Capacity Investment and Market-Driven Price Caps in Electricity Markets

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Abstract

I build a continuous-time model of incremental capacity investment in electricity generation by a representative firm with stochastically evolving electricity prices and time-to-build. The model results in a "market-driven price cap" on electricity prices at pledged capacity. This cap is increasing in the cost of investment, time-to-build, volatility of electricity prices, and the market price of electricity price risk. The cap is decreasing the elasticity of demand. It is shown that investment only takes place when demand is elastic and that electricity prices can still increase substantially, even after new capacity has been pledged, due to construction delays. This opens up the possibility of welfare-increasing policy intervention.

Keywords: capacity investment, Price caps, Barrier control

JEL classification:

1 Introduction

Over the last couple of years there has been a fierce debate about rising energy prices. Several policies have been proposed to help households and firms with fast rising energy costs. A popular demand is for price caps to be brought in. Opponents argue that price caps will reduce incentives for firms to invest in additional capacity, which will, in the longer run, imply even higher prices and more unfulfilled demand.

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Here I build a simple model of capacity expansion under uncertainty, which is inspired by Dixit and Pindyck (1994, Section 11.1). An additional feature is the introduction of a time to build. This has been motivated by a recently re-surfaced video from 2010 of the then deputy prime minister of the UK, Nick Clegg, in which he argues against investment in additional nuclear power capacity,[1] "because it would only come on-stream by 2021 or 2022; so it's not even an answer."

In this paper, I argue that there is a natural price cap. This cap arises because of (energy) firms' investment in new capacity to take advantage of higher prices. This additional capacity will put a downward pressure on prices. However, this "market-driven cap", if one could call it that, is negatively affected (from a consumer's perspective) by several parameters, some of which can be influenced by the government. In particular the market-driven price cap is increasing in

1. the cost of investment,
2. the time-to-build of new capacity,
3. the volatility of energy prices,
4. the market price of energy-price risk.

2 A Simple Model of Capacity Investment

I build a simple stochastic dynamic partial equilibrium model of capacity investment in electricity-generating capacity by considering a representative firm. Electricity prices exhibit substantial fluctuations, which I will model using a latent variable that evolves stochastically over time. Let $E = (\ell, u) \subset \mathbb{R}$ be a connected set, which acts as the state space for this latent variable. In addition, consider two functions $\alpha : E \to \mathbb{R}$ and $\sigma : E \to \mathbb{R}_{++}$, such that

$$|\alpha(x)| + |\sigma(x)| \leq C(1 + |x|) \text{ for all } x \in E, \tag{1}$$

for some $C \in \mathbb{R}$.

Define a standard Brownian motion $W = (W_t)_{t \geq 0}$ on the canonical probability space $(\Omega, \mathscr{F}, \mathsf{P})$, i.e., $B_0 = 0$, P-a.s. Standard results in the literature guarantee that there exists a unique strong solution to the stochastic differential equation (SDE) and a family of probability measures $(\mathsf{P}_x)_{x \in E}$, absolutely continuous with respect to P, such that

$$\mathrm{d}X_t = \alpha(X_t)\mathrm{d}t + \sigma(X_t)\mathrm{d}W_t, \quad X_0 = 0\,(> 0), \ \mathsf{P}_x - \text{a.s.}. \tag{2}$$

[1] See `https://twitter.com/mlanetrain/status/1556381583585804291`.

The process $X = (X_t)_{t\geq 0}$ is a time-homogeneous It'=o diffusion starting at x under P_x. The expectation operator generated by P_x is denoted by E_x. We assume that the end-points of E are not reached P_x-a.s. The *characteristic operator* of X on $C^2(E)$ is given by

$$x \mapsto \mathscr{L}\varphi(x) := \frac{1}{2}\sigma^2(x)\varphi''(x) + \alpha(x)\varphi'(x).$$

For now I will make the common assumption that X follows a *geometric Brownian motion* (GBM) on $E = (0, \infty)$, with law of motion $\frac{\mathrm{d}X}{X} = \alpha \mathrm{d}t + \sigma \mathrm{d}W$, where $\alpha \in \mathbb{R}$ is the trend and $\sigma > 0$ is the volatility. Note that, for any $\delta > 0$, $\mathsf{E}_x[X_\delta] = xe^{\alpha\delta}$.

