Energy – a missing dimension of economic models

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Abstract

Grasping specific mechanisms through which improvements in energy efficiency can backfire and result in higher energy consumption, referred to as the rebound effect, requires a good understanding of interactions between heterogonous agents on multiple markets. Otherwise, policies aimed at reducing energy use may render counter-expected and unforeseen consequences. In this paper, we propose a formal model, where technological change arises from interactions on three markets: heterogeneous power plants; finals goods, which production requires electricity as an input; and boundedly-rational consumers. The analysis provides insights to the role of technological change, supply-demand coevolution, and status-driven consumption in explaining the rebound effect. The model is employed to compare efficiency of economic policies aimed at reducing electricity used for production of consumer goods, namely: a tax on electricity; a tax on products which production is electricity-intensive, and 'nuclear obligations' to produce ten percent of electricity from nuclear energy.

Keywords: rebound effect, energy savings, optimal policy, bounded rationality, status consumption, electricity

JEL classification: D11, L22, 033, Q48

1. Introduction

A transition to sustainable economy is unimaginable without restructuring energy system, in the context of its fossil-fuel dependency. Still, the energy dimension of economic growth and industry dynamics is largely ignored in economic modelling (Foster, 2010; Stern, 2010). In fact, most mainstream models typically do not account for energy, focusing on primary factors of production such as capital, labor and land. The exception are specialized models, where resources are treated as constraints on economic growth (e.g. Solow, 1998; Aghion and Howitt, 1998). On the other hand, energy in an essential, and often the only, factor in production in ecological-economic models (Cleveland et al., 1984; Hall et al., 2003). None of this approaches provides a satisfactory explanation of linkages between energy and structural change in the economy (Stern, 2010).

In fact, there is little understanding of specific channels through which demand and supply can affect use, quality and composition of energy sources in production, and thus the environmental impacts of different pathways of change. This relates to the fact that neoclassical models are too abstract to deal with a changing structure of the economy because of their focus on equilibrium conditions and rationality of market participants (Ayres and van den Bergh, 2005). On the other hand, evolutionary-economic modelling provides tools and concepts to frame complex dynamics, dissipative structures, and self-organization processes.[1] However, so far, only a few evolutionary-economic models have explicitly accounted for an environmental dimension of economic dynamics either by specifying energy as an input in production (Nannen and van den Bergh, 2010) or by introducing an environmental ‘preferences’ into utility functions of consumers (Janssen and Jagger, 2002; Oltra and Saint-Jean, 2005; Windrum et al. 2009a,b). The main message from such models is that consumers are key drivers of sustainability: environmentally conscious consumers, who attach high weights to environmental features (service characteristics) of products, may initiate their wider adoption. However, focusing on the demand-side factors alone overlooks symptoms of, instead of focusing on causes of, environmental harm. Sinn (2008) argues that polices aimed at reducing demand for fossil fuels, such as carbon taxes, may paradoxically increase their supply. Resource owners, anticipating future polices damaging their prices, would extract their stocks more rapidly, this way accelerating global warming.

All in all, a transition to sustainability requires changes not only in preferences of consumers but also in the composition of inputs for production, in particular a shift towards less energy-intense and less polluting energy technologies. Because of feedback mechanisms and increasing returns underlying interactions between various types of heterogeneous agents, it is not clear which polices can be the most effective in guiding successful transitions here. Moreover, theoretical and empirical

[1] Evolutionary economics replaces neoclassical assumptions of rational, representative agents and equilibrium outcomes by notions of bounded rationality and out-of-the equilibrium dynamics due to the interplay of innovation and selection operating on diversity of technologies or behaviours.

evidence on how improvements in energy efficiency can render higher energy consumption, referred to as the rebound effect, remains partial and inconsistent (Sorrell, 2009) and lacking behavioral foundations. Without a good understanding of such mechanisms, polices aimed at reducing energy use may render unexpected and unintended consequences.

To our knowledge no model so far has explored the complex linkages between different fuel sources in production, technological change, evolving preferences and status-driven consumption. This is quite surprising given the urgency of tackling climate change and the need for transitions to a low carbon economy. To address this gap, we propose a formal model, where technological change results from interactions on three markets: heterogeneous power plants, final products, and boundedly-rational consumers. The model builds upon Safarzynska and van den Bergh (2010a) coevolutionary framework of demand and supply dynamics, and it extends its by adding a market of heterogeneous power plants producing electricity from diverse energy sources. Electricity is then introduced as an input for production of consumer products. This approach is motivated by the fact that electricity is an important input in manufacturing, which can reach up to 95 percent of total energy used for production, while there is little substitution between fuels in manufacturing sector (Steinbucks, 2010). Moreover, the more advanced manufacturing technologies (AMT) plants employ as a result of technological progress, the less energy-intensive and the more electricity-intense techniques dominate manufacturing over time (Doms, and Dunne, 1995).

In our model, the electricity market is composed of heterogeneous plants. The properties of the electricity industry have been extensively explored in Safarzynska and van den Bergh (2010b). The model proposed therein proved capable of generating patterns which replicated well past transition from coal to gas in the electricity production in the UK after liberalization of electricity market. In the framework, electricity is produced by power plants using different energy technologies (coal, gas and nuclear). Unlike in most models of electricity industry, long-term investment decisions over a size and fuel type of new power stations are endogenous, while the productivity of incumbent plants can change over time due to innovation and learning-by-doing. Electricity is simultaneously an output of production by power generators as well as an input for production of consumer products. On the market for consumer goods, a technological trajectory arises from the interplay of incremental innovation and the search for new product designs by individual firms, following the seminal work by Nelson and Winter (1982). Nelson and Winter argue that firms do not operate by constantly maximizing profits, but they behavior takes a form of complex routines.

On the demand side, consumer preferences change over time as a result of two disequilibrating forces: a desire for distinction and imitation of others within their social networks. The idea that the choices of consumers are driven by social considerations, such as status aspirations, conspicuous consumption and social comparisons, goes back to Veblen (1922) and Duesenberry (1949). In the model, we investigate the strength of three different types of the network effect, namely: operating through ‘market shares’, a ‘positional good’ and ‘conformity.’ According to the network effect operating through market share, consumer choices depend on the number of individuals within his/her network of peers who have already adopted a specific product. If the network effect occurs through a positional good, a consumer tends to buy a good that satisfies or exceeds a threshold level for product performance. The latter is defined as the quality adopted by the majority of consumers within his/her social network, and thus evolves over time. Finally, according to the network effect through conformity, consumers attain a higher utility the smaller the distance between product quality and such defined threshold level.

The proposed here model provides insights to the role of technological change, substitution of energy sources in electricity production, and status-driven consumption in explaining the rebound effect. In particular, we examine how electricity used for production of consumer goods changes as a result of an incumbent firm doubling its (electricity) efficiency. In addition, the model offers a platform to study and compare efficiency of different policy measures aimed at reducing electricity use and inducing change to a low carbon economy. We examine effects of three polices, namely: a tax on products which production is electricity-intensive; a tax on electricity; and ‘nuclear obligations’ to produce ten percent of electricity from nuclear energy. The remainder of this paper is as follows. In Section 2, we discuss the rebound effect. In Section 3, we provide a technical specification of our model composed of three heterogeneous populations of power plants, producers and consumers. Section 4 presents simulation results and compares efficiency of different policy options. Section 5 concludes.

