Systems Research and Behavioral Science
Syst. Res. **21**, 373–389 (2004)

DOI: 10.1002/sres.644

■ *Research Paper*

Consumers’ Bounded Rationality: The Case of Competitive Energy Markets

Isaac Dyner*† and Carlos Jaime Franco

Universidad Nacional de Colombia, Medellín, Colombia

The recent liberalization of the energy industry provides a challenge for understanding the decision-making processes of the agents involved in their markets. In this new environment, it is of particular interest to investigate consumers’ decisions with respect to energy efficiency for a range of purposes that include the assessment of government policy and traders’ strategy intents. The neo-classic methodologies reported in the literature generally make strong, and not evident, assumptions with respect to the decision-making processes of end-users, including: complete information, full rationality and lack of risk perception. In this paper, the concept of bounded rationality is incorporated, seeking alternative grounds to the traditional approaches. Against this background, we examine different sets of assumptions based on the concept of *rationally bounded energy use* and propose policies that may reduce some of the apparent market failures. However, both these claims, as well as the proposed system dynamics models that intend to account for bounded rationality, need to be clearly justified. Here, we do this by indicating, explicitly and implicitly, how bounded rationality operates and what policies and strategies might be appropriate to remove some of the consumers’ barriers when confronting decisions. The system dynamics models presented in this paper incorporate consumers’ behaviour and alternative policies to assess their likely impact on society. Examples related to the penetration of fuels and lighting appliances are provided, to illustrate the approach. Copyright © 2004 John Wiley & Sons, Ltd.

Keywords consumers’ choice; bounded rationality; system dynamics; simulation; energy efficiency; industrial organizations; institutional economics

1. INTRODUCTION

As the liberalization of the electricity industry is taking place globally, competition has been promoted at the retail level, resulting in the freedom of consumers to choose from competing suppliers, in many countries worldwide. In this environment, electricity providers are intensifying competition, reducing prices and making electricity more attractive to consumers, which conflicts with policies aimed at electricity savings and demand-side management (DSM; Sioshansi,

---

* Correspondence to: Isaac Dyner, Universidad Nacional de Colombia, Medellín, Colombia. E-mail: idyner@unalmed.edu.co
† Visiting Professor of the British Academy, Imperial College London.
Contract/grant sponsor: COLCIENCIAS.

1995; Hasset and Metcalf, 1995; Martinot and Borg, 1998). DSM encompasses the planning and implementation of actions intended to reduce electricity consumption. Under the old monopoly schemes, DSM policies achieved important benefits to end-users and power utilities, especially with respect to energy efficiency initiatives, direct load control, load interruption and hourly pricing (EIA, 1996). With the recent industry deregulation, DSM brings about opportunities for electricity retailers and traders as they can promote energy efficiency in at least three alternative forms, including the promotion of green energy products, medium-term contracts that provide electricity and enhance efficient services, and off-peak electricity use.

However, it is not clear whether the conditions for DSM and *rational energy use* under centrally planned set-ups still prevail when markets are liberalized (Sutherland, 1991; Jaccard, 1995; Goett *et al*., 2000). In this paper we explore this issue, as it has been reported in the literature that consumers are not behaving rationally according to the neo-classic precepts of efficient energy use (Hasset and Metcalf, 1995). The next section examines the implicit decision-making processes in energy consumption and appliances selection, under market conditions, and section 3 explores the basis for analysing alternative decision-making frameworks, as full rationality frameworks seem unsuitable; this is followed by section 4, which focuses on modelling bounded rationality. Sections 5 and 6 examine detailed SD frameworks that incorporate alternative consumer behaviours, which are applied to real cases in the UK and Colombia. The final section presents some concluding remarks.

2. EFFICIENCY AND RATIONAL ENERGY USE UNDER OPEN MARKETS

The effectiveness of market mechanisms in reaching socially desirable levels of efficiency has generated a debate among economists and policy-makers. On the one hand, Debreu (1959) and Arrow and Hahn (1971) established the main conditions for the appropriate operation of markets, which entails optimal resource allocation. On the other hand, Simon (1959), Akerlof (1970) and Grossman and Stiglitz (1980) found that market failures due to information asymmetries and other elements produce less than optimal utilization of resources. As consequence of the latter, it follows that in actual markets individual welfare does not necessarily lead to social welfare, for the manifested inefficiencies in the marketplace.

As real markets largely depart from ideal ones, Stiglitz (2003), Newberry (1999), Armstrong *et al.* (1994) and many others argue that, by and large, government regulation will be of great help to make markets work better, and vice versa, as both have a significant number of imperfections that could be reduced if they work together.

In the energy industries, policy-makers seek efficiency. The neo-classic assumptions of perfectly informed markets and rational individuals who consider all costs, when deciding what appliances to buy, may partially explain some of the ineffectiveness of DSM. Sioshansi (1995) considers that under open markets DSM programmes should operate more efficiently than under centrally planned schemes as prices should provide the appropriate signal for energy efficiency. However, the literature has already reported some difficulties (Sutherland, 1991; Jaccard, 1995; Goett *et al*., 2000).

Several researchers have noticed that substantial differences exist between the current levels of energy efficiency and those that should be observed if consumers had made the appropriate 'rational decisions' (Jaffe and Stavins, 1994). This problem is referred to in the literature as *the energy efficiency gap*, which will be discussed next.

Explanations to this issue have been attempted. Some have argued that for electricity consumption and appliance acquisitions agents seem to assume implicitly discount rates above 89%, which are much higher than those rates applied to other common investments (Hasset and Metcalf, 1995; Howart and Andersson, 1993; Hausman, 1979; Gately, 1980). Particularly, Jaffe and Stavins (1994) claim that consumers apply high discount rates, due to price and operational uncertainties, when acquiring some appliances and domestic technologies. Others argue that these high rates may be explained by the consumers' low revenues and their lack of means for investment. Both imply that consumers expect to recover investments in very short periods of time, which can be overcome by (a) providing guarantees and (b) subsidizing customers who have low incomes. In this respect, a critical issue consists of establishing the size of the energy gap and the definition of the optimal level of energy efficiency.

Apparently, some market inefficiencies are due to uncertainties and to other matters related to the decision-making processes of final users, including cultural barriers, aesthetic parameters, habits, asymmetric information or knowledge, and high risks. It is with respect to these issues that bounded rationality (Simon, 1979; Conlisk, 1996; March, 1988) and desires and opportunities (Elster, 1989) seem to provide insights for undertaking DSM and encouraging energy efficiency, under bounded conditions, referred to in this paper as rationally bounded energy use, which we will examine next.

3. DECISION-MAKING FRAMEWORKS

As the problem of achieving market efficiency is grounded in the decision-making mechanisms adopted by economic agents, it is important to note that two distinct approaches have been followed in the economics literature. On the one hand, neo-classic economists argue that, as rational agents, individuals maximize their utility function for assessing their options (Debreu, 1959; Arrow and Hahn, 1971; and many others). On the other hand, institutionalists largely acknowledge an uncertain future and other limitations in the decision-making process that turn individuals into satisficers rather than optimizers (Simon, 1959; North, 1990; March, 1988; Hodgson, 1998; Conlisk, 1996).