The electricity price is assumed to be affected by the stochastic process X as well as the total amount invested in capacity up to time t. The firm uses a production technology Q that transforms capital stock into output, i.e., the firm supplies $Q_t^s = Q(K_t)$, where $Q' > 0$ and $Q'' \leq 0$. At time t, the market price of electricity is equal to

$$P_t = P\big(X_t, Q(K_t)\big),$$

where I assume that

Assumption 1. P is homogeneous of degree 1 in X, with $P_X' > 0$, and $P_Q' < 0$.

That is, the stochastic shocks act in a way that is good for the firm's profitability, and energy is assumed to be a normal good. The firm's flow of revenues is then equal to,

$$R\big(X_t, K_t\big) := P\big(X_t, Q(K_t)\big)Q(K_t).$$

Note that, under Assumption 1, R is continuous, differentiable and homogeneous of degree 1 in X.

Two specifications that I will use in this paper are,

1. *iso-elastic demand*, $P(X, Q) = XQ^{-1/\varepsilon}$, $\varepsilon > 0$, with constant returns to scale $Q(K) = K$, so that $R(X, K) = XK^{1-1/\varepsilon}$, and
2. *linear demand*[2], $P(X, Q) = X - bQ$, $b > 0$, with constant returns to scale $Q(K) = K$, so that $R(X, K) = (X - bK)K$.

The representative firm has to decide on a capacity expansion schedule $I = (I_t)_{t\geq 0}$, which is assumed to be a non-negative, $\mathbf{F}$-adapted, and non-decreasing stochastic process. Investment in new capacity, $\mathrm{d}K$, is assumed to attract a proportional investment cost $\kappa > 0$. This cost can be thought

[2]This formulation has been been used by, e.g., Bigerna et al. (2019).

of as the levelized cost of energy (LCOE), i.e. it is the present value of *all* costs that this additional bit of capacity incurs over its life time. That life time is, for simplicity, assumed to be infinite.

To make the model more realistic, I assume that capacity that is decided on and paid for at time $t \geq 0$, only comes on stream after $\delta \geq 0$ periods. This drives a wedge between the time at which costs are incurred and uncertain revenues are received.

At any time $t \geq 0$, inverse demand P and production Q^s depend on capacity that has actually been installed, which I call *active capacity*. At $t = 0$, the active capacity stock is given by initial capacity $k > 0$, as well as investments that have been made in the time interval $[-\delta, 0)$. Therefore, the firm's capacity depends on the *history* of the firm's investment schedule. Let $I^0 = (I_t^0)_{t\in[-\delta,0)}$ denote that history. Combined with the firm's investment schedule $(I_t)_{t\geq 0}$, this means that the firm's active capacity at time $t \geq -\delta$ is

$$\begin{aligned} K_t &= k + \bar{I}_{t-\delta}, \quad t \geq 0 \\ &\equiv k + \begin{cases} I_t^0 & \text{if } t \in [-\delta, 0) \\ I_{0-}^0 + I_t & \text{if } t \geq 0. \end{cases} \end{aligned}$$

In order to value the firm's investment schedule, I assume that the risk in the firm's revenue stream, driven by the Brownian motion (W_t), can be replicated in financial markets by a risk-free bond with return $r > 0$ and a (portfolio of) risky asset(s) the price of which evolves according to the GBM

$$\frac{\mathrm{d}S}{S} = \mu_S \mathrm{d}t + \sigma_S \mathrm{d}W, \quad (\mu_S > r, \, \sigma_S > 0).$$

Here, μ_S denotes the total expected return on the risky asset, i.e. capacity gains augmented with the dividend rate. The stochastic discount factor that prices these assets follows the GBM (see, e.g., Cochrane, 2001),

$$\frac{\mathrm{d}\Lambda}{\Lambda} = -r\mathrm{d}t - h_S \mathrm{d}W, \quad \text{where} \quad h_S = \frac{\mu_S - r}{\sigma_S},$$

is the risky asset's *Sharpe ratio*.

The firm's problem can now be stated as follows: find the investment schedule I that maximizes the discounted expected stream of revenues net of the discounted stream of LCOEs. For a given investment schedule $I = (I_t)_{t\geq 0}$, the firm's present value is

$$F(x, k, I^0; I) \triangleq \mathrm{E}_x^{\mathrm{P}} \left[\int_0^\infty \Lambda_t \left\{ R(X_t, K_t)\mathrm{d}t - \kappa \mathrm{d}I_t \right\} \right].$$

