Energy saving investments: simple analytics and an application to electricity

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Abstract

We consider a simple model of energy saving investments under uncertainty of energy costs. Adjustment delays in replacing energy-intensive capital follow from two natural elements: uncertainty and heterogeneity of the existing capital structure. They imply a simple dichotomy where short-run output contracts, but the long-run output recovers and increases above the initial output, despite the increasing energy costs. To provide a quantitative assessment of the consumer price increase needed for the investments, adjustment delays, and policies expediting the change, the elements of the model are estimated using electricity market data. Counterfactual simulations show that large scale entry of green energy requires unprecedented energy cost and consumer price increases mainly due to rents of the existing capital. Subsidies to green energy can greatly benefit the consumer side at the expense of the old capital rents.

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1 Introduction

The replacement of energy-intensive capital by energy-saving capital goods plays a central role in efforts to reduce energy consumption. Energy use response to prices is dynamic, and existing approaches to understanding it are based on capital adjustment costs coming either exogenously (Pindyck and Rothemberg, 1983) or from a "putty-clay" structure (Atkeson and Kehoe, 1999).[1] However, it appears to have been overlooked that uncertainty of energy prices has unique implications for the price-induced capital replacement, and yet uncertainty seems an almost defining feature of energy prices.

We consider a simple model of equilibrium investments in energy savings, where a novel dynamic price response follows from two natural elements: energy prices are uncertain, and the existing capital structure is heterogeneously hit by higher energy costs. While the framework fits multiple contexts, the electricity sector is of particular importance.[2] Primary energy costs in this sector are notoriously uncertain, and the production capacity is heterogeneously dependent on fuel costs.[3] We find that these elements alone —uncertainty and heterogeneity— imply that short-run output contracts (consumer price increases) as a response to energy cost increases, but in the long-run the output recovers (consumer price declines) while simultaneously the primary energy cost keeps on increasing. The long-run output expands even beyond that prevailing before the capital replacement started, despite the fact that the only exogenous change is the increasing energy cost. The implied contraction-expansion pattern provides a simple framework for understanding the nature of adjustment costs in energy use change, and the role of policies expediting the change.

To provide a quantitative assessment of the contraction-expansion pattern and policy instruments, we estimate the elements of the model using electricity market data. We find that the uncertainty of conventional energy costs alone is a significant source of

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[1] Empirical research has found that the energy use is much more responsive to prices in the short run than in the long run (Berndt and Wood 1975, Griffin and Gregory 1976; see also Thompson and Taylor 1995). The putty-clay model can better explain this difference, but there are also other explanations. See Linn (2008) for a discussion, and for a plant-level empirical analysis. For empirical work on innovation induced by energy prices (rather than price-induced capital replacement), see Popp (2001, 2002). See also Jaffe and Stavins (1995) and Newell et al. (1999) for analysis and discussion of energy-saving innovations and investments.

[2] For example, in the US the sector uses 42 per cent of primary energy, 34 per cent of fossil fuels, and produces about 40 per cent of carbon dioxide emissions. See Joskow (2008).

[3] We may rank the technologies in the electricity sector in the order of increasing dependence on primary energy fuels as follows: hydro, wind, nuclear, coal, gas, and oil.

investor caution: even under the most optimistic scenarios, the price-cost margin exceeds investors' costs by multiple factors during the transition. As a result of this inertia, the transition in the electricity sector is likely to be very costly to consumers. Green energy subsidies can be extremely beneficial to consumers, even when they are distorting the overall welfare: the cost of the intervention falls to a large extent on the old capital rents. Our quantitative assessment suggests that subsidies can considerably expedite the transition, and increase the consumer welfare, even without externalities justifying the need to expedite the phase out of energy-intensive capital.

For the heterogeneity of the existing capital in general, note that the primary energy demand is derived from capital goods used, e.g., in transportation, housing, and manufacturing. As primary energy inputs such as fossil fuels become sufficiently expensive —either due to finiteness of their availability or policies making their use more costly— the value of the capital structure employing these inputs decreases. The old capital is no longer well suited to the new economic conditions. But clearly capital goods suffer heterogeneously when energy costs increase, as the capital goods differ in their efficiency in using the energy input.[4] This "energy quality" heterogeneity among the capital goods leads to the presence of Ricardian rents. Such rents are perhaps most visible in electricity production where the marginal producing unit is usually very sharply identified, leaving a price-cost margin to the remaining producers.[5] Rents reflect heterogeneity in the social value of the energy-intensive structure and, therefore, it will be socially optimal to replace the energy-intensive capital gradually as the energy cost increases.

For the energy input prices, note that they are likely to exhibit a long-run upward trend and they are also extremely volatile, as recent developments in the oil market vividly illustrate.[6] The energy cost volatility creates uncertainty not only about the prospects of the old energy-intensive capital goods but also about the profitability of the new energy-saving capital goods — the social value of the replacement depends crucially on the expected value of the capital replaced. The green energy investments obviously face multiple uncertainties, but the future cost of conventional energy seems the most fundamental uncertainty for the economists to include in the analysis of the energy demand change. Because conventional energy costs are uncertain, the social value of each

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[4] This can be due to various combinations of *ex ante* sunk costs and *ex post* variable costs such that the firms were indifferent between the combinations when they entered the industry in the past. See, e.g., Roques et. al. (2006) for analysis of the choice between nuclear power and gas technologies.

[5] It is a standard practice in electricity market studies to evaluate these rents to isolate them from rents arising from market power, for example. See Wolfram (2000) and Borenstein et al. (2002).

[6] see Hamilton (2009) for a recent discussion on the nature of crude oil prices.

replacement is also uncertain, generating equilibrium real options for green technology entrants and thus a separation of marginal costs and prices (see, e.g., Dixit and Pindyck 1994). Our benchmark description involves no distortions, so the equilibrium mark-ups are socially optimal reflections of investor caution.

Our main result —the output contraction-expansion patter— is in spirit similar with that implied by the putty-clay model (Atkeson and Kehoe, 1999), and therefore it is roughly consistent with data. The mechanism behind our result is quite different, however. The short-run output contracts in order to create a mark-up for early green entrants. The mark-up must exist to compensate for the downside risk that the conventional energy costs decline in the near future — the replacement is socially wasteful *ex post* if, e.g., the oil price sufficiently declines, or the externality costs of fossil fuels diminish. Moreover, the uncertainty transmitted from the input to final-good market increases during the output contraction phase; a novel feature of capital adjustment costs implied by our model. The greater is the heterogeneity of the existing structure, the larger is the output contraction, consumer price increase, and uncertainty needed for the capital replacement to take place. However, the long-run output expands, because the energy market becomes disconnected from the output market, and this shuts down the transmission channel for uncertainty to the output market and thus to the entrants' profits. The decline in uncertainty reduces the required mark-ups and boosts investment, leading to the recovery of output.

Our model is a simple supply and demand framework, where the equilibrium formulation and computation utilize results developed in Leahy (1993). We believe the framework is well suited for gauging the consumer price increase needed for the capital replacement to take place in particular industries. For the empirical illustration, we develop a more general version of the model, going beyond the simple analytics and lending itself to the analysis of estimated industry structure. We then undertake a detailed estimation of the supply curve of electricity generation to produce annual revenues as a function of fuel costs and existing capacity in an electricity market, the Nordic wholesale electricity market.[7] The estimation exploits big exogenous swings in hydro electricity availability allowing us to identify the thermal (fuel-dependent) supply curve. While there are multiple idiosyncratic uncertainties influencing revenues for entering new capacity (wind, hydro,

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[7] The approach is general and can be applied to other electricity markets as well. The Nordic market has the advantage that the data needed for the application is public. We discuss the institutional details below; for a description of the Nordic market, see M. von der Fehr et al. (2005) and Amundsen and Bergman (2006).

demand), the persistent uncertainty relevant for investments is coming from fuel costs which are mainly driven by oil prices. To generate the values of future income streams for entering plants, we take the fuel price uncertainty as characterized by Hamilton (2009) and Nordhaus (2007).

In Section 2, we describe the basic model, and in Section 3, we develop the simple analytics of the model and use figures to explain the basic mechanism (the analytical solution is in a supplementary Appendix). In Section 4, we describe the equilibrium more generally and connect the equilibrium to Leahy's results. In Section 5, we calibrate the model using data from the Nordic electricity market, and perform the policy experiments. The computational Appendix and the program for simulations (including data) is available on the authors' webpage.

2 The model

We describe the change of the energy-input demand in a simple final-good demand and supply framework. Denote the inverse demand of the final good by $p = D(q)$, where p is the price and q is the final good demand, and assume that the function is monotone and non-increasing. An example of the good produced is electricity, a case that we consider in our application, but we do not want to limit ourselves to this interpretation. Nothing in the structure of the model prevents thinking of any final good market whose supply side uses energy-inputs, or alternatively, energy-saving technologies.[8]

There are two basic sources of supply, namely the old energy using technology and the new input-free technology.[9] We can think of a continuum of old and new technology firms, each producing one unit of output. An old firm uses one unit of energy input to produce one unit of output, and old firms differ in their efficiency in using the input. Let x denote the price of a unit of energy, and let q^f denote the total final-good supply coming from the energy-using firms. We assume that the marginal cost of the last producing unit, denoted by $MC(q^f, x)$, is strictly increasing and differentiable in q^f for a given energy price x. We also assume that the marginal cost is strictly increasing in x for all $q^f > 0$.

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[8] We can thus think of a market where primary energy (crude oil, natural gas, coal) is used to produce secondary energy (electricity, gas, refined petrolium), or the output can be the final consumption good.

[9] The new technology may still use energy but this energy is not coming from the fossil-fuel inputs. It may also be the case the new technology saves primary energy in absolute terms. Both interpretations are consistent with the model, and we use interchangeably the wordings "energy-input saving" and "energy-saving" technology

The new technology firms produce the same output but use no energy input. We denote the number of these firms by k, i.e., k is the existing energy-saving capital stock. We will introduce the entry problem of a new firm shortly, but for a moment we take the existing k as given. Since we are interested in describing a situation where the new supply from k replaces the old supply structure, we can set its variable cost to zero; the exact level of this cost does not matter as long as the new capital is the least-cost option, once in place.[10] The combined total inverse supply can then be written as

$$S(q,k,x)=\begin{cases} 0 \text{ if } q\leqslant k \\ MC(q-k,x) \text{ otherwise.}\end{cases} \tag{1}$$

The usage of old structure, i.e., production $q^f=q-k$, is what clears the final-good market,

$$p=D(q)=S(q,k,x)>0, \tag{2}$$

for a given k and x. [11]

Let us introduce time and uncertainty into the analysis. We assume that time is continuous and that the energy cost x_t is the only source of uncertainty over time. We assume that the energy cost follows a general diffusion process of the form

$$dx=\alpha(x)dt+\sigma(x)dw, \tag{3}$$

where w is a Wiener process.[12] This formulation admits the commonly used specifications used in the analysis of irreversible investments under uncertainty. In particular, if $\alpha(x)=\alpha x$ and $\sigma(x)=\sigma x$, then the process is a Geometric Brownian Motion (GBM). We do not have to be specific about the process, as long as it is defined for arbitrarily high levels of x to induce the transition to the new technology. If there is not much uncertainty in the process (σ is close to zero), we assume a positive trend ensuring the high prices in the end (α is strictly positive). The assumptions on x_t introduce persistence into the fuel prices. If, for example, there is no clear trend in prices but there is significant volatility the process captures the idea that "to predict the price of oil one quarter, one year, or one decade ahead, it is not at all naive to offer as a forecast whatever the price currently happens to be" (Hamilton, 2009).