2. The rebound effect

It has been long recognized that policy measures, implemented with the aim of encouraging energy savings in production and consumption, can generate results opposite to expected. The phenomenon is captured by the rebound effect (e.g. Brookes; 2000, Berkhout et al., 2000; Sorrell, 2007; Sorrell & Dimitriopolous, 2007; Linares and Labandeira, 2010; van den Bergh, 2011a). It describes the situation when improvements in energy efficiency fail to bring a proportional reduction in energy use. The effect goes back to Jevons (1865), who suggested that improvements in efficiency of coal-fired steam engines would result in more coal consumption, ultimately offsetting benefits from increased efficiency. The economy-wide rebound effect can reach, or even exceed, 100 percent of energy savings, referred to as energy backfire (Sorell, 2009). Van den Bergh (2011a) indentifies four fundamental reasons behind the rebound effect. First, improvements in energy efficiency relieve resources (e.g. money, time), which increases the energetic and material dimensions of the economy. Second, diffusion of energy-efficient technologies stimulates their wider adoption. Third, bounded rationality implies that individuals are unaware of the energy-intensities of their everyday actions. As a result, energy saving from reducing the frequency of, or quitting, specific activities can be offset by individuals picking up other (more) energy-intensive activities. Finally, the population, affluence, and technological performance are interdependent. This implies that energy-efficient technologies interact with various aspects of the economy in a way, which may be difficult to foreseen, because of the complexity of socio-economic interactions. In fact, lacking is a solid understanding of specific mechanisms through which improvements in energy efficiency affect individual behaviours.

In general, the rebound effect can be classified as direct and indirect (Sorell, 2009). The direct rebound effect, which was first defined by Khazzoom (1980), implies that improvements in energy efficiency encourage greater use of the energy services. The so-called indirect rebound effects can take various forms, for instance (Sorell, 2009): embodied energy effects, re-spending effects, output effects, energy markets or composition effects. The embodied energy effect describes the phenomena when energy savings, due to diffusion of energy-efficient technologies, are offset by energy spending on manufacturing and installation of these technologies. The re-spending effect captures increasing consumption of energy-intensive goods and services due to additional income from adopting energy-saving technologies. On the supply side, producers may use savings from energy-efficiency to increase output, referred to as output effects. At the industry level, a large scale reduction in energy demand translates into lower energy prices, this way encouraging more energy consumption, which is captured by the energy market effect. Finally, the composition effect describes a shift in consumption from non-energy intensive towards energy intensive goods and services because of changes in their relative costs (as energy price rises). In addition, macro-economic consequences of the rebound effect can be distinguished, such as economy-wide and transformational effects (Greening et al., 2000). The economy-wide effect captures adjustments of economic macro variables to changing energy prices, while the transformational effect relates to institutional and behavioural changes on the demand side as a result of technological progress.

Empirical evidence regarding the direction and magnitude of the rebound effect vary greatly depending on whether analysis is conducted at the sector, industry or country level, the length of time period considered, and formal model used for estimations (Haas and Biermayr, 2000; Roy, 2000; Bentzen, 2004; Sanstad et al., 2006; Welsch and Ochsen, 2005; Sorell, 2009). In general, formal models can be classified as top-down or bottom-up approaches. According to the former, energy savings due to efficiency improvements are calculated based on aggregated data at the sectoral (or national) level. The analysis requires isolating the rebound effect from other factors associated with energy savings such as: autonomous energy efficiency progress, effect of earlier policies, price-induced energy efficiency progress, which may be difficult to conduct in practice. In addition, changes in quality and composition of energy sources in production are likely to affect the strength, direction and magnitude of the rebound effect, which is often neglected in related theorizing. Kaufman (1992, 2004) argues that the structural change towards high quality fuels may be a more important source of energy savings than improvements in energy efficiency.

Alternatively, rebound estimates are based on bottom-up models, where technologies are represented in detail. Here, the choice of specific functions is likely to pre-determine the results. For instance, Saunders (2008) shows that some production or cost functions are not flexible enough to conduct analysis of the rebound effect, as they are incapable of accommodating different types of 'energy behavior': from fuel-conserving, where the net effect of energy saving is positive due to efficiency improvements, to energy backfire, when the net effect of energy savings is below zero. Formally, the fuel conserving condition requires that an increase in fuel efficiency decreases the marginal productivity of fuel, lowering its consumption. Using this criterion, Saunders (2008) shows that some production functions are always fuel conserving (e.g. Leontief), while others are never conserving (e.g. Cobb-Douglass, Generalised Leontief). The most flexible is the Constant Elasticity Substitution (CES) Solow function, which behavior depends on the elasticity of substitution between energy and capital. In particular, for the value of the elasticity of substitution greater than unity, the CES function is fuel using, while for its value above unity the function is fuel conserving. Similarly, it has been shown that the magnitude of the rebound effect is sensitive to the precise values of the elasticity of substitution (e.g. Jaccard and Battaille, 2000; Saunders, 2008). As a consequence, evidence from empirical studies using specific production functions and parameter values needs to be interpreted with caution.

According to above-discussed approaches, studying the rebound effect rely on engineering calculations of system physical properties and cost estimates. This ignores behaviours of firms and households and thus may be insufficient to measure flexibility of the economy. For instance, the saturation of consumer needs has been identified as an important factor behind the rebound effect (Madlener and Alcott, 2009; Lorentz and Woesdorfer, 2009). Lorentz and Woesdorfer (2009) argue that technological change is likely to trigger the rebound effect only in case needs of consumers are not satisfied by existing technologies. Otherwise, consumer choices are less sensitive to changes in prices and more to social considerations, such as social aspirations and satiation of needs. The proposition, although interesting, has not yet been supported by empirical evidence.

Typically, demand- and supply-side aspects of the rebound effect are studied separately, as independent of each other. As a consequence, lacking is a good understanding of how evolving preferences of consumers impact technological change and energy use. Estimates of the rebound effect based on aggregate production functions cannot help to unravel specific mechanisms and channels through which improvements in energy efficiency affect energy use in the economy. On the other hand, empirical evidence on the rebound effect from consumer surveys is focuses on individual responses to changes in energy costs and incomes. This approach does not provide an explanation on how changes in the latter impact preferences of consumers and the direction of innovative activities by firms. We argue that these mechanisms are important for understanding the rebound effect. They can be examined in a coevolutionary model which accounts for interactions of heterogeneous agents on multiple markets. In the next section, we propose such a coevolutionary framework to study the direction and magnitude of the rebound effect. The model is novel in a sense that it allows studying the role of changes in the composition of fuels in electricity production, of improvements in electricity efficiency, and status-driven consumption in total energy use in the industry.

3. Model specification

3.1 An overview of model dynamics

The proposed model is composed of three heterogeneous populations: 11 electricity plants (the number of power plants is changing due to entry and exits of power stations); 5 producers of a homogenous, but highly differentiated with respect to price and quality, goods; and two classes of consumers: 11 members of the rich and 89 of the poor class. Time is discrete *t=1,2..;* each time unit corresponds to a period of 1 year.

On the electricity market, three energy technologies compete for adoption: gas, coal and nuclear. Electricity production by each power plant is described by a Cobb-Douglass function, which accounts for substitution of fuel, labour and capital in electricity generation. Productivities of incumbent plants can change over time due to innovations and learning-by-doing. Pricing and output decisions are modeled as the Cournot competition, during which power plants decide how much electricity to sell on the spot and forward markets. Unlike in most other models of electricity industry, long-term investments decisions over a size and fuel type embodied in a new power plant are endogenous, based on the discounted value of investments.

Demand and supply dynamics follow the approach proposed by Safarzynska and van den Bergh (2010a). The framework therein employs some elements from Nelson and Winter (1982), Malerba et al. (2001) and Windrum and Birchenhall (1998; 2005) models. In particular, following Nelson and Winter (1982), two types of innovation processes are distinguished: incremental improvements in product designs and the search for radical innovation. Incremental improvements in product designs depend on firms' experience in production, R&D activities, and accumulated knowledge. A firm may also engage in the search for a new design if its sales are very low. In our model, electricity is assumed to be an important input used for production of consumer goods, which distinguishes it from the framework in Safarzynska and van den Bergh (2010a).