A straightforward application of the Girsanov theorem shows that there exists a measure $\tilde{\mathsf{P}}$, equivalent to P, such that (cf., Thijssen, 2010)

$$F(x, k, I^0; I) = \tilde{\mathsf{E}}_x \left[\int_0^\infty e^{-rt} \{ R(X_t, K_t) \mathrm{d}t - \kappa \mathrm{d}I_t \} \right],$$

where, under $\tilde{\mathsf{P}}$,

$$\frac{dX}{X} = (r - \eta) \mathrm{d}t + \sigma \mathrm{d}\tilde{z}, \quad \eta = r + \sigma h_S - \alpha,$$

and $\tilde{W} = (\tilde{W}_t)_{t \geq 0}$ is a $\tilde{\mathsf{P}}$-Brownian motion. Note that η is the *net convenience yield*, or *rate of return shortfall*. In order for the problem to be economically meaningful, I assume that

Assumption 2. $\tilde{\mathsf{E}}_x \left[\int_0^\infty e^{-rt} |X_t| \right] < \infty$.

For the GBM case, this assumption is satisfied if, and only if, $\eta > 0$.

The firm's problem can, thus, be written as

$$F^*(x, k, I^0) = \sup_I F(x, k, I^0; I).$$

This is, in general, a difficult problem because of its dependence on the process I^0. However, following Aïd et al. (2015), it can be shown that the firm's value function can be split into two parts: one that depends on the history I^0 but not on the control I, and one that depends on the control I but not on the history I^0. The way to achieve this is by focusing on *pledged capacity*, rather than active capacity, the former being equal to

$$C_t := K_{t+\delta} = \underbrace{k + I^0_{0-}}_{=:c} + I_t, \quad t \geq 0.$$

Proposition 1. *For every investment policy I, the function F can be written as*

$$F(x, k, I^0; I) = J^0(x, k, I^0) + J(x, c; I),$$

where

$$J(x, c; I) = E_x \left[\int_0^\infty e^{-rt} \left\{ e^{-\eta\delta} R(X_t, C_t) - \kappa \mathrm{d}I_t \right\} \right],$$

and the function J^0 does not depend on the process I.

The first term of F is the value of capacity in place and the second term as the present value of future growth options.

Proof. The result follow from the Markov property of X and the fact that $\tilde{\mathsf{E}}_x[X_\delta] = xe^{(r-\eta)\delta}$:

$$
\begin{aligned}
F(k,x,I^0;I) =& \tilde{\mathsf{E}}_x\left[\int_0^\infty e^{-rt}\big\{R(X_t,k+\bar{I}_{t-\delta})\mathrm{d}t - \kappa \mathrm{d}I_t\big\}\right] \\
=& \tilde{\mathsf{E}}_x\left[\int_0^\delta e^{-rt}\big\{R(X_t,k+I^0_t)\mathrm{d}t - \kappa \mathrm{d}I_t\big\}\right] \\
&+ \tilde{\mathsf{E}}_x\Big[\int_\delta^\infty e^{-rt}\,\big\{R(X_t,k+I^0_{0-}+I_{t-\delta})\mathrm{d}t - \kappa \mathrm{d}I_t\big\}\Big] \\
=& \tilde{\mathsf{E}}_x\left[\int_0^\delta e^{-rt}\Big\{R(X_t,k+I^0_t)\mathrm{d}t - \kappa \mathrm{d}I_t\Big\}\right] \\
&+ \tilde{\mathsf{E}}_x\left[\int_\delta^\infty e^{-rt}\big\{R(X_t,c+I_{t-\delta})\mathrm{d}t - \kappa \mathrm{d}I_t\big\}\right] \\
=& \tilde{\mathsf{E}}_x\left[\int_0^\delta e^{-rt}\big\{R(X_t,k+I^0_t)\mathrm{d}t - \kappa \mathrm{d}I_t\big\}\right] \\
&+ \tilde{\mathsf{E}}_x\left[\int_0^\infty e^{-r(t+\delta)}\big\{R\big(X_{t+\delta},c+I_t\big)\mathrm{d}t - \kappa \mathrm{d}I_{t+\delta}\big\}\right] \\
\overset{(*)}{=}& \underbrace{\tilde{\mathsf{E}}_x\left[\int_0^\delta e^{-rt}\big\{R(X_t,k+I^0_t)\mathrm{d}t - \kappa \mathrm{d}I_t\big\}\right]}_{=:J^0(x,k,I^0)} \\
&+ \tilde{\mathsf{E}}_x\left[\int_0^\infty e^{-r(t+\delta)}\big\{R\big(\mathsf{E}_{X_t}[X_\delta],C_t\big)\mathrm{d}t - \kappa \mathrm{d}I_t\big\}\right] \\
\overset{(*)}{=}& J^0(x,k,I^0) + \tilde{\mathsf{E}}_x\left[\int_0^\infty e^{-r(t+\delta)}\big\{e^{(r-\eta)\delta}R\big(X_t,C_t\big)\mathrm{d}t - \kappa \mathrm{d}I_t\big\}\right] \\
=& J^0(x,k,I^0) + J(x,c;I),
\end{aligned}
$$

where both $(*)$ and $(**)$ follow from Assumption 1 (homogeneity of degree 1 of R in x). ■