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[10] Under this assumption, any positive flow cost can eliminated and incorporated into the initial investment cost of a new entrant.

[11] In equilibrium, where the amount of new capital k is determined endogenously, the price will remain positive, i.e., the lower bound for prices is $D(k)>0$.

[12] We assume that functions $\alpha(x)$ and $\sigma(x)$ satisfy standard requirements for the solution to exist.

Since the old fuel-using supply clears the output market for a given k, the stochastic fuel price implies that the output price is a stochastic process too, see equation (2). Because each entering new capital unit supplies one unit of output, the output price process is the revenue process for entrants. The new capital units thus make irreversible entry decisions under uncertainty. We assume that there is a continuum of potential entrants who can each invest in one capital unit by paying an irreversible upfront investment cost $I > 0$. The investors are risk neutral and face a constant market interest rate $r > 0$. Once in place, the new capital unit lives forever.

3 The simple analytics

We provide first the simple analytics of the model under the following assumptions. First, we assume that the variable x_t follows GBM with drift $\alpha > 0$ and standard deviation $\sigma \geqslant 0$,

$$dx_t = \alpha x_t dt + \sigma x_t dz_t. \tag{4}$$

Second, the final-good demand is linear

$$p_t = A - Bq_t, \tag{5}$$

and, third, the marginal cost for the old supply is additive in x_t and linear in $q_t^f > 0$,

$$MC(q_t^f, x) = x_t + Cq_t^f, \tag{6}$$

where the positive constants A, B and C satisfy the assumptions outlined above. In addition, we assume $r > \alpha$.

3.1 Transition without uncertainty

Let us first describe the build-up of the new energy-saving capital by eliminating uncertainty and assuming that the energy cost is on a deterministic upward trend, shifting gradually the old supply curve upwards. That is, set $\alpha > 0$ and $\sigma = 0$ in (4). We can now explain the distinct role of heterogeneity (Ricardian rents) as the source of gradualism in the transition.

In Figure 1, x enters as the intercept of the old supply curve — x can be thought of as the direct purchase cost of primary energy (fuel). The producer surplus (shaded area) illustrates the presence of Ricardian rents. The entry cost of one new capital unit is rI, expressed as a flow cost. When the energy cost is sufficiently low so that the output price

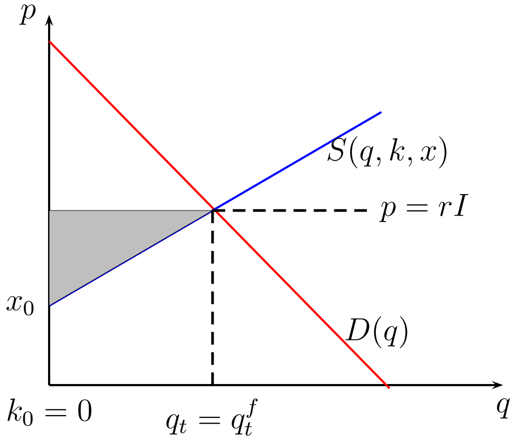

Figure 1: Entry of the first energy-saving capital unit under certainty.

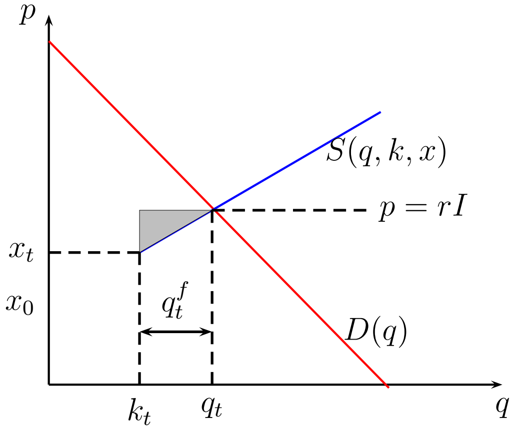

Figure 2: Entry of additional energy saving capital at k_t under certainty.

satisfies $p < rI$, the new technology units cannot enter, and the old structure satisfies the full demand. But since the energy price is on an upward trend, the output price must meet rI at some point. The first new capital then unit enters the market, as its present-value revenue p/r covers the investment cost I. This is the situation depicted in Figure 1.

As the energy cost keeps on shifting the supply curve up, there is a tendency for the output price to increase. But because of free entry, the consumer price cannot exceed $p = rI$, the entry cost of alternative supply. In Figure 2 we depict a situation where the fuel price has reached x_t, and there are k_t units of new capital in place. Recall that the new supply is the least-cost option, once in place, so the inverse supply is zero up to k_t, and then increasing for $q \geqslant k$, as depicted. The input-saving new technology has reduced the rents of the old supply structure when compared to the initial situation. Because these rents are sandwiched between the constant final-good price $p = rI$ and the increasing energy cost, they will vanish altogether at the moment the fuel cost meets the price $p = rI$. From this point onwards, the new technology serves the market alone.

3.2 Output Contraction

We assume now that there is volatility in the energy cost process, i.e., $\sigma > 0$ in (4). We look for the conditions under which the new technology starts to enter the market.

Recall that there is persistence in the fuel price process: both input and output prices are expected to remain high longer, the higher is x_t. The current level of x_t measures the profitability of entry directly, and it makes sense to enter only when x_t reaches new record levels. Let $\hat{x}_t$ to denote the highest energy price level seen by time point t, so that new entry will take place only if the fuel price process beats this record — previous entry considerations were made under fuel prices (weakly) lower than $\hat{x}_t$, so, all else remaining unchanged, additional entry requires a higher energy price. As a normalization, we denote the time where the first new firm enters by $t = 0$.

In Figure 3, the first new firm enters when the energy input price level reaches $\hat{x}_0$. The output price at the moment of entry is $P_H(\hat{x}_0)$, denoted this way to emphasize that it is the highest output price observed so far. We have drawn the Figure such that the new firm earns a mark-up above its entry costs, $P_H(\hat{x}_0) > rI$. This must hold because the new firm faces the downside risk that the fuel price and thus the final-good price starts to decrease after the entry; the lowest price conceivable is $P_L(\hat{x}_0)$.[13] For the mark-up to arise, the output must contract.

From the real options theory (Dixit and Pindyck, 1994), we know that the first entering unit requires a mark-up above its deterministic entry cost, $P_H(\hat{x}_0) > rI$, when facing the above described uncertainty.[14] Consider now how this mark-up develops in equilibrium when the energy demand continues to change. We argue that the mark-up and thus consumer price must increase as more energy-saving capital enters the market.

Figure 4 depicts time point $t > 0$ where there are k_t new units in place. We have drawn Figure 4 in the way that the output price is higher than the initial price at which the first new capital unit entered: $P_H(\hat{x}_t) > P_H(\hat{x}_0)$. This must hold, because the new entrant faces a higher risk of lower output prices when there is some new capital already in place — the overall supply capacity has increased while the process for x and the old technology supply curve remain the same.[15] As a result, the entry price must be higher and the output lower, to compensate for the increased downside risk. We see therefore that the energy price increase induces more entry but also higher consumer price levels, even though the substitute cost remains unaltered.

The consumer price increase and output contraction follow from the combination of

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[13] We denote the lowest price this way to emphasize that it depends on the state of the record $\hat{x}$.

[14] For a moment, we put aside the issues of how this firm conceives the future market development when more firms enter to the market. We come back to this issue in the formal characterization of the equilibrium. We can think that the first entrant mistakenly believes that it will be the only new firm ever entering the market. In fact, Leahy (1993) shows that the entry considerations can be correctly described this way. Based on this, it is clear from standard real options arguments that the first entrant requires the above mark-up, when there is uncertainty.

[15] That is, the output price process becomes less favorable to the entrant at each given x. This argument will be made formal in the next section.

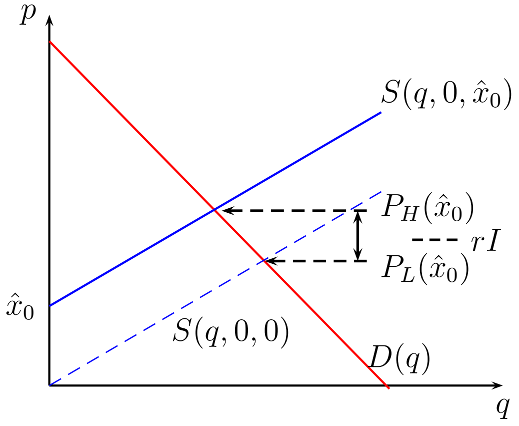

Figure 3: Entry of the first energy-saving capital unit under uncertainty.

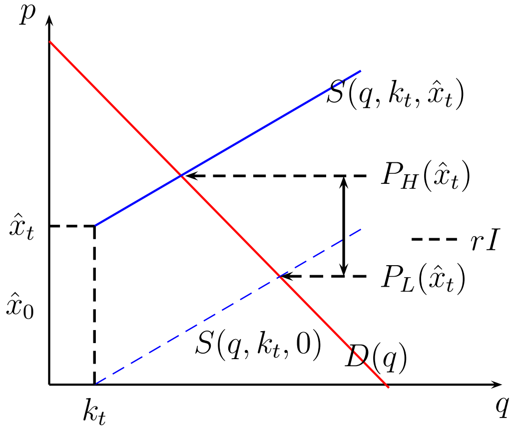

Figure 4: Entry of additional energy saving capital at k_t under uncertainty.

two elements in the model. First, the Ricardian rents ensure that the old production structure is replaced only gradually. Second, since the old structure remains in the market, it can benefit from the potential downside development in the fuel market, making the output market potentially extremely competitive.[16] This downside risk for the new entrant implies that the input-saving substitute can only enter when not only the energy but also the consumer price reaches record high levels. We see that uncertainty protects the rents of the old supply structure, as more extreme energy and consumer prices are needed to trigger entry than without uncertainty.

3.3 Output expansion

We have just demonstrated that the higher input price induces more entry but also higher output prices and lower output. We show now that the consumer price reaches a peak during the transition, after which the output recovers even though the energy prices increase. The final consumer prices will be lower and the output higher than the initial prices at which the transition started.

Consider now an input price so high that the entire old structure is just idle, i.e., the most efficient old unit is indifferent between idleness and production. We denote

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[16] One may ask if this property arises only because the old structure remains existing by assumption. We show in Section 4.2 that this is not case by assuming that the old structure decides also when to exit the market. In fact, we first developed the model for this case. Since that framework is considerably more complicated and the substantial results are the same, we can without loss of generality build up on the insights provided by this simpler model.