As the former hypothesis has not fully accounted for the energy efficiency gap previously discussed, we examine in this paper the likely constraints that agents may confront when consuming electricity, and investigate alternative policies that may eliminate or reduce some of the barriers that consumers confront.

Adaptations to the two alternative decision-making formulations have been extensively discussed in the literature: firstly, incorporating information asymmetries and/or accounting for uncertainties under a neo-classic optimization framework (Stiglitz, 2003; Tirol, 1989; Akerlof, 1970); secondly, adopting a form of institutional approach and trying to establish the relevance of organizations in the decision-making process under bounded rationality schemes (Simon, 1979).

In this paper an intermediate path is hypothesized by connecting North's (1990) and Simon's (1959) approach with Elster's (1989, 1990) view of decision-making, but replacing the optimization arguments by satisficing ones. According to Elster (1989), decisions depend on desires and beliefs, which at the same time are influenced by evidences. Thus decisions are made when these three elements coincide, as illustrated in Figure 1. The proposed decision-making framework is subsequently adjusted here to Simon's (1979) ideas, by defining a satisficing set which is found in the intersection of the sets of desires, evidences and beliefs.

Rather than an optimal process of choice, Simon (1979) argues that humans are fundamentally adaptive under satisficing criteria. In this context, in complex environments, the decision-maker is often forced to discard a large amount of information, not always reaching an optimal solution, because of his limitations in terms of (a) mental representations' boundedness and (b) limited mental processing capacity (Simon, 1979; Rubinstein, 2000). While computers disregard context, humans seem better able to integrate it into their decision-making processes. Under these conditions, what rationality can

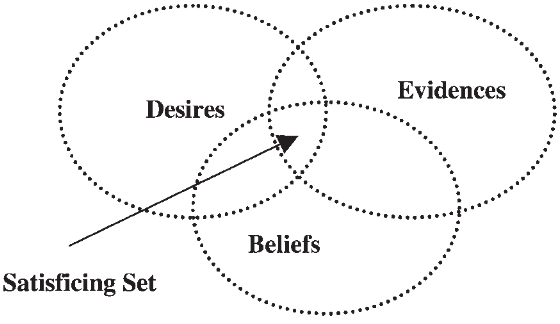

Figure 1. Sets of desires, evidences and beliefs

then be attributed to individuals? And, what would be an appropriate model approach to use?

In this paper we emphasize the relevance of bounded rationality in the decision-making process, for improved policy modelling. In the next section we address this issue, by proposing a modelling scheme which consists of a synthesis of Elster's and Simon's approaches, as it has been recognized that there are important links between the two (Cook, 1990).

4. MODELLING CONSUMERS' DECISION MAKING IN ELECTRICITY MARKETS

As different approaches have been unable to explain the efficiency gap in electricity markets (Hasset and Metcalf, 1995), here we hypothesized a mixed proposal based on Elster's ideas, under the institutionalist framework, to help us understand the rationality of energy consumers, in order to propose policies and strategies intending to make energy use more efficient.

The proposed approach is centred here on the problem of understanding the decision-making processes, with respect to energy efficiency, of the most relevant agents concerned with energy consumption—electricity traders and retailers—for effective policy making.

As has been discussed, desires and opportunities drive the decision-making processes. It has also been observed that the limitations in decision making may be explained by bounded rationality, which might be transformed by the actions of electricity traders. These actions, in turn, depend on both the environment and own goals, customers' feedback, via system reaction, and by the adjustments introduced to government's policy and electricity traders' strategy. This general decision-making framework is represented in Figure 2. The system evolves according to the actions of participants. The observed system evolution induces government policies (e.g. taxes and regulations), according to set goals, in order to modify customers' desires and opportunities. This framework represents the inherent sociological and psychological limitations of consumers.

In this context, given the number of variables involved and the non-linearities between their interactions, modelling is required for appropriate policy assessment if some 'adequate' level of energy consumption is pursued, under bounded rationality in competitive markets. When evaluating modelling alternatives for policy support, the literature provides foundations to carry it out using simulation and system dynamics. On the one hand, Bunn and Dyner (1996), Larsen and Bunn (1999), Ford (1999) and Dyner (2000) state that system dynamics may be a sensible option, especially if operating under rapidly evolving systems or under recently restructured markets. Furthermore, Morecroft (1983) argues that system dynamics implicitly uses bounded rationality frameworks, and that

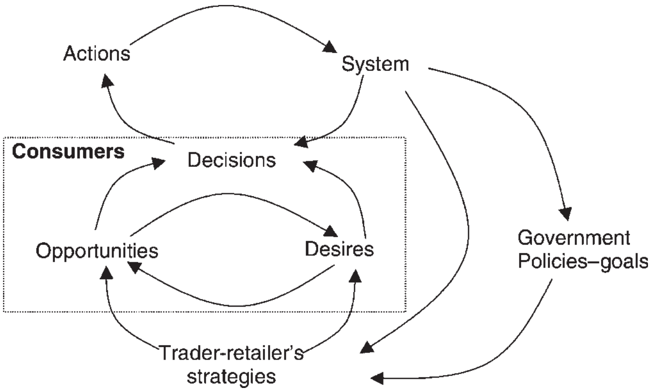

Figure 2. A general decision-making framework that includes feedbacks from government and traders

the behaviour of complex organizations can only be understood by taking into account the knowledge of individuals and their psychological limitations. Also, Pidd (1997) shows the advantages of soft methodology approaches in this kind of problem. On the other hand, there is a range of perspectives on the problem, going from agent-based simulation (Bunn and Oliveira, 2001; Bower and Bunn, 2000) to game theory (Ferrero *et al*., 1998). All these perspectives focus on information flows within complex systems, the quantity and quality of the information that is manageable in the decision-making processes and the decision rules being used.

It is at the level of information flows and decision-making where most of the fundamental ideas of bounded rationality coincide with simulation techniques, but it is also at this level that bounded rationality takes a different view from classic approaches. This becomes specific with respect to desires and opportunities in the selection of efficient technologies.

In this paper, given the feedbacks and delays involved in the system, we undertake an SD modelling approach to better explain consumers' decision-making processes, under bounded rationality conditions. The simulation models proposed here include desires, opportunities and the decision-making mechanism itself, as discussed next.

Modelling desires consists of determining the portion of the population that will not be shifting away from former energy technologies because they have no knowledge with respect to alternatives, or because they are reluctant to change (and they may not even consider the possibility of change), or even because they are risk averse. All these inhibit the entry of technology alternatives.