On the demand side, consumer preferences are interdependent. Two classes of consumers are distinguished: the rich and the poor. Consumer purchasing decisions are determined by two disequilibrating forces, namely: a snob and network effect. The former reflects a desire of rich consumers to distinguish themselves from the majority of poor consumers through a purchase of special status commodities. On the other hand, the network effect captures consumers imitating choices by others in their social network. We assume that the reference group (social network) of rich consumers in the rich classes itself, while of the poor consumer it is the total population.

Each time period, the following sequence of steps is repeated:

1) On the electricity market, each plant chooses how much electricity to produce given an inverse demand function.
2) The decisions by individual plants determine total supply of electricity and its price on the spot market.
3) A new power station enter a market. It embodies energy technology (coal, gas or nuclear) which ensures the highest discount value of investments. The plant starts operating after the construction period.
4) On the market for consumer goods, each consumer attempts to purchase a product that provides the highest utility: he (implicitly) ranks all offers and attempts to buy the most attractive product. If the supply of this product has run out, a consumer does not buy anything.[2]
5) Firms collect profits and set the desired production level for the next period as a weighted average of past sales and actual demand.
6) Next, firms purchase inputs for production: electricity and capital.
7) Firms invest a fraction of their profits in R&D research towards incremental improvements (redesign qualities).
8) If a firms report zero sales for sufficiently long time, it leaves the market and a new firm replaces it.

3.2 Technical specification

Below, we describe specific assumptions made about interactions: on the electricity market in Section 3.2.1; on the market for consumer goods in Section 3.2.2; and between two classes of consumers in Section 3.2.3.

3.2.1. Electricity market

Initially, the market is composed of 11 plants - 10 coal stations, each with 1200 MW installed capacity, and 1 nuclear with 800 MW capacity. Production of electricity is carried out in heterogonous plants i characterized by age $s_{it,}$, specific productivity v_{it} and energy source j (coal, combined cycles gas turbines, nuclear). Maximum output produced by plant i is constrained and determined by its installed capacity k_i. In particular, a plant can produce 8760 λ_i k_i KWh electricity per year, where each

[2] The consumers purchase products in a sequence: rich consumers make their choices first before poor consumers. The sequence in which consumer make their choices is important because if the supply of a particular good falls short of total demand, it determines which consumers ultimately will buy the good.

technology j is described by factor substitutions of inputs in production $(\alpha_{Kj}, \alpha_{Lj}\ \alpha_{Fj})$, fuel cost p_{jt}, maximum lifespan T_j[3] and capacity factor λ_j intended to capture periods of decreased production due to economic reasons (low profitability), obligatory maintenance, etc.

The structure of dynamics on the electricity market is as follows. In the beginning of each year t, plants set their production q_{it} and the amount of production they want to sell on the forward market f_{it} (given the capacity constraint $q_{it} < \lambda_i k_i$ and $f_{it} < q_{it}$) so as to maximize profits (Allaz and Vila, 1993):

$$\Pi_{it} = p_{et}q_{it} - m_{it}q_{it} - F_{it} + (x_t - p_{et})f_{it} \qquad (1)$$

p_{et} is the spot market price determined by a static demand function (below), m_{it} is a marginal cost, F_{it} represents a fixed cost (i.e. load capacity costs), and x_t is a strike price for a quantity f_{it}.. Consequently, $f_{it}(x_t\text{-}p_{et})$ captures the profit realized on the forward market. The fixed cost is computed so as it covers the initial costs of investments I_{jt} in a new power plant depreciated over its lifetime.

The contracts f_{it} do not involve the actual generation of electricity. If the spot price p_{et} is higher than the contract strike price x_t, then generators pay an amount $f_{it}(p_{et}\text{-}x_t)$ to the party in the contract, otherwise the generator receives an amount $f_{it}(x_t\text{-}p_{et})$.[4] The price of the contract is equal to the expected spot price: $x_t=E(p_{et})$. The cap on electricity price is imposed to keep electricity price within a range $(p_{e,min}, p_{e,max})$.

The electricity price is determined by an inverse demand function:

$$p_{et}=a\text{-}bD_t+\theta \qquad (2)$$

where demand D_t is equal to a total supply: $D_t = Q_t = \sum_i q_{it}$, and a and b are parameters. θ is a random variable drawn from normal distribution $N(0,1)$. Consequently, $E(\theta)=0$.

Following Allaz (1992) and Allaz and Vila (1993), a production decision is a sequential procedure, which involves a two-step maximisation problem to be solved backwards. In the second stage, a firm decide how much to produce given its forward position. It maximizes profits π_{it} with respect to its production q_{it} ($\frac{\partial \pi_{it}}{\partial q_{it}} = 0 \rightarrow q_{it}(f_{it},.. f_{nt})$) where n_t is the number of plants on the market at time t. In the first stage, a firm decides how much output to buy or sell under the forward contract, which is called for delivery in the next period. The production level in derived (from $\frac{\partial \pi_{it}}{\partial q_{it}} = 0$) as:[5]

[3] The maximum lifetimes of plants operating at time 0 were drawn randomly from the uniform distribution over the range (10, 50).

[4] This type of contract is referred to as two-way contracts-for-difference. A one way contract for difference is also possible, where generators are paid the difference between the pool and strike prices.

[5] We follow the approach adopted by Allaz and Vila (1993). Our solution differs as we assume asymmetric firms, i.e. characterised by different marginal costs.

$$q_{it} = \frac{a + \theta + n_t b f_{it} - b\sum_{i \neq j} f_{jt} - (n_t + 1)m_{it} + M_t}{(n_t + 1)b} . \quad (3)$$

Given the above reaction function, a firm sets in the first period the forward sales to maximize expect profits ($E\pi_{it}$)[6], which results in the amount:

$$f_{it} = \frac{(n_t - 1)(a - n_t(n_t - 2)m_{it} + n_t M_t)}{(n_t^2 + 1)b} \quad (4)$$

to be sold under the contract-for-difference.

A plant exits once $s_{it}>T_j$ where T_j is the expected lifetime of a plant (defined for each energy technology). It is also closed if profits are negative. If the owner decides to close the plant, he loses its production capacity forever (Atkson and Kehoe, 2007).

After setting production and their forward positions, plants decide how much inputs for production to employ so as to minimise total input costs. Electricity production by plant i using technology j is described by the Cobb-Douglas function (Nerlove, 1963):

$$q_{it} = a_{it} i_{Kit}^{\alpha_{Kj}} i_{Lit}^{\alpha_{Lj}} i_{Fit}^{\alpha_{Fj}} , \quad (5)$$

where a_{it} is the plant's specific productivity; i_{Ki^*}, i_{Li^*}, i_{Fi^*} describe capital, labour and fuel input respectively. α_{Kj}, α_{Lj} α_{Fj} are corresponding factor substitutions associated with technology j, where $\alpha_{Kj}+\alpha_{Lj}+\alpha_{Fj}=1$.

The parameter a_{it} is equal to $(\frac{1}{v_{it}})^{\alpha_{Fj}}$, where v_{it} is a thermal efficiency with which a plant can transform fuel into heat (energy).[7] The thermal efficiency, which is a measure of plants' productivity, can improve over time. Before each period, a random shock is drawn from the technology-specific distribution $\varepsilon_i \sim N(\mu_i,\sigma^2_i)$. A plant starts operating in the next period with a productivity equal to $v_{it+1}=v_{it}+\varepsilon_t$. This captures learning-by-doing: the longer the plant exists on the market the more efficiently it transforms basic energy inputs into electricity.