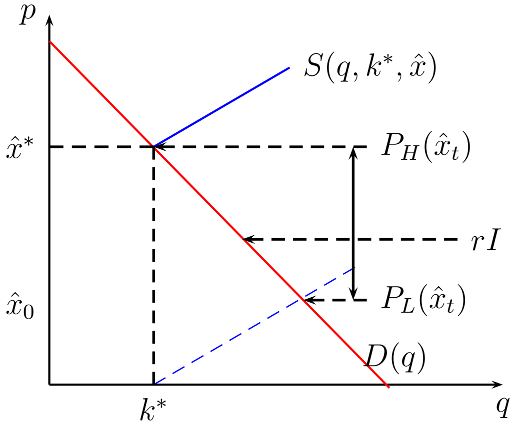

Figure 5: The consumer price peak

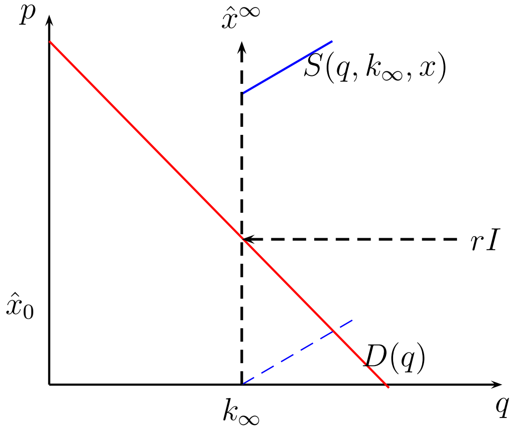

Figure 6: The long-run equilibrium

this input price by $\hat{x}^*$, and the corresponding new capital that serves the entire demand at that point by k^*. See Figure 5 for this situation. The market environment cannot become more risky for a new entrant than the situation described here, and therefore the mark-up above costs reaches its peak, $P_H(\hat{x}^*) - rI > P_H(\hat{x}_t) - rI$ for all $\hat{x}_t$.

Note that for the capital to increase above k^*, the energy price must reach values higher than $\hat{x}^*$. But then the old structure is not only idle at input prices $\hat{x}_t > \hat{x}^*$ but is also expected to remain idle in the immediate future; the input price must decline by the discrete amount $\hat{x}_t - \hat{x}^* > 0$ before the old structure can consider producing again. In this sense, the output price is expected to remain isolated from the input price uncertainty in the near future. For this precise reason, the new technology's prospects improve, and therefore it requires lower equilibrium entry prices. That is, the entry output price declines in $\hat{x}_t$ after peaking at $P_H(\hat{x}^*)$. In other words, the output recovers.

As sufficiently high $\hat{x}_t$ values are reached, the old structure produces with probability zero in the relevant future, implying that the entry becomes practically free of risk, and the consumer price approaches the deterministic entry cost, with which we started the analysis. The output has now fully recovered, and is larger than the output at all previous entry points.

Let us pull together this description more formally in the following Proposition.

Proposition 1 *There exists $\sigma^* > 0$ such that for $0 < \sigma < \sigma^*$, the equilibrium output contracts at investment points $0 < \hat{x} \leqslant \hat{x}^*$, and expands for $\hat{x} > \hat{x}^*$. Furthermore:*

- *peak price $P_H(\hat{x}^*)$ increases in C and σ*
- *replacement becomes a one-time event as $C \to 0$*

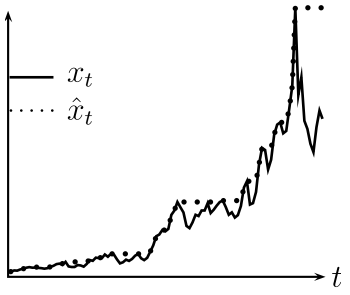

Figure 7: Sample path for the energy price

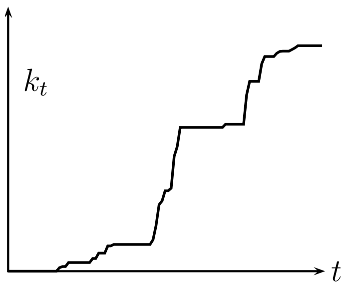

Figure 8: The energy saving capital stock

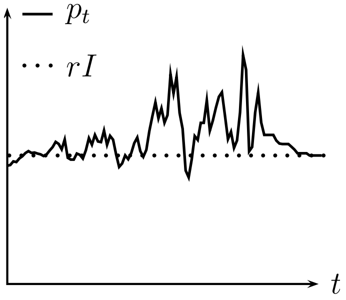

Figure 9: The consumer price path

- *investor mark-up disappears in the long run,* $P_H(\hat{x}_t) \to rI$ *as* $\hat{x} \to \infty$.

Proof. See Appendix. ■

The proof in the Appendix (supplementary material) is based on a connection to Leahy (1993) that we explain in detail in the next Section. The upper bound on uncertainty measured by σ^* ensures that entry starts before the market shuts down.[17]

The Proposition also shows how the resistance to entry depends on the Ricardian rents, measured by the slope of the supply curve, C. The greater is the slope C, the lower is the responsiveness of entry to energy prices, or the more protected are the old units from entry. On the other hand, when C is close to zero, the Ricardian rents are absent, and there is a large one-time replacement of old units as soon as the output price reaches a certain treshold level. Similarly, the energy cost uncertainty, captured by σ, provides protection to the old supply structure.

For illustration, see Figures 7-9 depicting equilibrium paths based on the specification (4)-(6). In Figure 7, we show a sample path for the energy price (solid line) and the historical maximum (dotted line). Figure 8 depicts the path for the energy saving capital. Figure 9 depicts the output price path, declining to the deterministic investment cost towards the end of the path. Figure 9 thus shows that the temporary increase and the final decline of the final-good uncertainty is a novel feature of capital adjustment process implied by this model.[18]

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[17] In this case, the peak output price would be the first entry price, and $\hat{x}^* = 0$.

[18] Note that the overall volatility of consumer prices increases temporarily during the transition because (i) for geometric Brownian motion larger x means higher absolute volatility for x, and (ii) the domain for conceivable consumer prices increases for reasons explained above.

3.4 Discussion

Before moving to the more general framework that prepares the ground for empirical applications, let us discuss the potential interpretations and extensions of the results. Being a simple supply and demand framework, the model should fit any context where these concepts can be applied. What is essential for the results is the payoff dependence of the old and new technologies. In electricity or manufacturing, this dependence is achieved by the fact that all technologies are serving the same final-good demand — the consumer does not care how much each producer spends energy as long as the final good is the same. In housing and transportation, the payoff dependence must be understood slightly differently, although the principle is the same. In housing, the final good is the service from heating or cooling the houses, and the capital structure is embodied in the fleet of houses. Old houses depend more on energy providers (e.g., gas, oil, electricity, co-generation) than newly insulated or otherwise restructured houses. The investments in heterogenous houses are made by owners, and they thus destroy demand of the energy providers. The better is the market-level insulation of houses, the lower is the demand for energy providers and thus the lower are the consumers' energy prices, for a given primary energy cost. Note that in this description the energy providers' marginal cost is increasing in the energy provided. Similar description applies to transportation, where consumers make investments in energy-using consumer durables (cars) providing the transportation service. Cars are heterogenous in their fuel efficiency, and consumers switch to more efficient cars when direct fuel costs increase. Here, the fuel cost to consumers is the price at the pump, which depends on refinery, transportation, and other costs of serving the gasoline, in addition to the primary energy cost. More investments mean lower demand for gasoline and thus lower prices, leading to the payoff dependence between technologies.[19]

Note that the supply curve $S(q,k,x)$ need not have to depend on k and x in the additive way as assumed for the illustration; the next section sets up a framework where the relationship between the equilibrium price, capital k, and cost x is general. This allows for multiple interpretations of how investments save energy, e.g., including piecemeal upgrades of old plants and structures, or new investments that are explicitly additional to the old ones. Another flexibility regarding investments that can be included is heterogeneity of investment costs — rather than assuming a fixed constant I we could work with

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[19] For studies considering energy efficiency in these sectors, see Linn (2008) for manufacturing, Fischer et al. (2007) for analysis of automobile fuel efficiency, and Jaffe and Stavins (1995) fo energy savings in housing.

an increasing investment cost function $C(I)$, reflecting underlying scarcities limiting the overall entry to the market and creating rents to early entrants. For example, the quality differences of wind and nuclear power sites, or the limited availability of special materials needed for alternative technologies may represent sources of increasing investment costs. Increasing costs over time, if considered reasonable, can have substantial implications in the sense that the overall entry can be limited to the extent that output contraction is not followed by recovery. However, in general, we like to make assumptions that favor entry to isolate transition delays coming from investor caution only.[20]

4 General analysis

4.1 Equilibrium

In this section we define formally the industry equilibrium, and show how it can be computed. Our formulation follows closely Leahy (1993). There is a continuum of identical potential entrant firms, and each may at any time enter by installing an infinitesimal capacity addition dk at cost Idk. Let k_t denote the aggregate capacity level at time t, and let $\{k_t\}$ denote the capacity path, i.e., the stochastic process governing its evolution in time. New entries increase k_t, and since there is no exit, $\{k_t\}$ must be an increasing process. To find an equilibrium, we must specify an entry strategy profile for the potential entrants and a corresponding capacity path such that (i) given the capacity path, the entry profile is optimal for each individual firm, and (ii) the entry profile induces the capacity path.

The profit flow to a holder of a capacity unit is given by the ouput price. In Section 2 output price was defined by equation (2), but the results hold generally for an output price function $p = P(k_t, x_t)$, where we assume that $P(k, x)$ is continuous in k and x, increasing in x, and decreasing in k. In addition, to ensure that profit for a unit of capacity is always finite, we assume that for any fixed value of k,

$$E\int_0^\infty P(k, x_\tau)e^{-r\tau}d\tau < \infty.$$

The information upon which the entering firms base their behavior at period t consists of the historical development of x_t and k_t up to time t. However, since $\{x_t\}$ is a Markov process, the state of the economy at any point in time is fully summarized by the current

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[20] In the empirical application, we discuss various elements that tend to further increase "adjustment costs" such as the investor heterogeneity.

values (k_t, x_t). It is therefore natural to restrict to Markovian strategies. Moreover, in the current context we can restrict further to strategies that can be expressed in cut-off form.

Definition 1 *A Markovian cut-off strategy is a mapping*

$$x^* : [0, \infty) \to \mathbb{R} \cup \infty \cup -\infty,$$

where $x^*(k)$ gives the lowest level for the shock variable at which the firm is willing to enter, given capacity k.

We use $x^*(k) = \infty$ to indicate that the firm does not enter at any level of x_t, and $x^*(k) = -\infty$ to indicate that the firm enters immediately for any value of x_t.

Remark 1 *Leahy (1993) expresses strategies as a cut-off level for the ouput price. If $P(k, x)$ is strictly increasing in x (which is assumed by Leahy), this is equivalent to our formulation: instead of $x^*(k)$, one could just as well use a strategy $p^*(k) = P(k, x^*(k))$, which defines the cut-off price at capacity k that triggers new entry. We express strategies in terms of x, because we do not require $P(k, x)$ to be strictly increasing. Despite this less demanding requirement for $P(k, x)$, the main results of Leahy (1993) hold in our context with some notational modifications.*

We will see that there is a symmetric equilibrium, where all the firms adopt such a cut-off strategy. To formalize this, we must derive the capacity path that such a profile induces. Let us assume an arbitrary symmetric cut-off profile x^*. There is a large number of potential entrants, each with a strategy commanding them to enter as soon as x_t hits $x^*(k)$. Of course, it would make no sense to assume that all the firms actually enter at the same time. Instead, as soon as the entry threshold is hit, capacity k_t will immediately increase up to the point where entry stops.[21] This happens every time x_t hits the relevant cut-off level $x^*(k_t)$, and consequently, we end up with a capacity path along which entry takes place only at such time moments where x_t hits new record-values. Note that we are not interested in the identities of actual entrants, but the aggregate capacity path.