From this proposition it follows that past investments do influence the firm's value, but not its optimal investment schedule going forward. Hence, we will focus on the problem

$$
J^*(x,c) := \sup_I J(x,c;I) = \sup_I \mathsf{E}_x\left[\int_0^\infty e^{-rt}\,\big\{e^{-\eta\delta}R(X_t,C_t) - \kappa \mathrm{d}I_t\big\}\right],
$$

The capacity investment taking place at time t only starts generating revenues at $t+\delta$, which leads to extra discounting, net of the expected growth in prices, over that time interval. Note, however, that this expected growth is tempered by the market price of energy price risk (h_S) and the volatility of electricity prices (σ). Therefore, any time-to-build effect is amplified by price volatility.

Given the assumptions made, a classical solution $J^* \in C^2(E)$ can be found via a standard verification argument. Let $\varphi \in C^2(E)$ and $\psi \in C^2(E)$ be the unique increasing and decreasing solutions, respectively, to the differential equation $\mathscr{A}f - rf = 0$, with boundary conditions

$$
\lim_{x\downarrow \ell}\varphi(x) = 0, \quad \text{and} \quad \lim_{x\uparrow u}\psi(x) = 0,
$$

respectively. For GBM, these solutions are

$$\varphi(x) = x^{\beta_1}, \quad \text{and} \quad \psi(x) = x^{\beta_2},$$

respectively, where $\beta_1 > 1$ and $\beta_2 < 0$ are the roots of the quadratic equation $\mathscr{Q}(\beta) = 0$, where

$$\beta \mapsto \mathscr{Q}(\beta) := \frac{1}{2}\sigma^2\beta(\beta - 1) + (r - \eta)\beta - r.$$

The final ingredient that is needed is the present value of revenues at a given, and constant, capacity level, i.e.,

$$\mathscr{R}(x, k) := \tilde{\mathsf{E}}_x\left[\int_0^\infty e^{-rt}R(X_t, k)\mathrm{d}t\right] \ (< \infty),$$

where finiteness follows from Assumptions 1 and 2. For our examples, we get the following:

1. *iso-elastic demand* if $P = XQ^{-1/\varepsilon}$, then
$$\mathscr{R}(x, k) = \frac{x}{\eta}k^{1-1/\varepsilon};$$
2. *linear demand* if $P = X - bk$, then
$$\mathscr{R}(x, k) = \frac{x}{\eta}c - 2\frac{b}{r}c^2.$$

Now consider the candidate solution

$$J^*(x, c) = e^{-\eta\delta}\mathscr{R}(x, c) + A(c)\varphi(x) + B(c)\psi(x).$$

Due to Assumption 1 (homogeneity of degree 1 of P) it holds that $J^* \in C^2(E)$.

As usual, the boundary condition $\lim_{x\downarrow\ell} J^*(x, c) = 0$ is imposed, so that $B(c) = 0$ for all $c > 0$. Hence,

$$J^*(x, c) = e^{-\eta\delta}\mathscr{R}(x, c) + A(c)\varphi(x).$$

Furthermore, when the firm expands capacity, that capacity's marginal value must equal its marginal cost, i.e.,

$$J^*_c(x, c) = \kappa \iff e^{-\eta\delta}\mathscr{R}'_c(x, c) + A'(c)\varphi(x) = \kappa.$$

Furthermore, the timing of the capacity expansion must be optimal, i.e.,

$$\begin{aligned} J^*_{cx}(x, c) = 0 &\iff e^{-\eta\delta}\mathscr{R}''_{cx}(x, c) + A'(c)\varphi'(x) \\ &\iff A'(c) = -e^{-\eta\delta}\frac{1}{\varphi'(x)}. \end{aligned}$$