There are some problems related to modelling these characteristics. Perhaps the main one relates to modelling habits (habits are less tangible than opportunities), which seem to be an important factor inhibiting technological changes. The general information flow diagram (arrows indicate influences) in Figure 3 describes the filtering processes of desires and opportunities. The filter of opportunities illustrates how decision-makers consider product availability, information about alternatives (opportunities known by consumers) and consumers' income. The filter of desires includes customers' habits of, and their willingness or stimuli required for, change. While innovators require limited

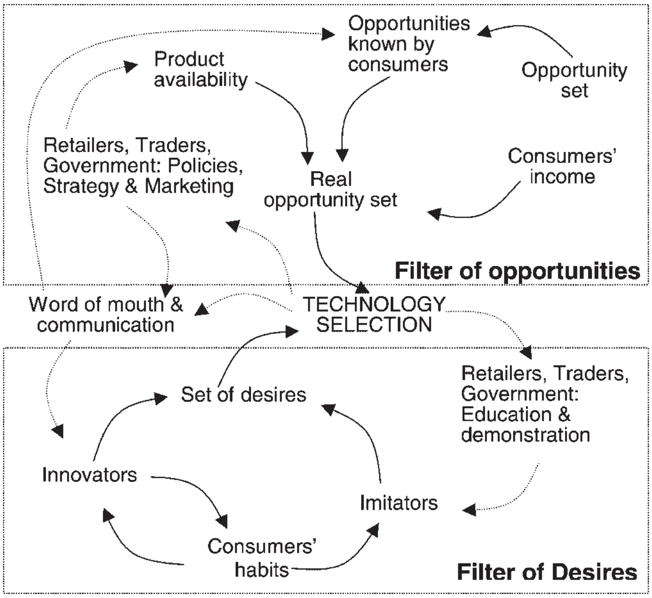

Figure 3. Double filter for technology choice: the case of electric appliances

information when deciding to acquire novel technologies, imitators need exposure to experiences, coaching and demonstrations.

It can be observed in Figure 3 that technology choice, in the electricity context, depends on real opportunities and desires. The consumer's real opportunity set is found in the intersection of the sets of known opportunities, product availability and consumer's payment capacity. Consumer desires vary depending on whether the individual is an innovator or an imitator. The characteristics of the product availability and the consumer's knowledge about the product depend on a number of factors including the provider's actions and the existing communication mechanisms in this environment; and, this in turn depends on technology penetration. Innovators and imitators are informed by available means and via displays and pilot experiences.

In this context, policies and strategies might be directed to stimulate opportunities and desires—they have to address the specific issues involved, if any effect is to be expected. Here, alternative policies are proposed for evaluation.

4.1. Policies Intending to Stimulate Opportunities

Policies intending to stimulate opportunities are easy to identify as 'Opportunities are external to individuals, while desires depend on them' (Elster, 1989). It is easier to change people's opportunities than to transform their ways of thinking. Policies intended to increase opportunities tend to be most effective if they counter the causes that restrict them. The different policies that may enlarge the opportunity set include:

- for the set of new opportunities—research and development of new technologies;
- for the set of opportunities known to the user—diffusion or marketing;
- for the set of real opportunities—improvement of distribution channels of technologies;
- for the set of economic opportunities—financing, soft credits.

4.2. Policies Intending to Stimulate Desires

There is no use for an extensive opportunity set if people have limited desires. To focus on policies that stimulate desires it is necessary to consider people's habits, intending to modify them. This could be accomplished by means of education or by demonstration (pilot schemes). Changing habits may sometimes be easily achieved by children's education.

We have set the theoretical foundations for developing a modelling framework that may account for the consumers' behaviour in the open energy market context, and which may partially explain inefficient energy use. This framework, if proved useful, may also be appropriate for policy assessment of energy efficiency. These will be examined next.

5. MODELLING ENERGY CONSUMPTION UNDER BOUNDED RATIONALITY

We will now turn to alternative modelling of the consumers' decision-making processes under bounded rationality. The initial problem under consideration is the market split between incandescent (traditional light-bulbs) and compact fluorescent light-bulbs.

The market split is established according to the following rationale: variation in the number of consumers that embrace a particular appliance or technology depends on new adopters and the ones that stop using it. Individuals adopt a particular technology at a rate AR_i, with time-delay l, and discard at a rate DR_i, as described by the following equations:

$$\begin{aligned}\frac{\mathrm{dTec}_i(t)}{\mathrm{d}t} &= \mathrm{Input}_i(t) - \mathrm{Output}_i(t)\\ \mathrm{Input}_i(t) &= \mathrm{Tec}_i(t-l)^{*}\mathrm{AR}_i\\ \mathrm{Output}_i(t) &= \mathrm{Tec}_i(t-l)^{*}\mathrm{DR}_i\end{aligned}$$

where Tec_i = installed technology i, AR_i = adop-adoption rate of technology i (fraction of total per time unit), DR_i = discarding rate of technology i (obsolescence rate of technology i per time unit), t = time, and l = delay.

Under a simplified optimization criterion (based only on prices and with no limitations of any sort), consumers would immediately acquire the 'best item'—for this, consumers do not consider attributes such as brand name or reliability. Alternatively, under more realistic conditions, the decision for adopting a particular item is assumed to depend on a 'sticky function' of the relative weight of the most important attributes of the technology (Bierlaire, 1998). The specific criterion of the adoption rate is as follows:

$$\mathrm{AR}_i = \frac{C_i^{-\gamma}}{\sum_j C_j^{-\gamma}} \qquad i = 1, 2, \ldots, k; \quad j = 1, 2, \ldots, k$$

where $i =$ technology, $\gamma =$ parameter that indicates willingness to change ($\gamma > 0$), and $C_i =$ item characteristics or attributes: price, colour, brand, size, etc.

This criterion, sometimes referred to as the Logit model, is placed somewhere between absolute and bounded rationality, as consumers are adopting the 'best' technology according to two factors: (a) a rate that depends on how good this technology is relative to alternative options, and (b) a parameter that indicates how strong the inclination will be for consumers to choose a technology that possesses 'good attributes'.

The corresponding system dynamics model is represented in Figure 4 (the Appendix includes the complete set of equations for this model). It can be observed that new bulbs are acquired according to an acquisition rate that depends on the availability of the different alternatives—fluorescent and incandescent—and an adjustment from the deviation between the actual and the 'ideal' technology split. This adjustment takes place over time with some delay. In Figure 4, the characteristic associated with the bulbs when using the Logit model is the monthly equivalent cost of either incandescent or fluorescent bulbs. This is calculated as a function of their electricity price, the average electricity

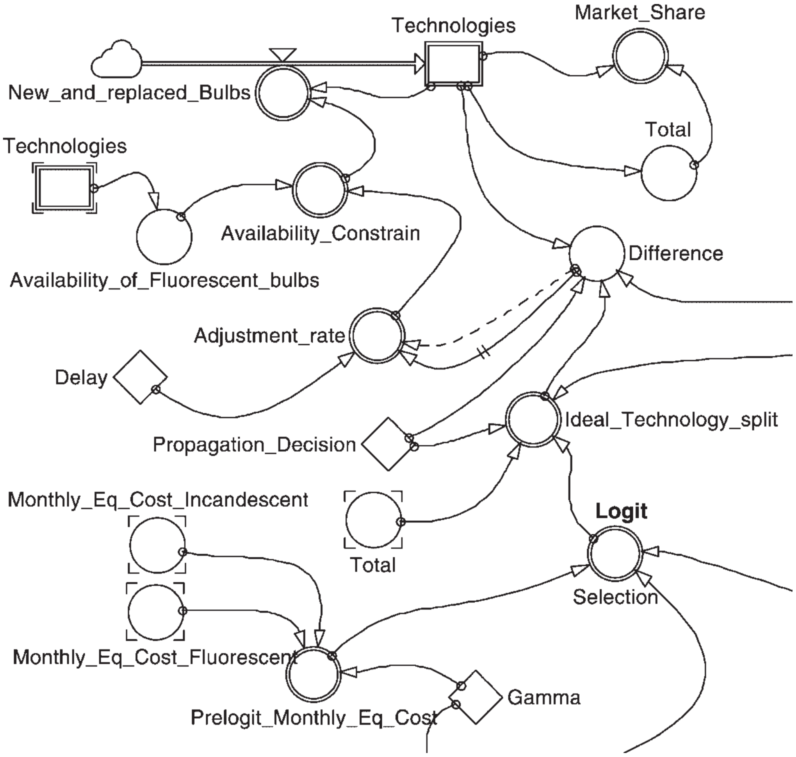

Figure 4. SD model of technology penetration for households lighting (figure has been copied from a model built in Powersim, 2003, which has been used as simulation software)

consumption, the actual bulb cost and the bulb life. Adoption and discarding rates are modelled within a single variable as inflow to or outflow from the variable technologies.