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[21] There are many ways how this "rationing" among entrants could be modeled more formally: 1) asymmetric strategies, 2) an additional sub-game within each entry point that allows firms to exit and re-enter until the number of entrants makes every firm indifferent, 3) mixed strategies, 4) introducing heterogeneity e.g. in entry costs and working in the limit where this heterogeneity vanishes. Since all firms are indifferent in our free entry equilibrium, all of these formulations would lead to the same outcome.

Let us denote by $\hat{x}_t$ the historical maximum value of x_t up to time t:

$$\hat{x}_t \equiv \sup_{\tau \leq t} \{x_\tau\}. \tag{7}$$

We can now formalize the above discussion by defining the aggregate capacity path as a function of $\hat{x}_t$.

Definition 2 *The capacity path induced by a symmetric cut-off strategy x^* is the stochastic process $\{k_t\} \equiv \{\mathbf{k}^* (\hat{x}_t; x^*)\}$, where*

$$\mathbf{k}^* (\hat{x}_t; x^*) = \inf\{k \geq 0 \,| x^* (k) > \hat{x}_t \ \}. \tag{8}$$

Note that $\{\mathbf{k}^* (\hat{x}_t; x^*)\}$ is an increasing stochastic process, and its value at time t is fully specified by the development of x_t up to time t.

Equation (8) together with (3) defines the law of motion of k for a given symmetric entry strategy x^*. To find an equilibrium, we must also check the optimality of the entry strategy agains a given capacity path. The entry problem of an individual firm can be written as follows. Let $\mathbf{k} : [x_0, \infty) \to \mathbb{R}_+$ denote an arbitrary increasing function that defines the aggregate capacity as a function of the historical maximum value of x_t. A potential entrant is effectively holding an option to install one capacity unit at cost I, so the entrant solves the following stopping problem:

$$F(x_t, \hat{x}_t; \mathbf{k}) = \sup_{\tau^* \geq t} E\left[\int_{\tau^*}^{\infty} P(\mathbf{k}(\hat{x}_\tau), x_\tau) e^{-r(\tau - t)} d\tau - I e^{-r(\tau^* - t)}\right], \tag{9}$$

where $F(\cdot)$ is the value of the option to enter.

The potential entrants are all alike and solve the same entry problem, but in equilibrium with unrestricted entry each entrant must remain indifferent between entering and staying out. We now define formally the competitive equilibrium as a rational expectations Nash equilibrium in entry strategies. Consider a symmetric candidate profile x^* and the induced capacity process $\{k_t\} \equiv \{\mathbf{k}(\hat{x}_t; x^*)\}$. We need two conditions. First, free entry eliminates any profits to the potential entrants. That is, for all x_t and $\hat{x}_t$, we have

$$F(x_t, \hat{x}_t; \mathbf{k}) = 0. \tag{10}$$

Second, whenever x_t hits $x^*(\mathbf{k}(\hat{x}_t; x^*))$, entrants must find it (weakly) optimal to enter, otherwise they would rather stay idle:

$$E\left[\int_t^{\infty} P(\mathbf{k}(\hat{x}_\tau), x_\tau) e^{-r(\tau - t)} d\tau\right] - I = 0. \tag{11}$$

Definition 3 *The industry equilibrium is a trigger strategy profile* x^* *and corresponding capacity path* $\{k_t\} = \{\mathbf{k}^*(\hat{x}_t; x^*)\}$ *such that*

- *(10) holds for all* $\hat{x}_t$ *and* $x_t \leq \hat{x}_t$ *when* $\mathbf{k} = \mathbf{k}^*(\hat{x}_t; x^*)$
- *(11) holds whenever* $x_t = x^*(\mathbf{k}^*(\hat{x}_t; x^*))$
- $\mathbf{k}^*(\hat{x}_t; x^*)$ *is given by (8)*

The key to finding such an equilibrium is the observation that a marginal firm which understands the stochastic process $\{x_t\}$ but disregards the other firms' entry decisions will choose the same entry time as a firm that optimizes against the equilibrium capacity path $\mathbf{k}^*$. This myopia result, due to Leahy (1993) and further elaborated by Baldursson and Karatzas (1997), can be formalized as follows. An entering firm that thinks the current capacity $\mathbf{k}^*(\hat{x}_t; x^*)) = k_t$ remains unchanged in the future solves the exit time from

$$F^m(x_t; k) = \sup_{\tau^m \geq t} E\left[\int_{\tau^m}^{\infty} P(k, x_\tau) e^{-r(\tau - t)} d\tau - I e^{-r(\tau^m - t)}\right]. \tag{12}$$

Note first that the solution to (12) can be expressed as a cut-off rule.

Lemma 1 *The optimal solution to (12) can be expressed as a cut-off rule* $x^m(k)$*, so that the optimal stopping time* τ^m *is the first moment when* x *hits* $x^m(k)$ *from below:*

$$\tau^m = \inf\{\tau^m \geq t \,| x_{\tau^m} \geq x^m(k)\}.$$

Proof. The problem (12) is a standard excercise problem of a perpertual call option, where the value of the underlying asset at time t is given by

$$V^m(x_t, k) = \int_t^{\infty} P(k, x_\tau) e^{-r(\tau - t)} d\tau,$$

and the cost of excercise is constant I. By assumption, $P(k, x)$ is increasing in x, so under our assumptions on $\{x_t\}$, V^m is also increasing in x. It is then clear that if excercising at x' is optimal, it must be optimal to excercise also at any $x'' > x'$. Conversely, if it is not optimal to excercise at x', it is neither optimal to excercise at $x'' < x'$. Thus, the solution is a cut-off rule. ■

The following proposition states that the model has an equilibrium that can be computed by solving the myopic problem (12) for all fixed values of k.

Proposition 2 *Under the assumptions stated, the model has an industry equilibrium, where the entry threshold* $x^*(k)$ *is given by the solution to (12). The corresponding capacity path is given by (8). The entry threshold* $x^*(k)$ *is increasing in* k*.*

Proof. By Lemma 1, the solution to (12) for any $k \geq 0$ is a cutoff policy, which we can denote $x^*(k)$. Since $P(k, x)$ is increasing in x and decreasing in k, it is a standard comparative static property of this type of a problem that $x^*(k)$ is increasing in k. The proof that the solution to (12) constitutes a competitive equilibrium can be constructed following the steps given in Leahy (1993). The only difference is that our assumptions on $P(k, x)$ are slightly less demanding than similar assumptions in Leahy (1993), but those differences are not crucial for this result. ■

4.2 Extension

One may argue that our description depends on the specific assumption that the old production structure is static and cannot respond by exit decisions to the changing market situation. This is not the case. In our working paper Liski and Murto (2006), we analyze a more general model, where the old capital can exit the market but the substance-related results remain essentially the same.[22] In that framework, we assume that there is a continuum of infinitesimal firms, and each active firm has one unit of capital of either type. If we let k_t^f and k_t^b denote the respective total fuel-dependent and fuel-free capacities at time t, then k_t^f and k_t^b denote also the numbers of firms at t. By k_0^f and k_0^b we refer to exogenously given initial capacity levels. Each factor-dependent firm that is still in the industry at some given t must choose one of the following options: produce, remain idle, or exit. To make the choice between idleness and exit interesting, we assume that staying in the industry implies an unavoidable cost per period. Let $c > 0$ denote this fixed flow cost. A producing unit in period t incurs a fuel-dependent production cost, as in the current paper, plus the flow cost $c > 0$. An idle unit pays just c. An exiting unit pays a one-time cost $I_f > 0$ and, of course, avoids any future costs. In equilibrium, firms (discrete) choices between production and idleness determine the overall utilization of the old capacity.

Let q_t^f denote the total output from the factor dependent capacity. Then, q_t^f is also the number of producing firms which satisfies $q_t^f = k^f$ if all remaining firms produce, and $0 \leq q_t^f < k^f$ if utilization is adjusted. We assume further that

$$I_f < \frac{c}{r} < I_f + I_b.$$

The first inequality implies that exit saves on unavoidable costs for an old capacity unit. The second inequality implies that replacing an old unit by a new unit is costly.

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[22] Note that the new entrants could also leave the market, but given the assumed cost advantage of existing new plants, the exit is more relevant option for old units.

Without the former restriction, old plants would never exit. Without the latter, the factor-dependent capacity would be scrapped and new capacity built immediately. For this structure, the equilibrium capital replacement path is a pair $\mathbf{k}(\hat{x}) = \left(\mathbf{k}^f(\hat{x}), \mathbf{k}^b(\hat{x})\right)$ which can be characterized as follows. The exit of the old technology may start before or after the entry of the new one, but both transitions end at the same factor market condition, i.e., at some $\hat{x} = b < \infty$. The result implies that as long as the transition is going on for both technologies, there is both exit and entry every time $\hat{x}$ reaches a new record value. Also in this framework the transition is gradual because of Ricardian rents. Finally, when there is sufficient uncertainty in the energy cost process, the consumer price must increase and the output contract during the transition because there is technology overlap: the new technology does not replace the old one-to-one, but is built to co-exist with the old structure during the transition. But there is also a final decline in the consumer price and expansion of the output, for the reasons explained in the current paper.

This feature is the key for the result that increasing consumer prices are needed for the transition to take place. In our current simpler model, the technology overlap is extreme as the the new input-saving technology is built to coexist with the old structure forever.[23]

5 Application to the Nordic electricity market

We now provide a quantitative assessment of the mark-ups needed for green electricity entry using electricity market data. Electricity generation uses primary energy (e.g., fossil fuels) to produce secondary energy (electricity), with long-lived capacity and relatively clear green electricity options such as those relying on wind and renewable energy sources. The data for the assessment comes from the Nordic electricity market, but the procedure is not specific to the Nordic market.[24] We believe that the main lessons apply to electricity markets in general because one key property of electricity generation is common across markets: persistent uncertainty comes from fuel prices which is transmitted to entrants

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[23] Methodologically, a distinct feature in comparison to the current paper is that there is a two-dimensional state space due to the capital stocks associated with the two technologies. In particular, the equilibrium concept and the technique for solving it can be seen as generalizations of Leahy (1993) to multiple dimensions.

[24] The Nordic case has the advantage that the data needed is publicly available, and that the relevant supply curve can be estimated with sufficient preciseness without using engineering approach on plant-level cost characteristics.

profits through thermal electricity generation. Uncertainties from other sources such as wind and hydro power availability, or demand are idiosyncratic by nature, as they are likely to look the same next year or after ten years.

5.1 Institutions

The Nordic wholesale power market developed to its current form through a series of steps when the four continental Nordic countries (Finland, Denmark, Norway, Sweden) underwent electricity market liberalization at different times in the 1990's. By several measures, it is relatively tightly integrated cross-border wholesale electricity market, serving majority of the ca. 400 Twh annual demand in the Nordic region.

Wholesale electricity trade is organized through a common pool, Nord Pool, which is a power exchange owned by the national transmission system operators.[25] Market participants submit quantity-price schedules to the day-ahead hourly market (Elspot market). The demand and supply bids are aggregated, and the hourly clearing price is called the system price. The Nordic market uses a zonal pricing system, in which the market is divided into separate price areas. If the delivery commitments at the system price lead to transmission congestion, separate price areas are established. For our study, the price areas are not important since we aggregate prices to the weekly level, and from these we construct annual revenues for new entrants to this market. At this level of aggregation, there is no loss of generality from working with the system price.[26]

When estimating the supply, we focus on period 2000-05 because the institutional and economic environment was relatively stable; that is, the market was not yet affected by the European emissions trading scheme and further integration to the continental Europe.[27]

Roughly one half of annual Nordic generation is produced by hydro plants. In 2000-

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[25] For more information about the pool, see www.nordpool.com. For a succint description of the Nordic market, see Amundsen and Bergman (2006).