Under the assumption that inputs are allocated according to their marginal productivity, inputs are equal:

$$i_{Kit} = \frac{\alpha_{Kj} p_{Fjt}}{p_{Kjt} \alpha_{Fj}} i_{Ft} v_{it} , \; i_{Lit} = \frac{\alpha_{Lj} p_{Fjt}}{p_{Lt} \alpha_{Fj}} i_{Ft} v_{it} , \text{ and } \; i_{Fit} = q_{it} \frac{\alpha_{Fj}}{p_{Fjt}} \frac{p_{Kjt}^{\alpha_{Kj}} p_{lt}^{\alpha_{Lj}} p_{Fjt}^{\alpha_{Fj}}}{v_{it} \alpha_{Kj}^{\alpha_{Kj}} \alpha_{Lj}^{\alpha_{Lj}} \alpha_{Fj}^{\alpha_{Fj}}} , \quad (6)$$

where p_{Kt}, p_{Ljt}, and p_{Fjt} is price of capital, labour and fuel j at time t respectively.

Prices of inputs (apart from capital) change over time. In particular, fuel prices follow a geometric Brownian motion (Brandt and Kinlay, 2008):

[6] under the assumption of $x_t=E(p_t)$ and $E(\theta)=0$

[7] For nuclear stations thermal efficiency is defined as the quantity of heat released during fission of the nuclear fuel inside the reactor (DTI, 2008).

$$dp_{Fjt} = \chi_j dt + \sigma_j dZ_t \ , \quad (7)$$

where σ is the volatility of fuel price j, Z_t is a Wiener process and χ is a drift.
Wages increase steadily over time according to:

$$p_{Lt} = p_{Lt-1} + \sigma_L . \quad (8)$$

σ_L is the annual increase in wages.

The marginal cost of plant i employing technology j is equal (from $m_{it} = \frac{\partial TC_{it}}{\partial q_{it}}$, where TC_{it} is the total cost of production):

$$m_{it} = p^o_j + \frac{p_{Fjt}}{v_{it}} \quad (9)$$

where p^o_j is operating cost of technology j.

In the beginning of each period, a new power plant enters the market. Formally, a planner evaluates capacity k_{ij} maximizing expected profits V_{ij} for each energy technology j (adapted from Takashima et al., 2008):

$$\begin{aligned} V_{ij} &= E[(\sum_{t=t_{sj}}^{T+t_{sj}} e^{-rt}(p\ (\lambda 8760 k_{ij}) - \hat{m}_{jt}) 8760 \lambda k_{ij} - e^{-rt_s} I_j k_{ij})] \\ &= \frac{-1}{-1+e^r}(e^{-r(T+2t_s)}(-1+e^{r+Tr})k_{ij}(I_j + 8760 e^{rt_s} \lambda (c - p(k_{ij}))\end{aligned} \quad . \quad (10)$$

Here, I_j is a fixed cost per KW of installed capacity k_{ij} capturing initial investment costs and maintenance expenses that need to be covered from the revenues over the entire life of the plant T_j, t_{sj} indicates the number of years before plant i (embodying technology j) can be operationalized, $\hat{m}_{jt}$ is the lowest marginal cost among incumbent plants embodying technology j at time t (best frontier technology), and r is an interest rate. A new plant starts operating in $t+t_{sj}$. It embodies technology j that ensures the highest value V_{ij}.

An optimal level of installed capacity k_{ij} equals (derived from $\frac{\partial V_{ij}}{\partial k_{ij}} = 0$):

$$k_{ij} = \frac{-I_j e^{-rt_s} + \lambda_j 8760 (a - bQ_{-i} - \hat{m}_j)}{153475200 b \lambda_j^2} , \quad (11)$$

where Q_{-i} indicates the expected level of production without a new plant.

Specific parameter values are described in the Appendix (Table A1). Whenever possible they were chosen based on historical data for the UK after liberalization of the electricity market in 90ties.[8] The proposed model proved capable of generating patterns which replicated well the past change from

[8] The reason is that data on the British electricity industry are well documented, whereas our model describes well arrangements in the UK during the period 1990-2002, before the New Trading Agreement (NETA) was introduced (on the spot and forward markets).

coal to gas in electricity production, including decreasing prices of electricity over time due to the rapid diffusion of cheap gas stations (Safarzynska and van den Bergh, 2010b).

3.2.2 Firms

Each firm j offers a single product, which design x_{jt} is randomly sampled from the range (0, $\rho\tilde{x}$) at the beginning of each simulation, where $\tilde{x}$ is the maximum attainable quality, and ρ is a positive fraction.

A firm j sets a target level of production for the next period as a weighted average of its current sales s_{jt} and actuak demand $d_{jt,}$ following Windrum and Birchenhall (1998, 2005):

$$\tilde{y}_{jt+1}=\zeta\, d_{jt}+(1-\zeta)\, s_{jt}. \qquad (12)$$

Here, ζ and (1- ζ) are weights assigned to sales and demand, respectively.

A price-setting mechanism follows a simple mark-up rule:

$$p_{jt}=(1+\eta)\, c_{jt}, \qquad (13)$$

where η is a mark-up and c_{jt} *is* the unit cost equal to:

$$c_{jt}=\frac{\theta+e_{jt}p^{c}{}_{et}+p_{ct}\Delta\tilde{k}_{jt}}{y_{jt}}+q(x_{jt}).^{9} \qquad (14)$$

Here, θ is a fixed cost of production, e_{jt} captures electricity with $p^{c}{}_{et}$ being price of electricity on the retail market, $\Delta\tilde{k}_{jt}$ is capital expansion in time t, p_{ct} refers to price of capital (set constant through simulation runs)[10], while $q(\cdot)$ is a monotonically increasing convex cost function of the jth design:

$$q(x_{jt}) =x_{jt}^{\nu}, \qquad (15)$$

where ν is a parameter.

Electricity price on the retail market is equal:

$$p^{c}{}_{et}=(1+\eta_{p})p_{et}, \qquad (16)$$

where p_{et} is the spot price determined by interactions between heterogeneous power plants on the electricity market, and η_p is a markup imposed by electricity retailers. Introducing electricity as an input in production is an important novelty of the framework proposed here, as an extension of the model developed in Safarzynska and van den Bergh (2010a).

Firm j's profit π_{jt} is equal to:

$$\pi_{jt} =p_{jt}\, s_{jt}-c_{jt}\, y_{jt}\,. \qquad (17)$$

Safarzynska and van den Bergh (2010a) use a Cobb-Douglas function with a parameter $\beta \in (0,1]$ to describe firms' production: $y_{it}=k_{jt}^{\beta}$. In this paper, we do not simply introduce electricity as an input into the Cobb-Douglass function. Instead, we employ a two-factor Constant Elasticity Substitution (CES) function. This is motivated by the fact that the CES function is more rebound-flexible, in a

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[9] The costs of new emerging firm is: $c_{jt}= \theta/y_{jt}+q(x_{jt}).^{9}$

[10] Setting price of capital constant allows examining an effect of changes in relative input prices (electricity and capital) on model dynamics.

sense of being capable of accommodating different types of the rebound effect. Saunders (2008) shows that the Cobb-Douglass function is never fuel conserving (always fuel using), whereas behaviour of the CES function depends on the value of the elasticity of substitution between energy and capital as compared to unity. As a result, the production function of firm *j* is described by:

$$y_{jt} = (a(k_{jt} + \Delta k_{jt})^q + (1-a)(\tau_j e_{jt})^q)^{1/q} \qquad (18).$$

Here, τ_j is electricity efficiency of firm *j*, a is a share of capital in production, and $q = \frac{\sigma-1}{\sigma}$, with σ being the elasticity of substitution between electricity and capital. Parameters a and σ are randomly generated in the beginning of each simulation runs and set equal for all firms.
Capital is subject to depreciation at the rate ξ:

$$k_{jt}=(1-\xi)k_{jt-1}. \qquad (19)$$

Each firm expands capital Δk_{jt} and employs electricity e_{jt} so as to minimize the total cost of the desired level of production $\tilde{y}_{jt+1}$ (derived from conditions $\frac{\delta y_j}{\delta \Delta k_j} = p_{ct}$ and $\frac{\delta y_j}{\delta e_j} = p_{et}$):

$$\Delta k_{jt} = e_{jt}\left(\frac{p_{ct}}{p_{et}}\right)^{\frac{q}{q-1}}\left(\frac{1-a}{a}\right)^{\frac{q}{q-1}}\tau_j^{\,q/q-1} - k_{jt} \qquad (20)$$

and
$$e_{jt} = \frac{\tilde{y}_{jt+1}}{[(1-a)\tau_j^{\,q}+a\left(\frac{p_{ct}}{p_{et}}\right)^{q/q-1}(\tau_j^{\frac{q^2}{q-1}})(\frac{1-a}{a})^{q/q-1}]^{1/q}} \qquad (21)$$

In the model by Windrum and Birchenhall (2005), profits are required to cover capital expansion. This assumption does not hold here. Instead, each firm employs as much inputs as it is necessary to produce the desire level of production and set its price to recover the incurred costs. The implicit assumption here is that firms can raise financial capital to buy necessary inputs for production as long as there is demand for their products. Profits are used for investments in research activities and productivity improvements.