The Bass model (Van den Bulte, 2002) is an alternative approach for representing technology penetration. This, however, does not consider the consumers' rationale with respect to the characteristics of the items under consideration, which is central to the proposed approach in this paper, but rather information-related technology dissemination such as word of mouth.

The results obtained with the Logit model, using just monthly equivalent cost as attribute, can be observed in Figure 5. The market share of compact fluorescent bulbs is larger than that of incandescent bulbs, but does not penetrate the whole market. Under these considerations, if consumers were absolutely rational (a very simplified optimization criterion) they would all adopt compact fluorescent bulbs after time zero (i.e. the market share of this technology would be 100%).

When modelling the acquisition rate under financial considerations, such as future value, one could determine the discount rates at which compact fluorescent bulbs would be most attractive. In this case, the model uses the same principle as the Logit model; however, future value is used instead of the present value of the item or its annual equivalent cost, to incorporate the concept of risk, via discount rates:

$$\mathrm{FV} = \mathrm{PV} * (1 + r)^n$$

where r = discount rate, FV = future value, PV = present value, and n = number of periods.

Figure 6 shows model results when financial decisions are made, under discount rates of 10% and 50% respectively. Hausman (1979) and Gately (1980) found that households apply discount rates above 100% when acquiring appliances. These discount rates differ between appliances; for example, while an electric water heater's implicit discount rate is 243%, a freezer's is 138% (Hausman, 1979). There are two other explanations for purchases of inefficient appliances: lack of information and lack of liquidity. In the USA, while appliances are relatively inefficient, partly due to lack of information to customers, there do not seem to be major acquisition barriers, as credit is widely available (Thaler, 1992). Results are as expected: to lower discount rates, increase penetration of the corresponding technology. These high discount rates could be reduced by means of educational programmes (oscillations result from delays in information flows).

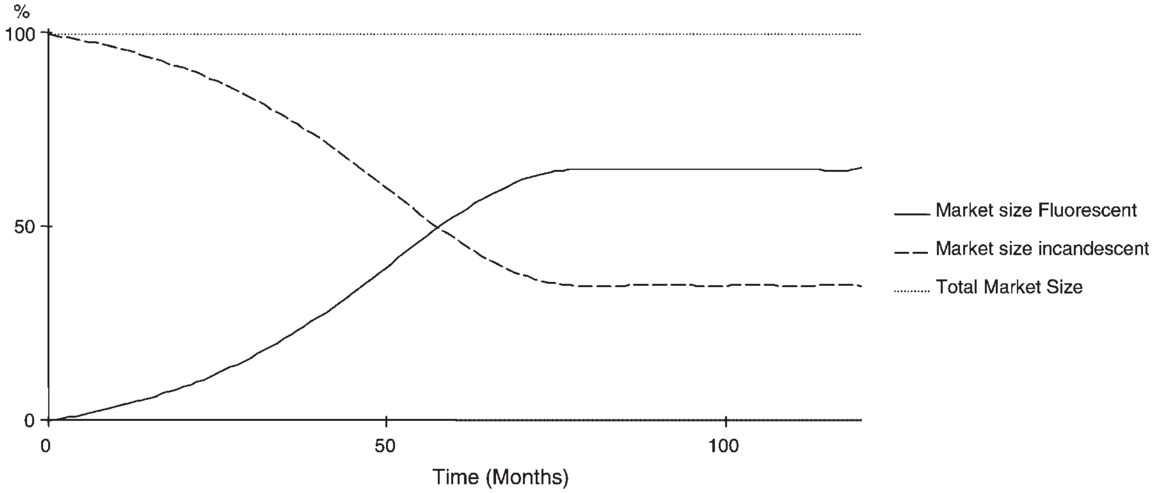

Figure 5. Technology propagation of light-bulbs using optimization and the Logit model (time in months)

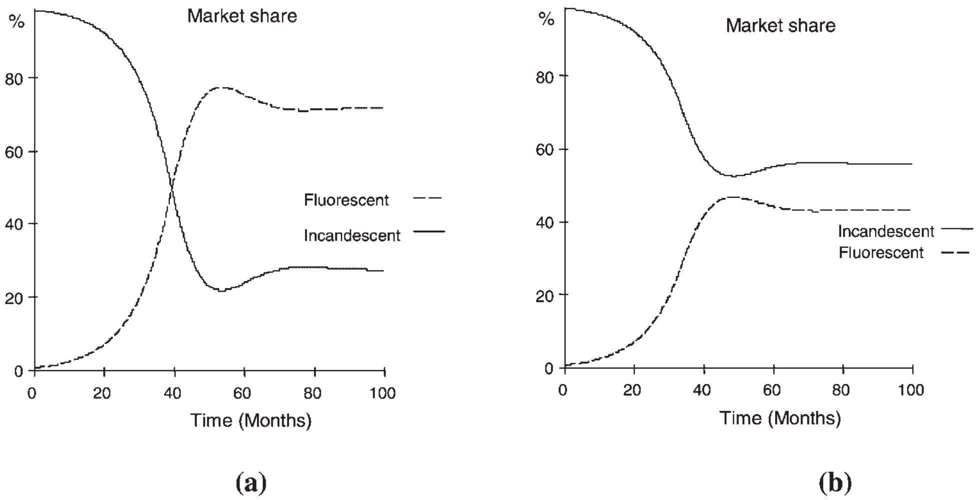

Figure 6. Results of the financial model for discount rates of (a) 10% and (b) 50%

When considering technology diffusion mechanisms that affect acquisition decisions (on top of financial arguments), where individuals are imitators, and never take their own decisions, the equations below explain the rate of propagation or diffusion of a particular technology or fuel. This behaviour has been referred to in the literature as contingent behaviour (Schelling, 1978):

$$\frac{\mathrm{dAR}_i(t)}{\mathrm{d}t} = \mathrm{Followers}(t) * \mathrm{Diffusion\_rate}$$

$$\begin{aligned}\mathrm{Followers}(t) &= \mathrm{Followers}(t-l) * \mathrm{Growth\ rate}\\ &\quad -\mathrm{Followers}(t-l) * \mathrm{Diffusion\_rate}\end{aligned}$$

where $\mathrm{AR}_i(t)$ = acquisition rate of technology i at time t, and imitators(t) = population whose behaviour depends on what others are doing at time t.