[26] The direction of congestion in the transmission links varies within the year, and also between the years depending on the division of labor between hydro-intensive and thermal-intensive regions in the market. See Juselius and Stenbacka (2008) for a study focusing on the degree of integration of the Nordic price areas at the hourly level.

[27] To recap the market development, we may call the years 2000-01 as years of abundant availability of hydroelectricity which led to low prices during these years. The year 2002 in turn was exceptional: the Fall rainfall and thus inflow was scant and the stocks were drawn down to approach historical minimums by the turn of the year. The price spike resulted, and it took almost two years for the stocks to recover. See Kauppi and Liski (2008) detailed explanation and analysis of the price spike.

05, 61 per cent of hydroelectricity was generated in Norway and 33 per cent in Sweden. Sweden is the largest producer of thermoelectricity with a share of 46 per cent of annual Nordic mean production, followed by Finland and Denmark, with shares of 35 and 19 per cent, respectively. Hydro availability is the one single market fundamental that causes significant swings in demand for other production technologies. These swings are exploited in our estimation of the non-hydro supply curve for this market.

In the Nordic area, the non-hydro production capacity consists of nuclear, thermal (coal-, gas-, biofuel-, waste- and oil-fired plants), and wind power. An important part of thermal capacity is combined heat and power (CHP) plants which primarily serve local demand for heating but also generate power for industrial processes and very cost-efficient electricity as a side product. An implication of CHP capacity is that the non-hydro market supply experiences temperature-related seasonal shifts, which we also seek to capture in our estimation procedure detailed later. Table 1 provides a breakdown of capacity in 2008.

	GW				
	Denmark	Finland	Norway	Sweden	Total
Installed capacity	12.6	17.0	30.8	34.2	94.6
Nuclear	-	2.6	-	8.9	11.5
Fossil fuels	8.8	9.2	.7	5.1	23.9
Renewable	3.8	5.2	30.1	20.6	59.1
-hydro	.01	3.1	29	16.2	48.9
-bio	.03	1.9	.01	2.7	5.0
-wind	3.2	.01	.04	1.0	4.8

Table 1: Installed capacity in gigawatts (GW) by energy source 2008. Annual statistics, Nordel 2008.

5.2 Empirical implementation

We estimate the weekly supply function of the thermal sector from data on the weekly system price and total non-hydro output in 2000-05.[28] We regress the thermal supply

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[28] We use weekly demand data for the Nordic market in 2000-05 as published by the Organization for Nordic Transmission System Operators (Nordel). The system price data is published by Nord Pool, while electricity production by technology is reported by Nordel. We used the European Brent spot price for the price of fuel oil as reported by Reuters.

(non-hydro supply) on the price of electricity, the prices of fossil fuels and the time of the year (month). A majority of the marginal cost of thermal plants consists of the price of the fuel. As explained, the thermal generation costs vary within the year for reasons related to heating demand and maintenance, both of which follow a seasonal pattern (nuclear plants and other large thermal power plants follow a seasonal maintenance schedule).

To capture these effects, we include month dummies d_t in the regression equation,

$$q_t^f = \beta_0 + \beta_1 \ln p_t^{elec} + \delta x_t + \gamma d_t + \varepsilon_t, \tag{13}$$

where q_t^f is the thermal supply, x_t is the vector of fuel prices, and t is week. Note that since dummies are defined for months, the estimation effectively produces a monthly supply curve. The generation q^f in this estimation is composed of all other production than hydro, including wind power and the net imports of electricity to the Nordic region.[29]

For detailed estimation results, we refer to Section 4.3. in Kauppi and Liski (2008), where the same equation is estimated for a different purpose. The output price depends on thermal generation, and is thus endogenous. There are two natural candidates for instruments, the hydro production and the level of reservoirs, both of which influence the price level but not the cost of thermoelectricity. Given the slightly better fit in the first stage, we use the model with reservoir levels as instruments (see Table 2 in Kauppi and Liski (2008)). We note that fossil fuel prices are strongly multicollinear, and all other fuel than oil prices can be dropped from the final estimation. Figure 3 in Kauppi and Liski (2008) illustrates the fit with observed prices, when actual non-hydro supply and oil prices are inserted to the estimated equation (13) to produce an estimate for the weekly electricity price.

We can now construct the price function $P(k_t, x_t)$ that determines the annual revenue for a new technology unit that enters this market, given the existing capacity k_t and oil price x_t. Using this price function we will generate equilibrium capacity path $\mathbf{k}(\hat{x})$, which then defines price $P(\mathbf{k}(\hat{x}), \hat{x})$ as a function of the oil price history. To this end, we compute the historical annual monthly supply profile of thermal power over the years from data, and use this profile together with the estimated thermal supply to generate an annual revenue for new plant that runs at full capacity through the year. An increase in the total new capacity k is assumed to decrease the residual demand for thermal power

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[29] We run the supply regression for thermal only, but this has very small effect on the results; probably so because the marginal plant is a thermal plant on both case and dummies capture well the seasonal utilization of other capacity types. For clarity, we therefore make the distinction only between hydro and non-hydro capacity.

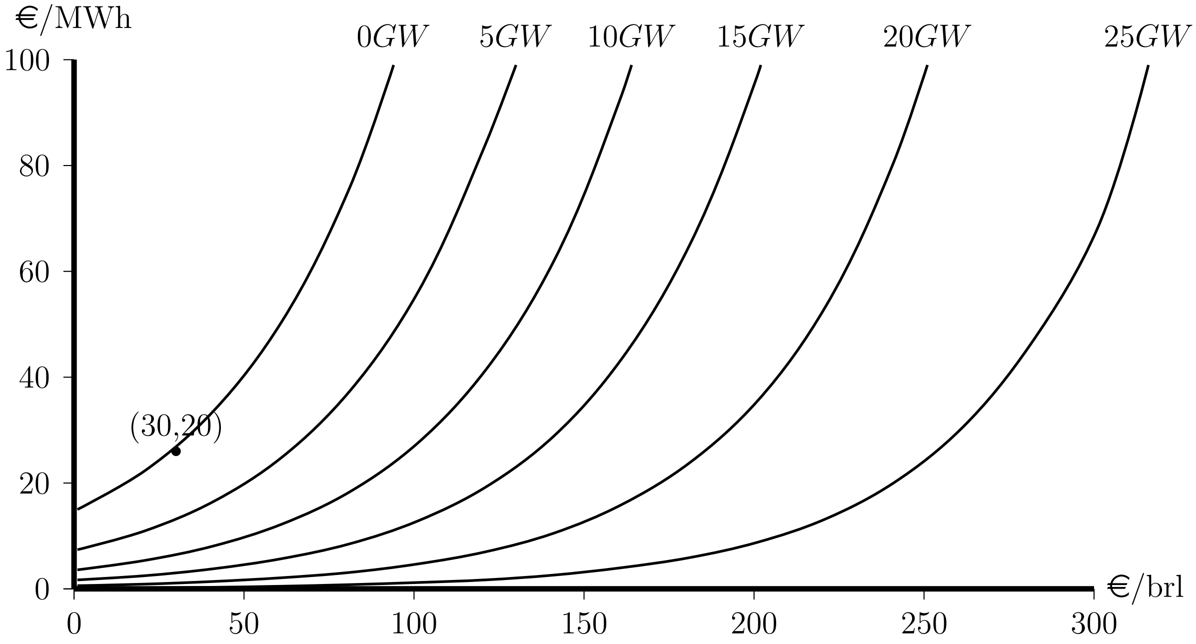

Figure 10: Average annual electricity price (€/MWh) as given by estimated $P(x, k)$. Oil price €/barrel on the horizontal axis. Installed new capacity in gigawatts indicated for each curve.

one-to-one — the estimated supply curve (13) is shifted horizontally to the right at a given electricity price level.

More formally, let q_i^h and q_i^d denote the realized monthly hydro production and final demands, respectively. The difference $D_i = q_i^d - q_i^h$ is the realized residual demand that non-hydro production must meet in the absence of new capital. When there is k units of new capital, non-hydro production is $D_i - k$, and the implied market price is given by the estimated supply curve (13). We assume that D_i follows a normal distribution with the first and second moments estimated from data.[30] We denote by M and H the number of months and hours in a year, respectively.[31] The expected annual average price can be expressed as follows:

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[30] We construct observations for D_i using data for demand and hydro production over the years 2000-2007, as published by Nordel. We use a slightly longer period 2000-07 for this estimation than that used for the thermal supply estimation, where we use the six years 2000-05. Including years 2006-07 in supply estimation is problematic because of regime changes such as introduction of emission permit markets. However, these changes do not significantly influence demand realizations and hydro availability.

[31] In our computations, one month is exactly 4 weeks, so we have $M = 13$. The number of hours per year is $H = 8760$.

$$P(k,x) = \frac{1}{M}\sum_{i=1}^{M}\int \Pi(i,x,D_i - k)dF_i, \tag{14}$$

where the monthly price $p_i = \Pi(.)$ is implied by the inverse of (13), and F_i is the cumulative distribution function for D_i in month i. Note that to get the expected annual revenue, we must multiply (14) by the number of hours per year, H. Because the uncertainty coming from monthly demand for thermal is idiosyncratic, we can apply $\widetilde{P}(k,x) \equiv H \cdot P(k,x)$ in the subsequent analysis exactly as before — $\widetilde{P}(k,x)$ satisfies the assumptions of Section 4.1.

Figure 10 depicts the basic properties of the estimated price function $P(k,x)$. We express it as the average annual price to make it comparable with historical prices observed in the market. Each graph depicts the relationship between electricity price (€/MWh) and oil price (€/barrel) for a given k. The upper-most graph corresponds to the historical capacity, i.e., $k = 0$. During the period 2000-05 the average price pair was close to 26 €/MWh and 30€/barrel, which is quite precisely what the $k = 0$ -graph indicates. In the Figure, we add new capacity in 5000 MW chunks ending at 30000 MW. [32]

The equilibrium is computed by setting up a discrete time version of the continuous-time model, where the fuel price follows a binomial approximation of the geometric Brownian motion with a short time interval between periods (we use period length $\Delta = 1/50$ years). The capacity is also added in small discrete units. The details of the computations, including the Matlab programs and the data files, are available on the authors' web pages.

5.3 Simulation results

For the counterfactual simulations, we take the fuel price as given by a Geometric Brownian Motion. Using the data in Nordhaus (2007) or Hamilton (2008), we conclude that there is no clear trend in prices 1970-2007, so we set $\alpha = 0$. Both data sets imply an extremely high annual volatility, $\sigma = .3$. We experiment with different levels of volatility and take $\sigma = .2$ as our benchmark case; $\sigma = .3$ implies extreme investor caution as explained in more detail below. We have no single estimate for the investment cost flow

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[32] The total capacity of fossil-fuel fired capacity in this market is 23000 MW; adding this much new capacity does not entirely eliminate dependence on fuel prices because of the idiosyncratic uncertainty in demand. We choose 30000 MW as the upper bound for new capacity in illustrations, because this is close to theoretical maximum entry in computations below.