Substituting this back into the condition $J^*_c(x, c) = \kappa$, we find the optimal trigger $c \mapsto X^*(c)$ for capacity expansion through the implicit equation:

$$\mathscr{R}'_c\big(X^*(c), c\big) - \mathscr{R}''_{cx}\big(X^*(c), c\big)\frac{\varphi\big(X^*(c)\big)}{\varphi'\big(X^*(c)\big)} = \kappa e^{\eta\delta}. \tag{3}$$

For the GBM-case, it holds that

$$\frac{\varphi(x)}{\varphi'(x)} = \frac{x}{\beta_1}.$$

In addition, because of Assumption 1, there exist differentiable mappings $c \mapsto f(c) > 0$ and $c \mapsto g(c)$, such that

$$R(x, c) = xf(c) + g(c),$$

from which it follows that

$$\mathscr{R}(x, c) = \frac{x}{\eta}f(c) + \frac{g(c)}{r}.$$

Therefore, the investment trigger can be solved for explicitly:

$$X^*(c) = \frac{\beta_1}{\beta_1 - 1}\frac{\eta}{f'(c)}\left(\kappa e^{\eta\delta} - \frac{g'(c)}{r}\right). \tag{4}$$

Thus, if currently pledged capacity is c, then the firm invests if the shift variable X exceeds the trigger $X^*(c)$. Then, a flow of additional capacity is pledged that keeps X on the curve $c \mapsto X^*(c)$. Note that this policy only makes sense if for all $c > 0$ it holds that $X^*(c) > 0$, i.e. if

$$\frac{\kappa e^{\eta\delta} - g'(c)/r}{f'(c)} > 0 \iff \begin{cases} \kappa > \frac{g'(c)}{r}e^{-\eta\delta} & \text{if } f'(c) > 0 \\ \kappa < \frac{g'(c)}{r}e^{-\eta\delta} & \text{if } f'(c) < 0. \end{cases}$$

For example, in the linear demand case, $P(x, k) = x - bk$, it holds that

$$X^*(c) = \frac{\beta_1\eta}{\beta_1 - 1}\left(\kappa e^{\eta\delta} + 2b\frac{c}{r}\right).$$

In terms of the market price this trigger can be written as

$$P^*(c) := X^*(c) - 2bc = \frac{\beta_1\eta}{\beta_1 - 1}\left(\kappa e^{\eta\delta} + 2bc\left\{\frac{1}{r} - \frac{\beta_1 - 1}{\beta_1\eta}\right\}\right).$$

Since

$$0 < \frac{1}{2}\sigma^2\beta_1(\beta_1 - 1) = r - (r - \eta)\beta_1,$$

it follows that

$$\beta_1\eta > r(\beta_1 - 1) \iff \frac{1}{r} > \frac{\beta_1 - 1}{\beta_1\eta},$$

so that the price trigger is increasing in c. That is, the more capacity has been pledged, the higher the electricity price needs to be to warrant further investment.

3 Iso-elastic demand and constant returns to scale

Suppose that the demand function is iso-elastic and that the production technology exhibits constant returns, i.e., that

$$P(X,Q) = XQ^{-1/\varepsilon}, \quad (\varepsilon > 0), \quad \text{and} \quad Q(K) = \theta K, \quad (\theta > 0),$$

then the trigger in terms of the market price is constant, i.e.,

$$P^* = \frac{\beta_1}{\beta_1 - 1}\frac{\varepsilon}{\varepsilon - 1}\frac{\eta}{\theta}\kappa e^{\eta\delta}.$$

There are several parameters that influence the trigger. For example, the trigger is higher in markets where demand is less elastic (i.e. for lower ε). Energy markets typically have fairly low levels of demand elasticity, so that the trigger can be quite high.

Secondly, if electricity price volatility (σ) and/or the market price of risk (h_S) are high, then so will be the trigger. Firms need to be sure enough that they will recoup investments and this requires a higher price. This effect is amplified by the time-to-build (δ). For energy projects, this delay is often substantial and this has, thus, an important effect on the trigger. This also shows that smaller projects that are quicker to build, attract investment for lower (expected) prices.

Note that σ also has another, indirect, effect on the trigger via β_1. An increase in σ increases the option value of waiting via a direct increase in β_1. However, it also decreases α, which, in turn, further increases β_1. An increase in β_1, in turn, leads to an increase in P^*.