The corresponding SD component of the model can be appreciated in Figure 7. It is shown that the population changes habits (imitators) depending on a 'contagion factor', which resembles the propagation of infections. The contagion factor is a multiplier that contributes to propagation of a particular technology. The percentage of the population with new habits to the total population influences the technology choice in a logistic manner, as previously modelled. In turn, the contagion factor is affected by the market share of the technologies and eventually policies and strategies of the other actors involved in the system (government and traders).

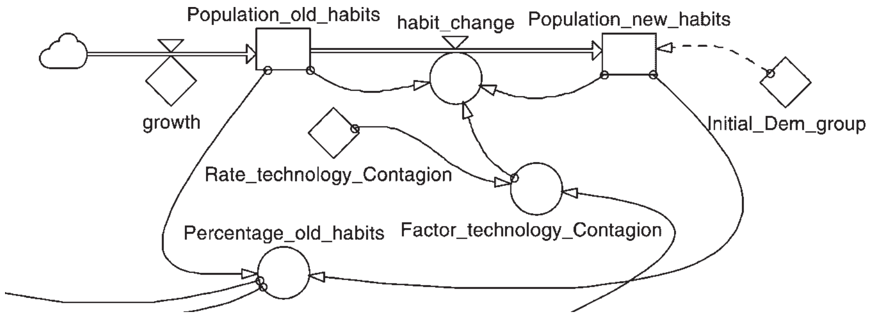

Figure 7. SD modelling of habit change regarding technology acquisition

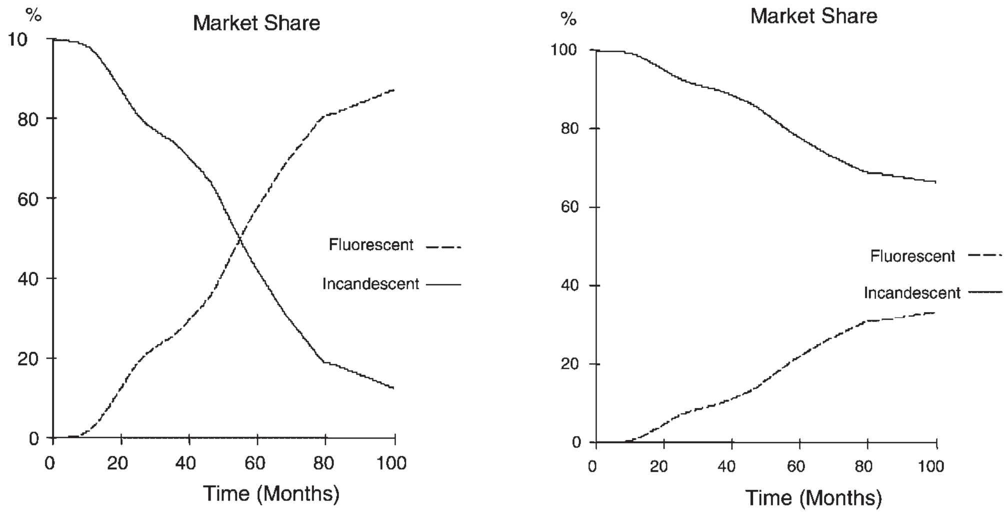

Figure 8. Technology diffusion when 8% of the population considers changing, using discount rates of 10% and of 50%, respectively

Model results can be observed in Figure 8. These results contrast with findings exhibited in Figure 6. This is due to the fact that only a small percentage of the population (8%—the approximate penetration of efficient light-bulbs in the UK in 1993) is capable of making decisions because of their lack of knowledge or fear of change. However, the propagation process helps in many occasions to defeat the incumbent technology.

In the following section we report how the modelling approach presented here cannot only explain technology penetration of compact bulbs in the UK but also natural gas penetration in the residential sector in Colombia.

6. BOUNDED RATIONALITY AND ELECTRICITY TRADING

The liberalization of energy markets has had profound implications for electricity trading, market evolution, companies' strategy and government policy. On the one hand, there has been intense competition in the market-place, where price and rudimentary forms of service improvement have initially played an important role during the infant stages of the development of the new markets. On the other hand, it has not always been possible for governments to lay back and wait for markets to develop on their own (regulation may often help improve market imperfections as previously discussed in sections 2 and 3). Long-term strategic issues, such as supply additions and DSM, have also been considered, as society is notably sensitive to these issues, especially with respect to their effect on the environment. In this section we examine examples of the proposed approach, with respect to both cases.

6.1. Penetration of Efficient Light-Bulbs in the UK

The end-users' market has been gradually liberalized in England and Wales since 1990. Initially, only large consumers could choose their suppliers; later, in 1994, medium-sized customers were allowed to do so, and finally households and the remaining small consumers were freely allowed to choose electricity supplier. It took three years for over half of the large and medium-sized consumers to move to alternative suppliers, and their bills were reduced by about 20% (Littlechild, 1998). For the household sector, changes have occurred at a rate of over 100,000 per week (OFGEM, 2001). This in itself prompts interesting research issues related to consumers' behaviour. However, what draws our attention in this paper is consumers' behaviour towards energy efficiency, which we will examine next. In particular we address the issue of penetration of efficient light-bulbs in the UK.

In general, barriers to inertia may easily be lifted when customers almost immediately experience the effect of their decisions. As has just been discussed above, electricity prices have provided a clear signal for UK customers to change providers; nevertheless, this has not always been the case in all cases and circumstances (Goett *et al*., 2000). For example, in terms of energy efficiency issues, such as light-bulbs, consumers have not always shifted to the most 'rational alternative', because of a number of possible barriers, as will be discussed below.

In the UK, before 1993 less than 10% of the population had at least one compact fluorescent lamp (CFL). By 1997 penetration had reached 23% of the market (Figure 9 indicates the historic penetration—this has been a calibration process of the model). This was basically the result of consumers' increasing awareness, which rose from 50% in 1993 to 75% in 1997 (Martinot and Borg, 1998).

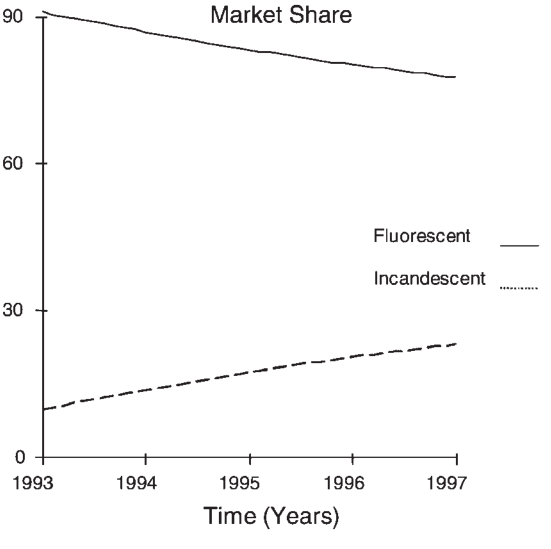

Figure 9. Model output after calibration. Penetration of CFLs in the UK and market loss by incandescent lamps

However, important barriers to a higher penetration of the CFLs have emerged. The most important ones include (Martinot and Borg, 1998; Palmer and Boardman, 1998):

- lack of information;
- cost;
- lack of incentives; and
- disbelief about the characteristics of the technology.