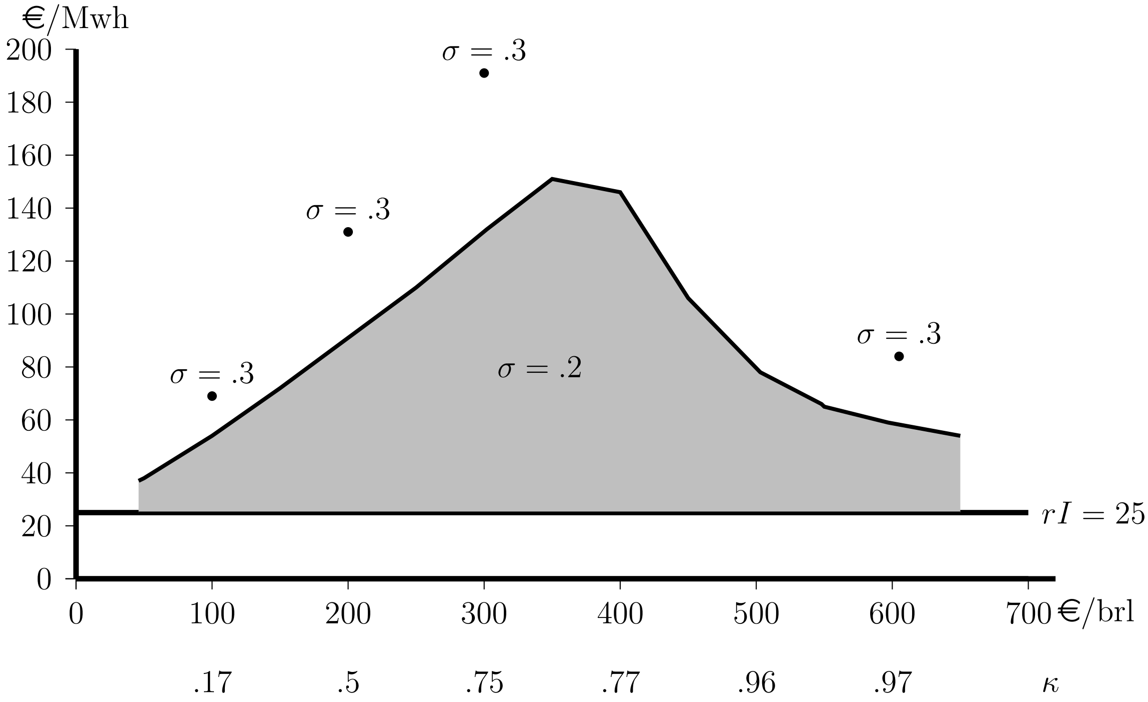

Figure 11: Equilibrium price-cost margin when $rI = 25$ and $\sigma = .2$. 'Dots' indicate individual mark-ups for ($\sigma = .3$). κ=fraction of capacity replaced (1=25 000 Mw).

rI,[33] but the subsidy levels applied in practice imply that new green capacity can enter when they receive a fixed-price in the range 25 €/Mwh to 80 €/Mwh.[34] We set the risk-free interest rate at 4 per cent.

See first Figure 11 which shows the equilibrium price-cost mark-up for new entrants as a function of the fuel price level (the shaded area). In this Figure, we assume $rI = 25$ and $\sigma = .2$, but individual mark-ups are also show for the higher uncertainty case $\sigma = .3$ (see dots). Note that the assumed entry cost is at the low end of the empirical support, and the uncertainty is lower than suggested by the historical fuel prices. Yet, the peak electricity price 160 €during the transition implies a 500 percent mark-up! However, a large fraction of the existing capital is replaced at much lower prices. We indicate this fraction by variable κ which gives the fraction of capital replaced as a function of the fuel price (the second horizontal axis below the Figure). Note that 50 percent of replacement

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[33] Since we want to express investment cost in units comparable with hourly prices, we must interpret I here as the investment cost for a capacity unit that yields one MWh per year, that is, constant output flow of 1/8760 MW.

[34] The cost obviously varies across technologies but also for the same technology depending, e.g., on the site properties. For a review of costs for wind power, see the IEA (2008) report and Benitez et al. (2008). For a cost comparison across technologies, see Heptonstall (2007).

requires that fuel price reaches 200 €/barrel but the electricity price is still in the domain of historical observations. But matching the historical uncertainty for fuels ($\sigma = .3$) leads to much higher resistance in replacement: the first 10 percent replacement requires a 100 €fuel price (not depicted), and unprecedented peak output price increases for electricity consumers.[35]

Figure 12 is otherwise the same but the investment cost $rI = 50$ is in the middle range of the empirical support.

5.4 Discussion

We have chosen relatively optimistic assumptions to quantify the investor caution coming from uncertainty alone. These include: unlimited free entry, risk-neutrality, and no capital depreciation. Let us now discuss other interpretations and the sensitivity of the results. We argue that the results are quite robust in the following sense: The mark-up of the first entrants, capturing the early friction, is not sensitive to changes in the environment due to our inability to model future events precisely. First, our revenue function may not be precise when oil prices and capacities are far off the empirical support, and therefore we not describe the profitability of the later entry precisely. However, this potential mistake has no effect on early entry: optimality of the entry at time t depends only on the price history up to t, and not on the properties of the revenue process defined for all prices higher than that at t. This follows from the Leahy's myopia result, as explained in Section 4.

Second, we may not have good a idea how the future cost of entry will develop. For example, there can be a sharper than anticipated increase in investment costs as more entry takes place, but this would leave the mark-up required by the first entrant untouched, all else equal. This follows again from the myopia result. In this sense, the degree of early friction in entry is unaffected by changes in costs of future entry, while the future costs will of course influence the long-run price levels.[36]

Third, we may consider the extended model discussed in Section 4.2, where the old capacity will leave the market gradually over time. Thus, if the old capital is costly to maintain and it will be scrapped at some point: the peak consumer price reached

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[35] The peak electricity price is 300 €/Mwh under $\sigma = .3$ (not depicted due to the scale).

[36] It is perhaps surprising that we can even think of declining entry cost, and the implied friction in early entry increases. Suppose there is a constant investment cost but Poisson arrival rate for a permanent cost reduction. It is straightforward to show that the early mark-up will increase if such a possibility is included.

during the transition will be lower if fraction of the old capital leaves the market for good. However, the mark-up for the first entrant is independent of the future price path, viewed at the point of entry, and thus it is independent on how exactly the two capital goods interact in equilibrium, provided the old capital is not so unproductive that it decides to exit before new entry takes place.

In addition to these elements, it is clear that trends in demand, fuel prices, capital depreciation, or risk aversion of investors can shape how exactly the future prices increase and then finally decline.

To conclude, let us discuss a feature specific to the electricity application. Recall that the output should contract in order to create the real-options mark-ups for early entrants. How does this pattern arise in electricity markets where demand and thus total output are relatively inelastic? Obviously, no output contraction is necessarily needed, if the demand is totally inelastic and the supply curve just shifts up with increasing fuel costs. However, in this market, there can be contraction of the demand without change in total production since large industrial consumers are on both sides of the wholesale market. Sufficient price increases mean contraction of industrial demand as more of this demand is met by own production facilities; lower prices lead to expansion in the market demand from these sources.[37]

5.5 Policy experiments

Primary energy inputs, mostly fossil fuels, are often imposing external costs to the society, when their use releases unabated pollutants leading to a variety damages. If the social cost is fully internalized through a first-best penalty on the use of the inputs, the model description remains valid, with the modification that the social cost is added to the private supply curve. The gradualism and price dynamics are efficient features of the transition, even when externality prices are included.

However, the problem is that the social cost is in most cases not exactly known and its presence has emerged as a surprise to policy makers and citizens, and therefore there is a need to expedite the demand change, e.g., due to accumulated pollutant stocks such as greenhouse gases. There are multiple policy instruments currently in use, or under planning, in countries interested in inducing a faster than market-led demand change for

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[37] This description applies well to the paper and pulp industry, for example. We have not undertaken a separate industrial demand estimation but this supply is included in the aggregate supply used in our estimation. See Johnsen et al. (1999) for a discussion of the industrial demand in Norway.

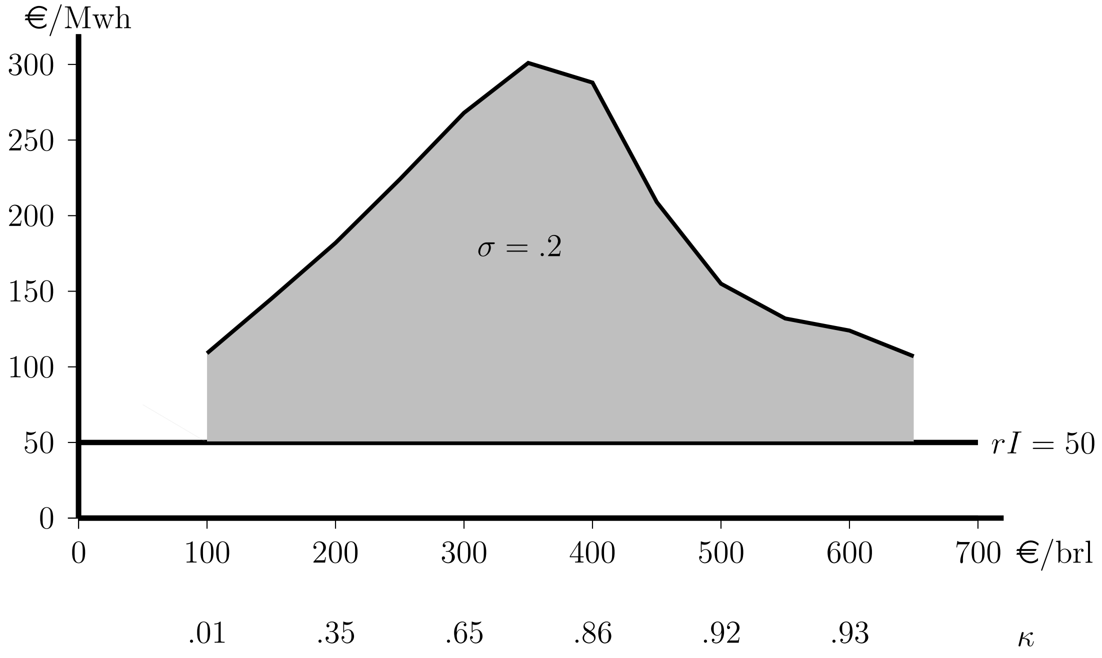

Figure 12: Equilibrium price-cost margin when $rI = 50$ and $\sigma = .2$. κ=fraction of capacity replaced (1=25 000 Mw).

energy. [38]

Perhaps the most important policy instrument applied in the electricity sector is a price subsidy called feed-in tariff. There are different versions of the feed-in tariff in use, but the common idea is to provide a price insurance to the new technology producer, i.e., a fixed-price or variable-price subsidy providing a pre-determined minimum revenue over time.[39] We consider the subsidization of entry below, and the analysis applies to multiple forms of subsidies, but we frame the subsidy as a feed-in tariff to fix ideas. We consider the following case: the tariff is a price floor ensuring that the new technology producer's sales price does not drop below a certain pre-determined level. Let τ denote the tariff level and assume

$$\tau < rI. \tag{15}$$

Whenever the final-good price falls below τ, all new producers are compensated for the difference $p - \tau$. We assume that the tariff cost is collected from the consumers in a non-distorting manner. The effect of the tariff on the equilibrium can be understood by

