 (Electricity Supplier Financed-Competitive Roll Out)

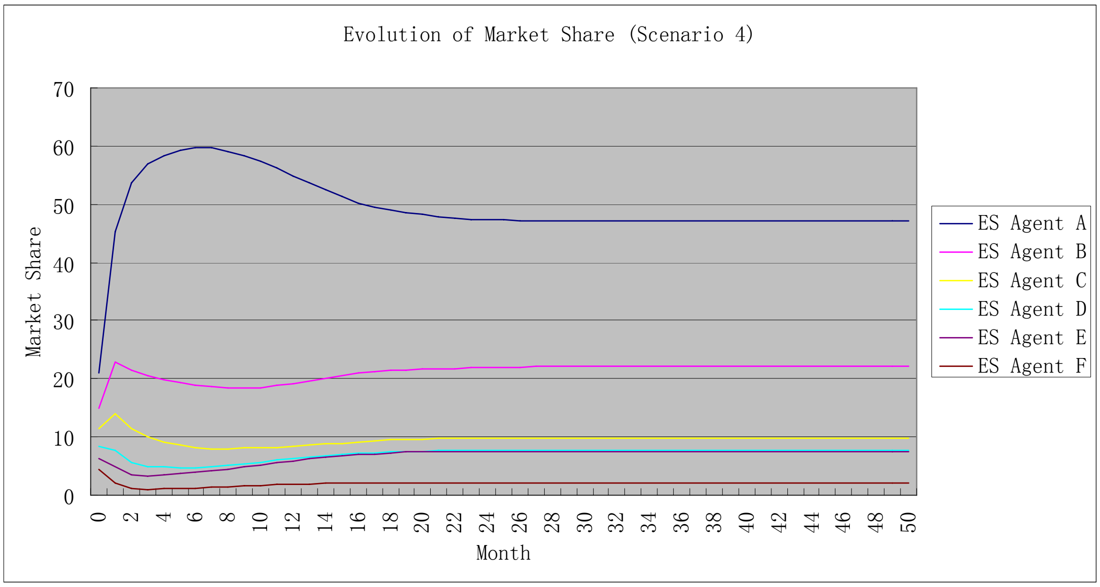

Figure 11: Evolution of electricity supplier agents' market shares in Scenario 4 (DNO Financed-Monopoly Roll Out)

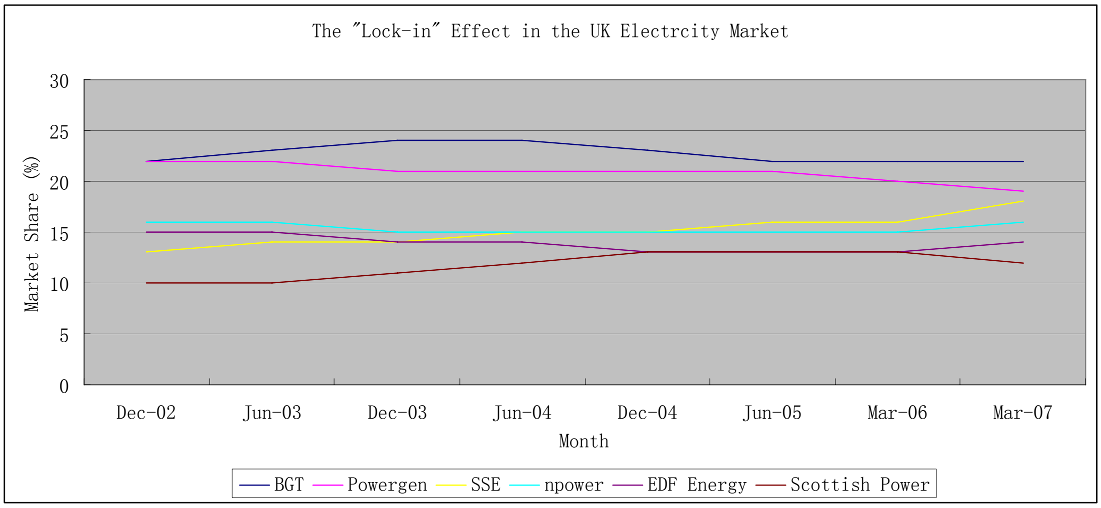

Figure 12: The "Lock-in" Effect in the UK Electricity Market (Data Source: Domestic Retail Market Report, Ofgem, June 2007)

Figure 13: Monthly residential consumer agent transfer flows

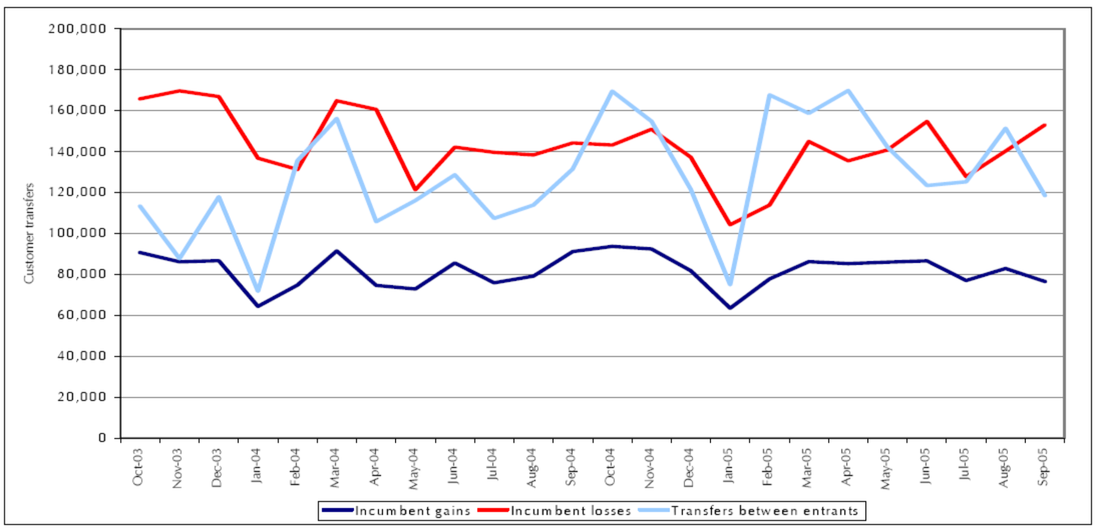

Figure 14: Monthly transfer flows in the real UK electricity market (Data Source: Domestic Retail Market Report, Ofgem, 2005)

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