Figure 10 shows the results of policy simulations geared to (a) reductions of the consumers' discount rate, via exhibition programmes, advertising and product guarantee, and (b) subsidizing CFLs by as much as one half of the price.

These results suggest that price reduction of fluorescent lamps would not make much difference, as they will still be much more expensive in absolute terms than incandescent lamps. However, demonstration programmes and guarantee schemes may have an important impact on the penetration of fluorescent lamps. With appropriate marketing, penetration could be at even higher rates, as has happened in the mobile telephone industry.

6.2. Penetration of Natural Gas in the Household Sector in Colombia

The penetration of natural gas in the household sector in Colombia provides a second case for illustrating how bounded rationality has an effect on decisions with respect to energy efficiency issues. This case shows that government goals might sometimes be outperformed, when there is intense competition or suitable incentives are offered (volume sales and profits).

In the early 1990s the Colombian government decided to promote the use of natural gas in the household sector, especially for cooking and water heating. It structured a plan which included setting in place a gas transportation network, as well as the legislative industry framework for production, distribution and pricing (LEY 142, 1994). Note that in some Colombian regions sales to end-users have been a highly competitive business.

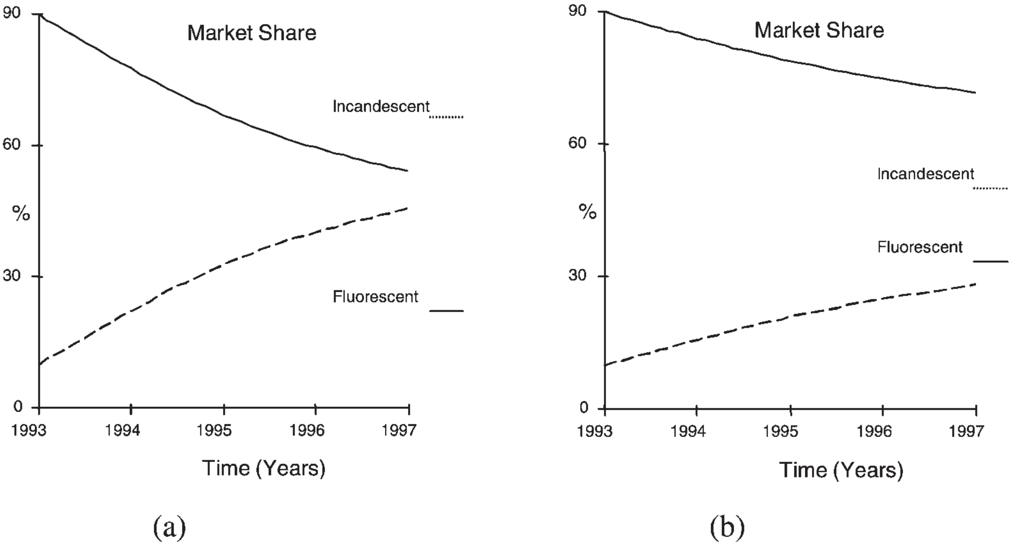

Figure 10. Likely impact of the penetration of fluorescent bulbs under (a) demonstration programmes and product guarantees, and (b) subsidies

The question of the speed of gas penetration has been of especial interest as this has a major impact on the finances of investors. Initial calculations indicated that the annual equivalent costs of electric cookers and water-heaters were much higher than for gas-fired ones, providing the right incentives for shifting source were established. The price of natural gas for residential users is about US $7 per MBTU, while for electricity it is nearly US $39 per MBTU. However, some likely barriers have been detected for households, including entry expenses, habits and availability.

To counter these barriers, subsidies, instalment payments and exhibition programmes were put in place. As a result, penetration has been about 18%

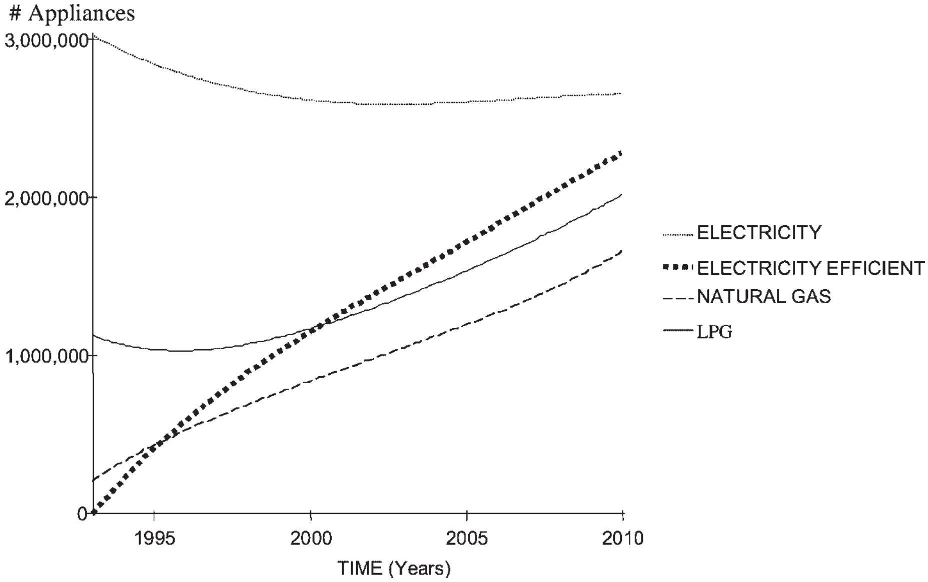

Figure 11. Simulating the evolution of stoves, by source of fuel, in Colombia

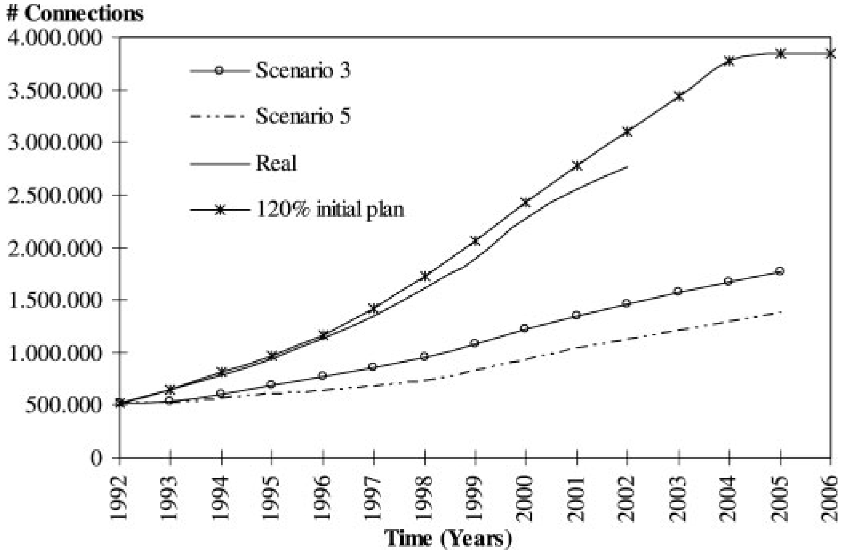

Figure 12. Penetration of natural gas in Colombia

per year during the period 1994–2000, which is higher than originally planned. Nevertheless, this could have been even higher if more connections and other programmes had been available to customers, as discussed in Dyner (2000).