After purchasing in inputs for production, firms invest a fraction of their profits (if positive) in R&D activities i_{jt}:

$$i_{jt} = \varsigma\, \pi_{jt}. \qquad (22)$$

If profits are zero or negative, firms cannot afford to undertake investments in design improvements. Otherwise, the quality changes according to a function of the length of the period during which the firm produces a particular good v_{jt}, the maximum attainable quality $\breve{x}_t$ at time *t*, and investments devoted to the quality improvements i_{jt}:[11]

$$x_{jt}=x_{jt}\,(\breve{x}_t - x_{jt})^{\delta} v_{jt}^{\,\ddot{\imath}} i_{jt}^{\,\iota} \qquad (23)$$

The parameter δ measures the speed of autonomous improvements towards the maximum attainable quality, $\ddot{\imath}$ denotes the competence elasticity; and ι is the elasticity of incremental improvements (from research activities).

[11] The form of a quality function is modified from Malerba et al. (2001).

The remaining fraction of profits (1-ς) determines the probability with which a firm improves its electricity efficiency τ_j (see Section 4.1). It can be interpreted as a fraction of profits devoted towards research on electricity efficiency improvements.

If a firm reports zero sales for γ consecutive periods, it leaves the market and a new firm replaces it. A newborn firm offers a quality sampled from (0, $\tilde{x}$). Parameters characterizing the new emerging firm are described in the Appendix (Table A2).

A firm that has not sold a single unit of production for ψ consecutive periods ($\psi < \gamma$) and intends to change its design, samples the quality from (0, $\breve{x}_t$); here $\breve{x}_t$ is the maximum attainable quality in time t, defined as a quality offered by the most technologically advanced firm ($\breve{x}_t \leq \tilde{x}$):

$$\breve{x}_t = arg\ max\{x_{1t}, \ldots, x_{nt}\}, \tag{24}$$

where n is the number of firms. A new design cannot exceed the performance accomplished by the most technologically advanced firm in a current period. This assumption is motivated by the fact that incumbent firms are likely to shift R&D efforts from product- to process-oriented innovations as they grow and mature. Thus, they are more likely to focus on improving the efficiency of existing techniques rather than developing new products.

3.2.3 Consumers

The model distinguishes between two types of consumers, who belong to the rich and the poor class respectively. Consumers in each class are heterogeneous. They differ with respect to their inclination towards product quality relative to price (as discussed below). The utility evaluated by each consumer i from adopting a good j depends on the product quality x_{jt}, its price p_{jt} (cheapness), the network effect n_{jt}, the number of poor class consumers purchasing a particular product l_{jt}:

$$u_{it} = \frac{x_{jt}^{\alpha_i}\ n_{jt}^{\zeta}}{p_{jt}^{0.5-\alpha_i}\ l_{jt}^{\kappa}}. \tag{25}$$

The parameter α_i captures i's inclination towards the product quality, and 0.5-α_i is i's inclination towards product cheapness; ζ is the network elasticity; and κ denotes the snob effect (equal to zero if a consumer belongs to the poor class), while l_{jt} is a number of poor consumer purchasing product j in time t. The parameter α_i is randomly distributed across consumers. Its value is sampled from (0, ώ) for each member i of the poor class, and from (ώ, 0.5) for the rich class members ($0 <$ ώ < 0.5).[12] The lower the value of α_i, the less consumer i is willing to pay for the quality improvement.

The network effect is extremely important for the coevolution of demand and supply as shown by Safarzynska and van den Bergh (2010a). Following the approach developed therein, we investigate

[12] This distinction is introduced to capture different attitudes of the upper and the lower class towards quality and cheapness.

three different forms of the network effect: through market share, a positional good, and conformity. The network effect operating through market shares is the most common formalization in the literature. It assumes that preferences change depending on the number of individuals within the social network who have already purchased a particular product: $n_{jt}= m_{jt-1}$, where m_{jt} is the market share of firm *j*. The reference group of rich consumers is a group of rich consumers, while for poor consumers it is the total population. This assumption holds also for alternative network effects. If $m_{jt} = 0$ then n_{jt} is set to 0.1 in order to ensure the visibility of new emerging products on the market.

As one alternative, we introduce the network effect through a positional good. In this case, a consumer tends to buy a good that satisfies or exceeds the threshold level for product performance in his social network: $n_{jt} = x_{jt} - \bar{x}_{t-1}$, where $\bar{x}_{t-1}$ is defined as the mode, i.e. the quality of the product purchased most frequently in the consumers' reference group. In case $-1 < (x_{jt-1} - \bar{x}_{t-1}) < 1$ then $n_{jt} = 1$, while if $(x_{jt} - \bar{x}_{t-1}) < -1$ then $n_{jt} = 0.005$. These assumptions imply that consumers are incapable to perceive small differences in product qualities. In general, $\bar{x}_t$ determines an individual's threshold level for product performance, which a given product must deliver in order for a consumer to consider it. Such threshold levels are important where status-seeking consumers engage in interpersonal comparisons (Adner and Levinthal, 2001).

Finally, we consider the conformity effect: $n_{jt} = \tilde{x} - \left| x_{jt} - \bar{x}_{jt} \right|$. The component $\left| x_{jt} - \bar{x}_{jt} \right|$ denotes the distance between the product quality and the quality consumers aspire to purchase. The closer a product quality is to the aspiration level, the higher the value of the expression $\tilde{x}$ - $\left| x_{jt} - \bar{x}_{jt} \right|$. Similarly to the above, $\bar{x}_{t-1}$ is defined as a quality adopted by the majority of consumers within their social network. A slightly worse product may be preferred over an item that is much better, if the distance to the desired performance is smaller (see Janssen and Jager, 2002).

4. Simulation results

In this section, we present simulation results from three versions of the model: with the network effect through market shares, a positional good and conformity. For each version of the model, we run simulations for 100 times steps, which corresponds to a period of 100 years. We discuss which variables, and under which conditions, are important determinants of electricity used for production of consumer goods. Formally, we look at a variable, referred to further on in the text as the indicator, defined as the sum of electricity used by all firms in the second 50 time steps of the simulations (from 51st to 100th time step) to electricity used in the industry during the first 50 times steps (from 1st to 50th time step):

$$i = \frac{\sum_j \sum_{t=51}^{100} e_{jt}}{\sum_j \sum_{t=1}^{50} e_{jt}}. \qquad (26)$$

where e_{jt} is electricity use by firm *j* on the market for consumer goods in time *t*.