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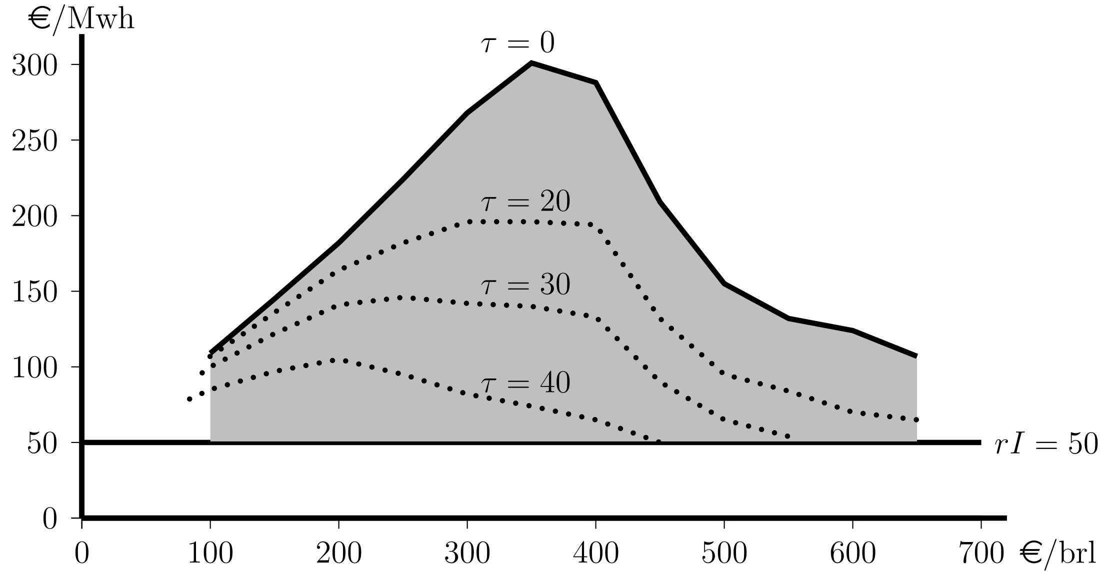
[38] For a discussion on existing subsidies in the EU, see European Commission (2005).

[39] The subsidy is collected from consumers as part of the electricity bill, explaining in part the popularity the instrument; the costs do not appear in the government budget (in contrast to direct subsidies).



.01	.35	.65	.86	.92	.93	$\kappa_{\tau=0}$
.01	.39	.71	.89	.94	.96	$\kappa_{\tau=20}$
.03	.43	.75	.92	.96	.98	$\kappa_{\tau=30}$
.07	.49	.81	.95	.99	.99	$\kappa_{\tau=40}$

Figure 13: Equilibrium price-cost margin at tariff levels $\tau = 0, 20, 30, 40$ €/Mwh, when $rI = 50$ and $\sigma = .2$. κ_τ=fraction of capacity replaced when tariff is τ (1=30 000 Mw).

studying a price floor of the form

$$P_L(\hat{x}_t) \geqslant \tau. \tag{16}$$

The tariff pre-determines the lowest sales price for an entering new capital unit and, therefore, it influences the riskiness of the environment to which the new technology enters. For τ sufficiently close to rI, the new technology faces practically no risk and, as a result, entry takes place whenever the market price reaches rI. On the other hand, when τ is sufficiently low, it can be below the lowest prices conceivable during some part of the transition, and then it does not essentially change our description of the demand change without the tariff. However, a tariff that is between these extreme levels —full elimination of uncertainty, or no change in uncertainty faced by new firms— it has interesting implications for the transition from the consumers' point of view.

We are interested in the effect of the tariff on the development of the price-cost markup that we have described for the case without a tariff. In addition, we wish to illustrate the total welfare loss as well as the division of the loss between consumers and producers. Since we have non-elastic (stochastic) demand, the change in consumer surplus is captured by the change in the total cost of procuring electricity for the consumers. Recall that demand D_i follows a stochastic process where the monthly demand is drawn from distribution F_i. For fixed k and x, the expected total annual cost of procuring the electricity needed to satisfy the demand is given by:

$$C(k,x) = H \cdot \frac{1}{M} \sum_{i=1}^{M} \int \Pi(i,x,D_i - k) \cdot D_i \cdot dF_i.$$

In addition to this cost, the consumers must also pay for the subsidies that accrue to the new capacity units through the feed-in tariff. At given k and x, the expected annual subsidy is:

$$S_\tau(k,x) = H \cdot \frac{1}{M} \sum_{i=1}^{M} \int \max\left[\tau; \Pi(i,x,D_i - k)\right] \cdot k \cdot dF_i.$$

The total expected cost for consumers with tariff τ calculated at an arbitrary t, x_t, and $\hat{x}_t$ is given by:

$$\mathbf{C}_\tau(x_t,\hat{x}_t) = \mathbb{E}\int_{s=t}^{\infty} e^{-r(s-t)}\left[C\left(\mathbf{k}_\tau(\hat{x}_s), x_s\right) + S_\tau\left(\mathbf{k}_\tau(\hat{x}_s), x_s\right)\right] ds.$$

The change in consumer surplus due to tariff τ is then given by:

$$\Delta_\tau \mathbf{C}(t) = \mathbf{C}_0(x_t,\hat{x}_t) - \mathbf{C}_\tau(x_t,\hat{x}_t).$$

Similarly, let $W(k,x)$ denote the expected annual profits accruing to the old capacity units at given k and x:

$$W(k,x) = H \cdot \frac{1}{M} \sum_{i=1}^{M} \int \left[\int_{q=k}^{D_i} \Pi(i,x,D_i - k) - \Pi(i,x,D_i - (k+q))dq\right] dF_i.$$

The total expected profits with tariff τ calculated at an arbtrary t, x_t, and $\hat{x}_t$ is

$$\mathbf{W}_\tau(x_t,\hat{x}_t) = \mathbb{E}\int_{s=t}^{\infty} e^{-r(s-t)} W\left(\mathbf{k}_\tau(\hat{x}_s), x_s\right) ds.$$

The change in producers' surplus due to tariff τ is then:

$$\Delta_\tau \mathbf{W}(t) = \mathbf{W}_0(x_t,\hat{x}_t) - \mathbf{W}_\tau(x_t,\hat{x}_t).$$

Finally, the change in the total surplus is given by:

$$\Delta_\tau \mathbf{C}^{soc}(t) = \Delta_\tau \mathbf{C}(t) + \Delta_\tau \mathbf{W}(t).$$

This is the social cost due to the distorted investment path that the tariff induces, calculated at some t.[40]

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[40] Note that the tariff is only one way of implementing a faster replacement of capital. We could choose any distorted capacity path such that $\widetilde{\mathbf{k}}(\hat{x}) \geq \mathbf{k}_0(\hat{x})$, and compute the implied subsidy from the requirement that the entrants make exactly zero expected profit with the subsidy.

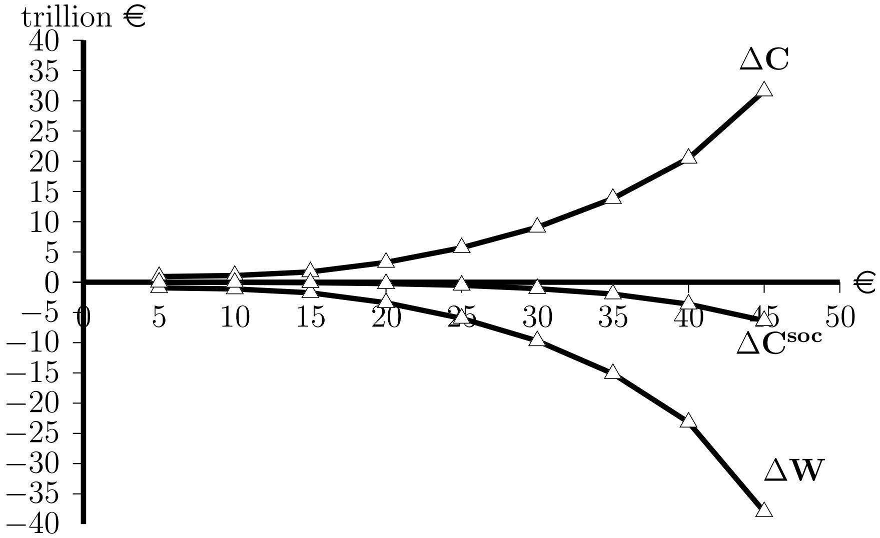

Figure 14: Consumers' gain ($\Delta\mathbf{C}$), producers' loss ($\Delta\mathbf{W}$), and the total welfare loss ($\Delta\mathbf{C^{soc}}$) for tariff levels $\tau = 5, 10, 15, ..., 45$. All expressions evaluated at the fuel price of the first entry when $\tau = 45$.

We examine first how the tariff changes the investment path and the development of the real-options mark-up. In Figure 13, we depict the equilibrium entry mark-up for different tariff levels when the investment cost and uncertainty are as in Figure 12 ($rI = 50, \sigma = .2$). In general, the tariff speeds up the replacement rate and lowers the entry output price at each level of the energy cost. The tariff of 20 €/Mwh has a relatively moderate effect on replacement speed, although the effect on peak output prices is significant. The highest tariff considered covers 4/5 of the investment cost. The price profile falls into the historical empirical support but, despite the large subsidy rate, the capital replacement still requires extremely high fuel prices (indicated by the numbers under the Figure).

Let us then consider the changes in the consumer surplus $\Delta_\tau \mathbf{C}$, the old producers' surplus $\Delta_\tau \mathbf{W}$, and the social loss $\Delta_\tau \mathbf{C}^{soc}$. In Figure 14 we depict these changes as a function of the tariff level $\tau = 5, 10, 15, ..., 45$. All expressions are calculated at $t = 0$, where $x_0 = \hat{x}_0$ is chosen to be the first entry point of the most front-loaded capacity path induced by the largest tariff $\tau = 45$.

The subsidization of new entry must obviously destroy a fraction of the rents of the existing production structure. However, the overall social loss is remarkably small relative to the transfers between consumers and producers, while the absolute sums are large (trillions €). The main result is that consumers can appropriate the old capital rents by destroying relatively little of the total surplus, even in the absence of un-modeled benefits of front-loading the investments.[41] The result emerges much stronger here than in equivalent static contexts because the investor caution and the implied protection of the old structure, a key determinant of surplus shares in the dynamic context, is very sensitive to subsidization.

To better understand the magnitudes, let us transform the consumers' gain to annuity, i.e., to a number that gives the annual average saving in the cost of procuring the electricity. Dividing this sum by the annual expected consumption indicates the reduction in the price of Megawatt/hour. This saving is $.2, .3, .5, ..., .5.6, 8.6$ € for tariff levels $\tau = 5, 10, 15, ...40, 45$, respectively. Thus, the largest saving, 8.6 €is about 17 per cent of the investment cost level $rI = 50$.

6 Concluding remarks

Our results is at the crossroad of several branches of the previous literature on energy costs. We conclude by discussing the potential extensions to the directions suggested by the literature.