Figure 11 shows simulation results of appliances chosen for cooking, supposing that agents behave according to the bounded conditions of the Logit model (Dyner, 2000, includes a full description of the model and some findings). It can be appreciated that the curve representing appliances that use traditional electricity fall at the expense of all other appliances that use alternative sources (gas, LPG and efficient electricity—microwave cooking). We can also observe, in Figure 12, the actual gas penetration in the residential sector, the planned penetration that the government envisaged and a number of other scenarios, including one that makes available 120% of the planned number of installations to customers.

Plan implementation has been successful as loans, financial services and demonstration programmes have been widely available to households. Simulation results indicate that the gas plan was outperformed because connections to the transport network were widely available to customers (this validates government policy as we are contrasting real penetration of the gas plan with alternative intents).

7. CONCLUSIONS

We have shown that the supposedly 'irrational' behaviour of consumers with respect to electricity consumption, apparently manifested by the electricity efficiency gap that has been reported in the literature, is partly a fallacy grounded in customers' bounded rationality.

We have analysed the decision-making process undertaken by consumers, in order to understand the rules and habits that have major influences on their behaviour. We did this to make explicit the likely barrier to the adoption of efficient fuels, appliances or technologies.

The proposed hypothesized approach provides grounds for the understanding of such consumers' limitations and habits. We have examined alternative government policies and traders' strategies that might lift such barriers to consumers making efficient decisions. We also considered the impact of advertising, demonstration programmes and word of mouth on technology propagation. We indicate that these strategies may make important contributions to changing habits. Simulation results show that the energy efficiency gap may be closed under such policies.

The case of slow penetration of compact fluorescent bulbs in the UK might be partly explained by the lack of incentives to customers, including the high entrance cost. The Colombian case related to natural gas penetration has been successful, as incentives have been correctly placed, swiftly eliminating entry barriers, and helping to meet the initial goals rapidly.

These cases illustrate how policies could be geared to influencing customers' desires and opportunities, lifting some of the penetration barriers to energy efficiency. These in turn will contribute to more sustainable forms of energy use, partly overcoming disputes between marketers and conservationists. There is still room, under competitive markets, for policy incentives that contribute to lowering customer bills and energy-efficient consumption.

ACKNOWLEDGEMENTS

The authors sincerely appreciate the financial support provided by COLCIENCIAS (the Colombian Research Council). Isaac Dyner acknowledges the British Academy for supporting his visit at Imperial College London. The authors thank the two anonymous referees for their useful comments and constructive criticism.

REFERENCES

Akerlof G. 1970. The market for 'lemons': quality uncertainty and the market mechanism. *Quarterly Journal of Economics* **84**(3): 488–500.

Armstrong M, Cowan S, Vickers J. 1994. *Regulatory Reform, Economic Analysis and British Experience*. MIT Press: Cambridge, MA.

Arrow K, Hahn F. 1971. *General Competitive Analysis*. North-Holland: Amsterdam.

Bierlaire M. 1998. Discrete choice models. In *Operations Research and Decision Aid Methodologies in Traffic and Transportation Management*, Labbé M, Laporte G, Tanczos K, Toint Ph (eds). No. 166 of NATO ASI Series, Series F, Computer and Systems Sciences.

Bower J, Bunn DW. 2000. Model-based comparisons of pool and bilateral markets for electricity. *Energy Journal* **21**(3): 1–29.

Bunn DW, Dyner I. 1996. Systems simulation to support integrated energy analysis and liberalised planning. *International Transactions in Operational Research* **3**(2): 105–115.

Bunn DW, Oliveira FS. 2001. Agent-based simulation: an application to the new electricity trading arrangements of England and Wales. Working Paper, Decision Sciences, London Business School, London.

Conlisk J. 1996. Why bounded rationality? *Journal of Economic Literature* **34**: 669–700.

Cook KS. 1990. *Limits of Rationality*. University of Chicago Press: Chicago.

Debreu G. 1959. *Theory of Value: An Axiomatic Analysis of Economic Equilibrium*. Yale University Press: New Haven, CT.

Dyner I. 2000. Energy modelling platforms for policy and strategy support. *Journal of the Operational Research Society* **51**: 136–144.

EIA. 1996. *US Electric Utility Demand-Side Management 1996*. DOE: Washington, DC.

Elster J. 1989. *Nuts and Bolts for the Social Sciences*. Cambridge University Press: Cambridge, UK.

Elster J. 1990. When rationality fails. In *The Limits of Rationality*, Cook KS (ed.). University of Chicago Press: Chicago.

Ferrero RW, Rivera JF, Shahidehpour SM. 1998. Application of games with incomplete information for pricing electricity in deregulated power pools. *IEEE Transactions on Power Systems* **13**(1): 184–189.

Ford A. 1999. Cycles in competitive electricity markets: a simulation study of western United States. *Energy Policy* **27**(11): 637–658.

Gately D. 1980. Individual discount rates and the purchase and utilization of energy-using durables: comment. *Bell Journal of Economics* **11**(1): 373–374.

Goett AA, Hudson K, Train KE. 2000. Customers' choice among retail energy suppliers: the willingness-to-pay for service attributes. *Energy Journal* **21**(4): 1–28.

Grossman S, Stiglitz J. 1980. On the impossibility of informationally efficient markets. *American Economic Review* **70**(3): 393–408.

Hasset KA, Metcalf GE. 1995. Energy tax credits and residential conservation investment: evidence from panel data. *Journal of Public Economics* **57**: 201–217.

Hausman J. 1979. Individual discount rates and the purchase and utilization of energy-using durables. *Bell Journal of Economics* **10**: 33–54.

Hodgson GM. 1998. The approach of institutional economics. *Journal of Economic Literature* **36**(1): 166–192.

Howart RB, Andersson B. 1993. Marker barriers to energy efficiency. *Energy Economics* **15**(4): 262–272.

Jaccard M. 1995. Oscillating currents, the changing rationale for government intervention in the electricity industry. *Energy Policy* **23**(7): 579–592.

Jaffe AB, Stavins RN. 1994. The energy-efficiency gap, what does it mean? *Energy Policy* **22**(10): 804–810.

Larsen ER, Bunn DW. 1999. Deregulation in electricity: understanding strategic and regulatory risk. *Journal of the Operational Research Society* **50**: 337–344.

LEY 142. 1994. Ley de servicios públicos. *The Colombian Congress*, Republica de Colombia, Bogotá.

Littlechild SC. 1998. The generation and supply of electricity: the British experience. In *Competition in Regulated Industries*, Helm D, Jenkinson T (eds). Oxford University Press: Oxford; 193–212.

March JG. 1988. *Decisions and Organizations*. Blackwell: Oxford.

Martinot E, Borg N. 1998. Energy-efficient lighting programs: experience and lessons from eight countries. *Energy Policy* **26**(14): 1071–1081.

Morecroft JDW. 1983. Portraying bounded rationality. *OMEGA* **11**(2): 131–142.

Newberry D. 1999. *Privitization, Restructuring and Regulation of Network Utilities*. MIT Press: Cambridge, MA.

North D. 1990. *Institutions, Institutional Change and Economic Performance*. Cambridge University Press: Cambridge, UK.