The value of indicator *i* exceeding unity implies that electricity use increased in the second period compared to the first, while its value below 1 implies that electricity consumption decreased over time. We employ the Monte Carlo method to check the robustness of our results. For each version of the model (with the network effect operating through market share, a positional good and conformity) we simulate 500 model runs with initial parameters: the snob and network elasticity, the elasticity of substitution between capital and energy, price of capital, and the share of capital in production randomly generated (within plausible range of values). These parameters were identified in initial exploratory simulations as important determinants of electricity use. Other parameters are held constant (as described in the Appendix).

First, in Section 4.1, we examine the effect of a random firm having its productivity doubled in the 50th time step on total electricity used for production of consumer goods. In Section 4.2, we compare the effect of two types of taxes introduced in the 50th time step. The first tax is imposed on firms which production is characterised by the above-average electricity per output. The second tax increases price of electricity as an input for production. In Section 4.3, we discuss the effect of policy, which we call nuclear obligations. Accordingly, if a share of nuclear energy in electricity production on the electricity market is below ten percent, a new nuclear plant is installed regardless of the discounted value of investments in nuclear stations.

4.1 The rebound effect

In this section, we examine changes in total electricity used for production of consumer goods after (electricity) efficiency of a randomly choosen firm doubles. The firm is selected with the probability proportional to its profits, and thus dominant (incumbent) firms are more likely to improve their efficiency. Formally, the value of indicator *i* above 1 captures ‘electricity’ backfire, according to which improvements in electricity efficiency increase electricity use; $i=1$ describes a full rebound; and $i<1$ captures a situation when efficiency improvements are electricity conserving.

Table 1 summarizes the results from logit regressions with an independent variable taking value 1 if indicator *i* exceeds, or is equal to, 1 and 0 otherwise. Formally, the logit model can be expressed as: $\Pr(y_t = 1) = \frac{\exp(\beta x)}{1+\exp(\beta x)}$ where y_t equals 1 if the event (the rebound effect) occurs at time *t* and is 0 otherwise, with *x* being a vector of independent variables, and β the vector of coefficients. Accordingly, coefficients in Table 1 capture changes in the logarithms of the odds ratio, i.e. of the probability of the rebound effect occurring to the probability of electricity conservation, as a result of a unit change in independent variables: the snob and network elasticities, the share of capital in production, the elasticity of substitution between capital and electricity, and price of capital. The results are discussed below:

Table 1. Results from the logit regression with the dependent variable ‘indicator’

Independent variable:	**The network effect through:**					
	Market Share		**A positional Good**		**Conformity**	
	σ<1	σ>1	σ<1	σ>1	σ<1	σ>1
Snob elasticity	1.04* (0.05)	0.75 (0.45)	0.52 (0.31)	1.4* (0.01)	-0.10 (0.85)	-0.91 (0.07)
Network elasticity	-1.95* (0.00)	0.03 (0.97)	-0.30 (0.57)	-0.83 (0.09)	-0.52 (0.31)	0.02 (0.95)
Substitution elasticity (σ)	3.22* (0.00)	-9.40* (0.00)	2.45* (0.00)	-2.39* (0.00)	2.39* (0.00)	-1.49* (0.00)
Share of capital in production (a)	3.14* (0.00)	9.06* (0.00)	-1.10 (0.21)	2.46* (0.01)	1.72* (0.04)	2.48* (0.01)
Price of capital	0.02 (0.50)	-0.04 (0.43)	-0.01 (0.71)	-0.001 (0.95)	0.02 (0.34)	0.002 (0.91)
Constant	-3.64* (0.00)	-9.40* (0.01)	0.56 (0.48)	1.76 (0.10)	-1.13 (0.14)	1.156 (0.13)
Number of observations	271	229	0.09	0.12	0.08	0.06
Pseudo R^2	0.19	0.51	264	236	264	236

*variables significant at the 5 percent level
p-values for *z*-statistics are in parentheses

The elasticity of substitution between electricity and capital

Table 1 summarizes results from logit estimations of the data generated by model simulations with differently conceptualised network effects. For each version of the model, we present results for two sub-samples separately: with the elasticity of substitution σ below 1, which implies that electricity and capital are poor substitutes, and with σ above 1, according to which these inputs are good substitutes. Results from initial regressions indicate a structural break in the data: the magnitude and direction of estimated coefficients change depending on whether the value of the elasticity of substitution is above or below the unity. For this reason, we report the results for these two groups separately.

In fact, there is a large literature regarding whether capital and energy are good substitutes, and the precise value of the elasticity of substitution between the two (Thompson and Tayor, 1995; Frondel and Schmidt, 2002; Koetse et al., 2008). The empirical evidence suggests that the substitution between energy and capital is limited, and thus the elasticity of substitution lies most likely below unity (Stern, 2010). A value 0.5 of the elasticity is most commonly used in empirical studies (Saunders, 2008). This suggest that estimates for $\sigma<1$ in Table 1 are more plausible.

Our results suggest that in case electricity and capital are poor substitutes ($\sigma<1$), an increase in the elasticity of substitution between these two factors (but below unity) raises the probability of the rebound effect occurring. This result is consistent with our expectation and relates to the technical specification of the CES function. Saunders (2008) shows that the closer σ is to unity, the more substantial increase in output is expected as a result of improvements in energy efficiency. On the other hand, in case electricity and capital are good substitutes ($\sigma>1$), the higher the value of sigma above unity, the lower probability of the rebound effect. This relates to the fact that in our model, due to rapid diffusion of cheap gas stations on the electricity market, the price of electricity decreases at first. However, with time, the cost of gas surges driving up price of electricity. The better substitutes capital and electricity are, the more firms substitute capital for electricity (reducing electricity use) as electricity price increases. This effect is likely to reinforce electricity conservation due to improvements in electricity efficiency.

Network effect

The network effect captures the tendency of individuals to conform to choices made by others. Lorentz and Woesdorfer (2009) suggest that conformity is likely to make the rebound effect less likely to occur as it stabilizes consumption patterns, i.e. locks-in consumers' choices. Our results confirm this hypothesis but only for the network effect operating through market shares, and moreover, only in case the elasticity of substitution is below unity. In this version of the model, consumers evaluate attractiveness of different products based on their relative market shares, which can be interpreted as capturing the effect of brand recognition or increasing informational returns. Here, the higher value of the network elasticity, the more likely consumers purchase a product with already established market shares. New products have little chance to diffuse on the market due to their initially negligible shares. As a result, the probability of the rebound occurring is low for the strong network effect: an incumbent firm, which improves its electricity efficiency, reduces its electricity use and subsequently the price of its product, while consumer inertia prevent consumers altering their purchasing decisions. For the elasticity of substitution above unity, the network elasticity is insignificant in explaining the rebound effect. In this case, the network effect is likely to be dominated by the effect of substitution of inputs for production as their relative prices change.

Figure 1 present results form an illustrative simulation of our model with the network effect through market shares for the strong snob and strong network effects (in case $\sigma<1$). Model dynamics render here clustering of consumer choices around two distinct niches: product 3 in Figure 1, which production is more electricity per output intensive, is bought mostly by rich consumers. On the other hand, product 2, characterised by lower electricity per output, has been purchased by the majority of poor consumers. In the 50th time step, electricity efficiency of firm 2 has doubled, and as a result electricity per output of this firm felt significantly.

In alternative versions of the model, with the network effect operating through a positional good and conformity, the quality purchased by the majority of others in the social network determines product attractiveness. The network elasticity turned out to be insignificant in explaining the probability of the rebound effect occurring here. Results from illustrative simulations suggests that in case consumers evaluate products attractiveness based on its quality (relative to quality of products purchased by others), model dynamics resembles fashion markets with cyclical sales of different firms, and short expected lifetimes of their products. A new product with no established market shares, can compete for adoptions if it quality exceeds (according to the network effect through a positional good) or is enough close to (according to the network effect through conformity) the one bought by the majority in one's peer group. As a consequence, improvement in electricity efficiency of a random firm has negligible impact on total electricity use in the industry. This is because such firm is likely to be wiped out by market selection over a short time span, i.e. before benefits from improvements in electricity efficiency can be realized or noticeable at the market level.