There is a large literature on the exhaustible-resource nature of the energy commodity supply and the so called backstop technologies (for early papers, see Nordhaus 1973, Dasgupta and Heal 1974, Heal 1976; and for a later application, see, e.g., Chakravorty el al. 1997). This research casts the adoption problem in an exhaustible-resource framework without uncertainty. The models from the 70s typically feature a switch to the backstop as soon as the resource is physically or economically depleted. While such models are helpful in gauging the limits to resource prices using the backstop cost data (see the seminal work by Nordhaus), the predictions for the backstop technology entry are not entirely plausible if one accepts uncertainty and adjustment delays as characteristic features of the energy demand change.[42] However, while being less explicit about the

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[41] Consumers can find the tariff beneficial due to risk aversion that we have not explicitly modeled. The tariff can be seen as an insurance against extreme electricity prices. Yet another un-modeled reason for tariffs is an exogenous benefits from the decline in the energy input use (import dependence or pollution externalities).

[42] A more realistic approach to the energy demand change is described in Chakravorty et al. (1997) where the demand for exhaustible factors is heterogenous and backstop technologies such as solar energy have a declining trend in adoption costs. We provide a complementary and simpler approach to gradual energy demand technology transition, capturing similar features, but arising from Ricardian rents and

capital replacement on the demand side, the exhaustible-resource approach is needed for understanding the long-run supply of the energy resource commodities. The inclusion of the resource supply would be a step towards a general equilibrium description of the energy demand change.[43]

Yet another step towards general equilibrium relates to the macroeconomic effects of the energy demand change. Macroeconomists have found it puzzling that the oil prices have an aggregate effect despite the low cost share of oil in GDP (See, e.g., Barsky and Kilian (2004) and Hamilton (2008)). One potential explanation is that factor price changes are propagated through movements in other factor prices they induced. We believe our explanation for the consumer price increase is different from previously identified propagation channels but, as such, it cannot be used to explain the historical macroeconomic experiences. It would be valuable to have a quantitative assessment of the effects identified in this paper in a macroeconomic context.[44]

7 Proof of Proposition 1 (Supplementary material)

This proof builds on the myopia result explained in Section 4. We derive the stopping rule for a myopic investor when the aggregate capacity k is taken as given, and from this we derive the equilibrium path $k = \mathbf{k}(\hat{x})$ and its properties. Define

$$\begin{aligned}
\beta_1 &= \frac{1}{2} - \frac{(r-\delta)}{\sigma^2} + \sqrt{\left[\frac{(r-\delta)}{\sigma^2} - \frac{1}{2}\right]^2 + \frac{2r}{\sigma^2}} > 1, \\
\beta_2 &= \frac{1}{2} - \frac{(r-\delta)}{\sigma^2} - \sqrt{\left[\frac{(r-\delta)}{\sigma^2} - \frac{1}{2}\right]^2 + \frac{2r}{\sigma^2}} < 0.
\end{aligned}$$

Lemma 2 *Given the specification (4)-(6), the optimal cut-off rule for a myopic investor as defined in Lemma 1 is*

$$x^m(k) = \begin{cases} \frac{\delta\beta_1(B+C)}{rB(\beta_1-1)}\left(rI - \frac{AC}{B+C} + \frac{BC}{B+C}k\right) & \text{for } x \leq A - Bk \\ \left(-\frac{\beta_1(B+C)\left(\frac{A-Bk}{r} - I\right)}{(A-Bk)^{1-\beta_2}B\left(\frac{\beta_1}{r} + \frac{(1-\beta_1)}{\delta}\right)}\right)^{\frac{1}{\beta_2}} & \text{for } x > A - Bk. \end{cases} \tag{17}$$

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persistent uncertainty in the energy input supply.

[43] Pindyck (1978) characterizes the traditional Hotelling model under uncertainty.

[44] See Wei (2003) for a general equilibrium assessment of frictions in capital replacement under a putty-clay approach.

Proof. Given k, the revenue process for an existing new plant is defined by

$$\begin{aligned} P(x;k) &= \begin{cases} \frac{C(A-Bk)}{B+C} + \frac{B}{B+C}x, \text{ for } x \leq A - Bk \\ A - Bk, \text{ for } x > A - Bk \end{cases} \\ &= \begin{cases} Q(k) + Rx, \text{ for } x \leq A - Bk \\ A - Bk, \text{ for } x > A - Bk \end{cases} \end{aligned}$$

where we use the definitions

$$Q(k) = \frac{C(A-Bk)}{B+C}, R = \frac{B}{B+C}.$$

The value of an existing plant, denoted by $V(x;k)$, satisfies the following ordinary differential equation:

$$\frac{1}{2}\sigma^2 X^2 V''(x;k) + (r-\delta)xV'(x;k) - rV(x;k) + P(x;k) = 0,$$

where r is the discount rate, and $\delta = r - \alpha$. The general solution of the equation is

$$\begin{aligned} V(x;k) &= \begin{cases} V_0(x;k), \text{ for } x \leq A - Bk \\ V_+(x;k), \text{ for } x > A - Bk \end{cases} \\ &= \begin{cases} B_1^0 x^{\beta_1} + B_2^0 x^{\beta_2} + \frac{Q(k)}{r} + \frac{Rx}{\delta}, \text{ for } x \leq A - Bk \\ B_1^+ x^{\beta_1} + B_2^+ x^{\beta_2} + \frac{A-Bk}{r}, \text{ for } x > A - Bk. \end{cases} \end{aligned}$$

where

The two boundary conditions $\lim_{x \to 0^+} V(x;k) = \frac{Q(k)}{r}$ and $\lim_{x \to \infty} V(x;k) = \frac{A-Bk}{r}$ imply that $B_2^0 = 0$ and $B_1^+ = 0$. The two remaining parameters would be easily solved by requiring that the first and second derivatives of the value functions match at $x = A - Bk$.

Denote the value of the option to install such a plant by $F(x;k)$. This must satisfy the following differential equation:

$$\frac{1}{2}\sigma^2 X^2 F''(x;k) + (r-\delta)XF'(x;k) - rF(x;k) = 0,$$

which has the general solution

$$F(x;k) = C_1 x^{\beta_1} + C_2 x^{\beta_2}.$$

The boundary condition $\lim_{x \to 0^+} F(x;k) = 0$ implies that $C_2 = 0$. The problem is to find C_1 and the myopic investment treshold x^m. There are two possible cases that must be considered separately: (1) $x^m \leq A - Bk$, and (2) $x^m > A - Bk$.

The boundary conditions in case $x^m \leq A - Bk$ are (taking into account that $B_2^0 = 0$):

$$\begin{aligned} C_1 x^{\beta_1} &= B_1^0 x^{\beta_1} + \frac{Q}{r} + \frac{Rx}{\delta} - I \\ \beta_1 C_1 x^{\beta_1 - 1} &= \beta_1 B_1^0 x^{\beta_1 - 1} + \frac{R}{\delta}. \end{aligned}$$

The ceiling $A - Bk$ is irrevelant in this case, and one can solve variable $C_1 - B_1^0$ instead of C_1. To see this, write these equations as

$$\begin{aligned} \left(C_1 - B_1^0\right) x^{\beta_1} &= \frac{Q(k)}{r} + \frac{Rx}{\delta} - I, \\ \beta_1 \left(C_1 - B_1^0\right) x^{\beta_1 - 1} &= \frac{R}{\delta}. \end{aligned}$$

From these, we obtain the following linear relationship between x^m and k:

$$x^m = \frac{-\delta \beta_1 \left(\frac{Q(k)}{r} - I_r\right)}{R\left(\beta_1 - 1\right)} = \frac{\delta \beta_1 (B + C)}{rB(\beta_1 - 1)}(rI - \frac{AC}{B + C} + \frac{BC}{B + C}k). \tag{18}$$

The boundary conditions in case $x^m > A - Bk$ are

$$\begin{aligned} C_1 x^{\beta_1} &= B_2^+ x^{\beta_2} + \frac{A - Bk}{r} - I \\ \beta_1 C_1 x^{\beta_1 - 1} &= \beta_2 B_2^+ x^{\beta_2 - 1}. \end{aligned}$$

This implies that the investment trigger is given by the non-linear equation:

$$x^m = \left(- \frac{\beta_1 \left(B + C\right) \left(\frac{A - Bk}{r} - I\right)}{(A - Bk)^{1 - \beta_2} B \left(\frac{\beta_1}{r} + \frac{(1 - \beta_1)}{\delta}\right)} \right)^{\frac{1}{\beta_2}}.$$

■

For the properties of the equilibrium it is enough to focus on the case $x^m \leq A - Bk$. Let us now use the notation $\hat{x}$ for the equilibrium investment trigger which is defined by the myopic trigger $x^m(k)$. We can see from (17) that for $x^m \leq A - Bk$, the myopic investment trigger $x^m(k)$ defines the equilibrium capacity as a linear function of the current record $\hat{x}$

$$\mathbf{k}(\hat{x}) = \frac{r(\beta_1 - 1)}{\beta_1 \delta C} \hat{x} + \frac{AC - rI(B + C)}{BC}.$$

Let us now explain the role of volatility for the equilibrium description to apply. Recall that $\hat{x}^*$ is the equilibrium investment trigger at which $\hat{x}^* = x^m = P = A - Bk^*$. Using the formula for $x^m\,(k)$ as given in (18), we can solve k^* from

$$\frac{\delta \beta_1 (B + C)}{rB(\beta_1 - 1)}(rI - \frac{AC}{B + C} + \frac{BC}{B + C}k^*) = A - Bk^*, \tag{19}$$

which gives

$$\begin{aligned} k^* &= \frac{\beta_1(\delta AC + rAB - \delta rI(B+C)) - rAB}{B(\beta_1(rB+\delta C) - rB)}, \\ \hat{x}^* &= \frac{rI\delta\beta_1(B+C)}{\beta_1\delta C + rB(\beta_1 - 1)} \end{aligned}$$

where the latter equation is obtained by evaluating $x^m(k)$ at k^*. Consider now $k = 0$ and the condition (19). The ratio $\beta_1/(1-\beta_1)$ increases in σ monotonically so that the left-hand side of (19) exceeds the right-hand side even at $k = 0$. This would imply that the market must shut down before new entry can take place. There is therefore a unique σ^* such that equation (19) holds as equality when $k = 0$. For all $\sigma < \sigma^*$ we can find a strictly positive value for k^* and thus for $\hat{x}^*$.

The investment trigger in terms of output price is

$$P_H(\hat{x}) = \frac{C(A-Bk)}{B+C} + \frac{B}{B+C}\hat{x} = rI + \frac{\beta_1 B(\delta - r) + rB}{\beta_1\delta(B+C)}\hat{x} \text{ for } x \le \hat{x}^*.$$

We see that the price is increasing in $\hat{x}$, implying contraction of output for $x \le \hat{x}^*$. The price trigger is

$$P_H(\hat{x}) = A - B\mathbf{k}(\hat{x}) \text{ for } x > \hat{x}^*,$$

which is decreasing in $\hat{x}$. The output thus expands for $x > \hat{x}^*$.

The peak price follows by direct substitution

$$P_H(\hat{x}^*) = \frac{\beta_1\delta rI(B+C)}{\beta_1(rB+\delta C) - rB},$$

which is increasing in C and σ. When $C \to 0$, the myopic investment trigger approaches

$$x^m \to \frac{\delta\beta_1 B}{rB(\beta_1 - 1)}rI,$$

which is independent of k. Thus, once this trigger is reached, there is a discrete one-time jump in the capacity path. This completes the proof of the Proposition.

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