OFGEM. 2001. *Ofgem 2000 Annual Report*. Ofgem: London.

Palmer J, Boardman B. 1998. *Delight, Domestic Efficient Lighting, Energy and Environment Programme*. Environmental Change Unit: University of Oxford, Oxford.

Pidd M. 1997. *Tools for Thinking: Modelling in Management Science*. Wiley: New York.

Powersim. 2003. *Powersim Constructor Version 2.51*. Isdalsto, Norway.

Rubinstein A. 2000. *Modeling Bounded Rationality*. MIT Press: Cambridge, MA.

Schelling TC. 1978. *Micromotives and Macrobehavior*. W. Norton: New York.

Simon HA. 1959. Theory of decision-making in economic and behavioural sciences. *American Economic Review* **49**(2): 253–283.

Simon HA. 1979. *Models of Thought*. Yale University Press: New Haven, CT.

Sioshansi FP. 1995. Demand side management: the third wave. *Energy Policy* **23**(2): 111–114.

Stiglitz J. 2003. *The Roaring Nineties: Seeds of Destruction*. Penguin: London.

Sutherland R. 1991. Market barriers to energy efficiency investments. *Energy Journal* **12**(3): 15–34.

Thaler RH. 1992. *Winner's Curse: Paradoxes and Anomalies of Economic Life*. Princeton University Press: Princeton, NJ.

Tirol J. 1989. *The Theory of Industrial Organizations*. MIT Press: Cambridge, MA.

Van den Bulte C. 2002. Want to know how diffusion speed varies across countries and products? Try using a Bass model. *PDMA Visions* **26**(4): 12–15.

APPENDIX: MODEL EQUATIONS

Stocks

```
difference_ac_goal(t+dt) = difference_ac_goal(t) + dt*difference_goal
    difference_ac_goal(initial) = 0

Population_new_habits(t + dt) = Population_new_habits(t) + dt*habit_change
    Population_new_habits(initial) = In_Dem_group

Population_old_habits(t + dt) = Population_old_habits(t) + dt*growth - dt*habit_change
    Population_old_habits(initial) = 1000

Technologies(t + dt) = Technologies(t) + dt*New_and_replaced_Bulbs
    Technologies(initial) = [1,99]
```

Auxiliaries

```
difference_goal = Analysis_goal^2
habit_change = MIN (Population_new_habits * Factor_technology_Contagion, Population_old_habits)
New_and_replaced_Bulbs = IF (Technologies(inc) > 100, 100-Technologies(inc),
    IF(Technologies(inc) < 0, -Technologies(inc), Availability_Constrain(inc)))*[0,1]
    + IF (Technologies(fc) > 100,100-Technologies(fc), IF (Technologies(fc) < 0, -Technologies(fc),
    Availability_Constrain(fc)))*[1,0]

Adjustment_rate = DELAYMTR (Difference,Delay,3)*[1,0]–DELAYMTR (Difference,Delay, 3)*[0,1]
Analysis_goal = (Goal_Penetration_FC - Technologies(fc))*Type_policy + (Goal_Diffusion -
    Population_new_habits)*(1-Type_policy)
Availability_Constrain = MIN(Availability_of_Fluorescent_bulbs,Adjustment_rate(fc))*[1,0]/10
    + IF(Availability_of_Fluorescent_bulbs < Adjustment_rate(fc),
    Availability_of_Fluorescent_bulbs,Adjustment_rate(inc))*[0,1]/10
Availability_of_Fluorescent_bulbs = Technologies(fc)
Consumption_monthly = (Technologies(fc)*Consumption_fc +
    Technologies(inc)*Consumption_inc)*24*30
Cost_monthly = (Technologies(fc)*Monthly_Eq_Cost_Fluorescent +
    Technologies(inc)*Monthly_Eq_Cost_Incandescent) *24*30
Difference = (Ideal_Technology_split(fc)-Technologies(fc))*(1-PC_old_habit*Decision_propagation)
Factor_technology_Contagion = Rate_technology_Contagion*Propagation_policy
Ideal_Technology_split = (Total*Selection(fc)*[1,0] + Total*Selection(inc)*[0,1])*(1
    -PC_old_habit*Decision_propagation)
incentive = IF(TIME < 50,2,1)
Market_Share = Technologies/Total
Goal_Difussion = GRAPH(TIME,0,11,[0,20,70,140,230,350,640,810,860,880"Min:0;Max:1000"])
Goal_Penetration_FC = GRAPH(TIME,0,10,[5,8,17,24,29,34,36,38,39,39"Min:0;Max:100;Zoom"])
Monthly_Eq_Cost_Fluorescent = Operation_cost_fc+Price_FC/Life_span_FC
Monthly_Eq_Cost_Incandescent = Operation_cost_inc+Price_INC/Life_span_INC
Operation_cost_fc = Monthly_use_hours*Electricity_tariff*Consumption_fc
Operation_cost_inc = Monthly_use_hours*Electricity_tariff*Consumption_inc
PC_old_habit = Population_old_habits/(Population_old_habits + Population_new_habits)
```

Propagation_policy = IF(Analysis_goal > 0,incentive,disincentive)*Prop_policy+(1-Prop_policy)
Prelogit_Monthly_Eq_Cost = [1,0]*Monthly_Eq_Cost_Fluorescent^Gamma +
[0,1]*Monthly_Eq_Cost_Incandescent^Gamma
Prelogit_VP = [1,0]*PV_FC^Gamma+[0,1]*PV_INC^Gamma
PV_FC = FV(r_fc,Life_span_FC, -Operation_cost_fc)+ FV(r_fc,Life_span_FC,0,-Price_FC)
PV_INC = FV(r_inc_ope,Life_span_FC, -Operation_cost_inc) +
FV(r_inc_inv,Life_span_FC/Life_span_INC-1,-Price_INC,Price_INC)
r_fc = Disc_rate_CFL/12/100
r_inc_inv = (1+r_inc_ope)^(Life_span_FC/Life_span_INC-1)-1
r_inc_ope = disc_rate_Inc/12/100
Selection = (Prelogit_Monthly_Eq_Cost(fc)/ARRSUM(Prelogit_Monthly_Eq_Cost)*[1,0] +
Prelogit_Monthly_Eq_Cost(inc)/ARRSUM(Prelogit_Monthly_Eq_Cost)*[0,1])*DM_Eng_dec +
(Prelogit_VP(fc)/ARRSUM(Prelogit_VP)*[1,0] +
Prelogit_VP(inc)/ARRSUM(Prelogit_VP)*[0,1])*(1-DM_Eng_dec)
Total = ARRSUM(Technologies)

Constants

growth = 0
Consumption_fc = 18/1000
Delay = 8
disincentive = 0.05
Disc_rate_CFL = 40
disc_rate_Inc = 10
DM_Eng_dec = 0
Electricity_tariff = 200
Gamma = -0.8
In_Dem_group = 1000*.01
Life_span_FC = 80.2
Life_span_INC = 5.6
Monthly_use_hours = 180
Prop_policy = 0
Price_FC = 16000
Price_INC = 700
Rate_technology_Contagion = .08
Type_policy = 0
Consumption_inc = 80/1000
Decision_propagation = 0