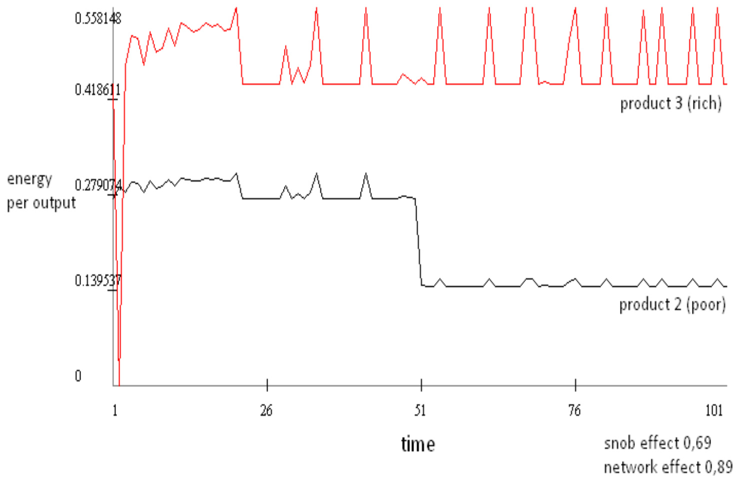

Figure 1. Electricity per output of dominant firms.
The network effect operating through market shares.

Snob effect

The snob elasticity captures the desire of rich consumers to distinguish themselves from the poor through special status commodities. The variable turned out to have a positive and significant effect on the probability of the rebound effect in models with the network effect operating through market shares (for σ<1) and a positional good (for σ>1). This relates to the fact that rich consumers have a higher inclination towards quality than price. As a result, they tend to choose better quality products regardless of their price. A firm, which electricity efficiency improves, is likely to decrease the price of its product, as it reduces its electricity per output. This way its product becomes more attractive to poor consumers. However, a product adopted by many poor consumers loses its special status. Thus, the stronger the snob effect, the more likely affluent individuals will look for alternative products (to the one produced by the firm which efficiency improved) to distinguish themselves from others. Such goods are likely to be more expensive, while their production more electricity-intense. This may offset electricity reductions due to improvements in electricity efficiency.

On the other hand, where the network effect operates through conformity, individuals attempt to minimize the distance between the product quality and the quality bought by the majority of others in their network. The snob effect (as well as the network effect) is insignificant in explaining the rebound effect here. This relates to the myopia of boundedly rational consumers, who are assumed to be indifferent between two products, which qualities are respectively better and worse than the desire quality, as long as their distance to the desired performance is the same. As a result, consumers are less sensitive to social considerations like status comparisons, as compared to alternative versions of the model.

Share of capital in production and price of capital

Higher values of share of capital a imply lower shares of electricity in production. A coefficient corresponding to this variable has a positive, and statistically significant, impact on the probability of the rebound effect occurring in most versions of the model. This supports that improvements in energy efficiency are likely to increase energy use if expenditures on energy constitute a high share of total cost of energy services, as suggested by Howarth (1997). On the other hand, price of capital turned out to be insignificant in explaining the rebound effect. This result does not come as a surprise: it is a relative price of capital to electricity that matters, rather than its absolute value.

4.2 Tax on electricity-intensive products versus tax on electricity price

In this section, we compare two types of taxes introduced in 50th time step on the total electricity used for production of consumer goods. According to the first type of tax, from 50th time step onwards, the tax equal 0.4 is imposed on all firms which production is characterised by the above-average electricity per output. According to the second type of policy examined here, the tax 0.4 is imposed on electricity. Thus, the first tax affects consumer prices, while the second producer costs. Table 2 summarizes results from 100 simulations for different versions of the model. The mean value of the indicator above 1 indicates that on the average policy increased electricity use (after the tax was introduced), while its mean value below unity suggests that imposing the tax typically decreased it. It is important to note that without any policy intervention, electricity use typically increases in the second period (after 50th time step) compared to the first, as a result of complex interactions on three markets. Thus, the value of the indicator needs to be normalised by its average value in the absence of any policy intervention (normalised values in brackets in Table 2).

The results suggest that the tax on electricity-intensive products is effective in reducing electricity use only in models with the network effect through conformity and a positional share but not in the model with the network effect through market shares. This relates to the fact that in the latter case, the probability of clustering of consumer choices is higher (compared to alternative versions of the model), with two niches likely to form. Rich consumers typically buy a product characterised by the above-average electricity per output, which is then subject to taxation. As rich consumers are less sensitive to price considerations, the tax is unlikely to alter their choices.

On the other hand, tax imposed directly on electricity proved effective, in terms of reducing electricity use, in all versions of the model. An increase in electricity price renders firms to substitute electricity by capital in production. This result is supportive of the view that setting input prices right, so as they reflect the environmental damage, is likely to be an effective way to reduce a negative impact of production and to induce energy-saving innovations (van den Bergh, 2011b).

Table 2. The average indicator over 100 simulations

Network effect through:	Type of policy intervention				
	No intervention	Energy efficiency Of a random firms	Tax 0.4 on energy-intense products	Tax 0.4 on electricity input	Nuclear Obligations
Market share	1.07	0.87 (0.81)	1.07 (1)	0.97 (0.91)	1.09 (1.01)
A positional good	1.10	1.11 (1)	1.06 (0.96)	0.98 (0.89)	1.12 (1.02)
Conformity	1.11	1.08 (0.97)	1.06 (0.95)	1.01 (0.91)	1.15 (1.04)

* in brackets values of the indicator normalised by its average value in the absence of policy intervention

4.3 Nuclear obligation

In this section, we examine the effect of introducing "nuclear obligation" in the 50th time step. The policy works as follow: from 50th step onwards, if a percentage of electricity produced with nuclear energy (on the electricity market) is below ten percent, a new nuclear power plant is installed regardless of the net value of investments in nuclear plants. Although, in our model, production of electricity from nuclear energy is cost competitive, installing nuclear power plants is not. As a consequence, electricity market typically becomes dominated by gas stations in the absence of any policy intervention. This is explained by the fact that gas stations are the cheapest and quickest to install.

Table 3 summarizes the share of total electricity generated with nuclear energy used for production of consumer goods (its mean value over 100 simulations). In all versions of the model, nuclear obligations render about 35 percent of electricity to be produced with nuclear energy.

However, introducing nuclear obligations simultaneously increased total electricity used for production as suggest by the mean value of the indicator in Table 2. In fact, the total amount of electricity generated from fossil fuels (in production of consumer goods) has increased after nuclear obligations were implemented: in 8 percent of simulations of the model with the network effect through market shares; 13 percent of simulations with the network effect through a positional good; and in 14 percent of simulations with the network effect through conformity. This suggests that the efficiency of polices aimed at lowering a share of fossil fuels in electricity production needs to be interpreted with caution. In fact, Sinn (2008) argues that such 'demand reducing policies' are likely to be counter-effective if not accompanied by supply-side polices directly focused on reducing extraction of fossil fuels. In the absence of the latter, promoting non-fossil fuels for electricity production may simply create additional demand for energy, without reducing fossil fuel consumption.

Table 3. A share of nuclear energy in electricity generation after introducing 'nuclear obligations'

Network Effect through	Mean over 100 observations	Standard Deviation	Minimum	Maximum
Market Share	0.34	0.06	0.22	0.48
A positional Good	0.35	0.08	0.19	0.62
Conformity	0.37	0.08	0.19	0.78

5. Conclusions

So far, empirical evidence and theoretical knowledge about the rebound effect is very limited. This relates to the fact that demand- and supply-side aspects of the rebound effect are studied separately: either based on engineering estimates of different technologies or consumer survey. Nevertheless, to comprehend mechanisms through which improvements in energy efficiency may lower energy consumption, feedback loops and increasing returns underlying demand-supply coevolution need to be understood.

In this paper, we proposed such a coevolutionary model to examine the probability of the rebound effect occurring. The framework is composed of three heterogonous populations of power plants; producers of final products; and two classes of consumers: rich and poor. In the model, electricity is an input for production of final goods but also a final product produced by heterogeneous power plants embodying different energy technologies (coal, gas and nuclear energy). This is motivated by the fact that electricity is an important input for production in manufacturing, and it tends to dominate other energy sources in production as manufacturing technologies advance. Electricity can be produced from various energy sources, and thus a specific energy mix in electricity production affects an environmental impact of production in manufacturing. This effect is undertheorized in the literature on the rebound effect.

On the market for final products, technological change arises as a result of the interplay of incremental improvements in product designs and the search for radical innovations by incumbent firms. Changes in consumer preferences affect the direction of these processes. In particular, consumer preferences evolve over time as a result of two disequilibrating forces, namely: the desire to distinguish from others through special status commodities, captured by the snob effect, and the network effect. The later describes how individuals imitate other within their social networks. We examined three types of the network effect, referred to as ‘market share’, a ‘positional good’ and ‘conformity’. The network effect operating through market shares assumes that consumer’s choice depends on the number of individuals within his/her social network who purchased a particular product. Alternatively, the network effect through a positional good rewards the consumer for purchasing a product which quality exceeds the quality bought by most consumers within his social network. Finally, according to the network effect through conformity, consumers attain a higher utility the smaller the distance between the product quality and the socially-determined threshold level of product performance.

Our results support earlier findings that in case electricity and capital are poor substitutes, an increase in the elasticity of substitution between these two factors (but below unity) raises the probability of the rebound effect occurring. The opposite is true in case these factors are good substitutes. In addition, the results suggest that clustering of consumer choices is an important factor making the rebound effect less likely to occur. In favour of this hypothesis, the snob and network effects turned out to be statistically significant in explaining the probability of the rebound effect occurring in the model with the network effect through market shares. Here, the probability of clustering of consumer choices is higher than in alternative versions of the model. New emerging products have little chance for adoption as consumers evaluate product attractiveness based on established market shares, which are negligible for new firms. Consequently, improvements in (electricity) efficiency of a dominant firm reduce its electricity use and the price of its product, without affecting relative sales due to consumer inertia. In alternative versions of the model (with the network effect through a positional good and conformity), model dynamics resemble fashion markets with a high turnover of firms. Here, improvements in electricity productivity are insignificant is explaining changes in electricity use. This relates to the fact that consumers are more sensitive to quality/price than social considerations, and thus a new emerging product is likely to attract them if it offers outstanding quality. As a result, a firm, which efficiency improves, is likely to be shortly wiped out by market selection, before benefits from improvements in electricity efficiency are noticeable at the market level.

We examined effectiveness of different types of policies aimed at reducing electricity used for production of consumer goods, namely: a tax on electricity; a tax on electricity-intensive products, and ‘nuclear obligations’. The latter required investing in a new nuclear plant when a share of nuclear energy in electricity production felt below ten percent. Our results suggest that the tax imposed on electricity-intense products is less effective than the tax imposed directly on electricity. This relates to the fact that electricity-intense products are typically more expensive, and thus bought mostly by rich consumers, who are less sensitive to price considerations. On the other hand, the tax on electricity renders firms to substitute electricity for capital, reducing total electricity use. Finally, nuclear obligations, as intended, increase a share of electricity generated with nuclear energy. However, they simultaneously can increase the amount of electricity produced from fossil fuels, which occurred in 8-14 percent of our model simulations depending on the specific network effect. This implies that efficiency of such demand policies needs to be interpreted with caution.

The simulation results of our model suggest that interdependencies and feedback loops underlying interactions of heterogeneous players at the multiple markets are important in explaining the rebound effect. Without their proper understanding, policies aimed at reducing energy use can result in unexpected and unintended consequences. Our framework offers a starting point for studying specific mechanisms related to the rebound effect, including the role of status consumption, technological change and a mix of energy sources in electricity production.

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APPENDIX

Table A1. Parameter values: electricity market

A1.1 Energy technologies

Energy technology j	**Description**	**j=coal**	**j=nuclear**	**j=gas**	**Source of data**
α_k	Elasticities of substitution	0.452	0.876	0.2	McGuire and Westoby (1984); Roques et al. (2005)
α_l		0.077	0.035	0.07	
α_e		0.471	0.089	0.73	
M	Mean of the growth rate in thermal efficiencies	-0.002	0.005	0.008	own estimations, based on data from DTI (2008)
σ_j	Standard deviations of the growth in thermal efficiencies	0.013	0.009	0.016	
v_{i0}	Initial thermal efficiency	36.5%	37%	45.2%	DTI (2005), Table 5.10 data for 1997
max v_{it}	Maximum thermal efficiency	45%	40%	50%	UKERC (2007) for the period 2005-2015; for nuclear station sown estimates based on DTI (2005) data.
$\chi -0.5\sigma_j^2$	Mean value of changes in fuel prices	-0.01	-	0.04	own estimations, based on data from DTI (2008)
σ_j	A standard deviation of changes in fuel prices	0.08	-	0.11	
p_{j0}	Initial price of fuel	0.611	0.5	0.706	
T_j	Maximum lifespan	45	40	30	
p^o_j	Operating cost (p/kWh)	1.95	1.37	20 (£/kW)	Own estimates for coal and nuclear based on IEA (1989); gas estimate based on Green and Newberry (1992)
F_{jt}	Fixed cost (£/kW)	73.35	127.1	34.08	Own estimates for coal and nuclear based on IEA (1989); gas estimate based on Green and Newberry 1992
t_{sj}	Construction time	5	6	3	Green and Newberry (1992)
I_j	Initial investment cost (£/kW)	892	1524	400	Own estimates for coal and nuclear based on IEA (1982); gas estimate based on Green and Newberry (1992)
λ_j	Capacity factor	0.8	0.75	0.85	

A1.2 Other parameters

Parameter	**Description**	**Value**
a	Parameter in the demand function	2500
b	Parameter in the demand function	0.005
$p_{e,min}$	Minimum spot price	0.1
$p_{e,max}$	Maximum spot price	20
σ_L	Increase in the annual wage	0.04*
p_{l0}	Price of labour in time 0	0.731
r	Interest rate	0.08

* estimate based on UNDATA (2008)

Table A2. Parameter values: producers

Parameter	Description	Range/Value
η_p	A markup on electricity cost	0.25
p_{ct}	Capital price	(10,30)
y_{j0}	Initial level of output*	10
k_{j0}	Initial level of capital*	10
ξ	Depreciation rate	0.02
ς	A fraction of profits devoted to incremental innovations	0.6
ζ	A weight attached to sales in desire production	0.5
θ	Fixed cost	2
$\ddot{i}$	Competence elasticity	0.03
ι	Incremental elasticity	0.02
δ	Autonomous improvements	0.001
v	A parameter in the cost function	0.5
ψ	Length of a period a firm can operate with zero sales before it engages in radical innovations	5
φ	Length of a period a firm can operate with zero sales before it leaves the market	7
$\tilde{x}$	The maximum attainable quality	50
η	A markup on price	0.25
a	A fraction of capital in production	(0.2, 0.8)
σ	The elasticity of substitution	(0,2)
ρ	A fraction of the maximum quality	0.1

* indicated values describe initial conditions of new emerging firms and of firms existing in the beginning of simulation run

Table A3. Parameter values: consumers

Parameter	Description	Range/Value
κ	Snob elasticity	Randomly generated from (0,1) for rich consumers; 0 for poor consumers
α_i	Price versus quality inclination	(0 - 0.5)
ζ	Network elasticity	(0,1)
ώ	Parameter	0.375