Note that $P^* > 0$ only if $\varepsilon > 1$. That is, capacity expansion only takes place in markets with elastic demand. Electricity markets are typically characterized by inelastic demand. Based on estimated price elasticities for domestic and industrial demand reported in Csereklyei (2020) and the composition of demand as observed in the UK (DfES&NZ, 2023), a reasonable estimate for the UK is $\varepsilon = 0.77$. A potential way to make investment in electricity-generating capacity economical might be to introduce a subsidy, possibly dependent on capacity, so that the LCOE of capacity expansion becomes $Q^s \mapsto \kappa(Q^s)$. In that case, the optimal trigger becomes

$$P^* = \frac{\beta_1}{\beta_1 - 1}\frac{\varepsilon}{\varepsilon - 1}\frac{\eta}{\theta}e^{\eta\delta}\kappa'(Q^s).$$

If $\varepsilon \in (0,1)$, then this trigger is positive only if the marginal cost of installing a unit of capacity, i.e. the LCOE, is negative. That is, someone else rather than the firm should pick up the tap.

Alternatively, the firm could be given a *price mark-up*, say $Q^{\chi-1}$ ($\chi > 0$), so that the revenue of producing Q units at time t becomes $X_t Q^{1+\chi-1/\varepsilon}$. The trigger then equals

$$P^* = \frac{\beta_1}{\beta_1 - 1} \frac{\varepsilon}{\varepsilon\chi - 1} \frac{\eta\kappa}{\theta} e^{\eta\delta},$$

so that

$$P^* > 0 \iff \chi - 1 > \frac{1-\varepsilon}{\varepsilon}.$$

To illustrate the model, I simulate a sample path for X and record the corresponding sample paths for pledged and active capacity, as well as for the market price at pledged and active capacity levels. The parameter values used are given in Table 1. I assume here that the risk in investing in electricity generation is spanned by a risk-free asset and the S&P500. For this base-case it holds that $P^* \approx 130$. Note that $\beta_1 \approx 14.15$, so that option values of waiting are very high. While volatility is quite low at 11%, this is more than offset by a high rate of return shortfall $\eta = 12.6\%$. Assuming that the current price is $P_0 = 110$/MWh, simulated price paths at pledged and active capacity can be found in Figure 1. Corresponding capacity levels can be seen in Figure 2.

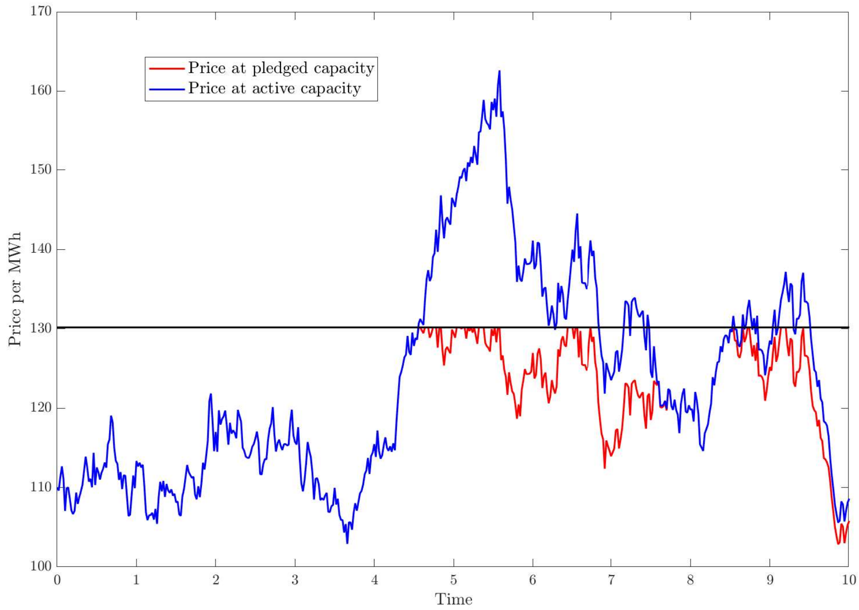

Figure 1: Simulated sample paths of market prices at active capacity (blue line) and pledged capacity (red line).

Parameter	Symbol	Value	source
Spot price growth rate	α	-3.5%	own calculation
			(data from DfES&NZ, 2023)
Spot price volatility	σ	25%	own calculation
			(data from DfES&NZ, 2023)
LCOE of investment	κ	€90 mn	Compernolle et al. (2022)
Current active capacity	K_0	75.3TW	DfES&NZ (2023)
Demand elasticity	ε	0.77	own calculation (data from
			DfES&NZ, 2023 and Csereklyei, 2020)
Price mark-up	χ	1.37	assumed
Current pledged capacity	C_0	75.3TW	assumed
Risk-free rate	r	3.5%	`worldgovernmentbonds.com`
			(accessed 16/6/23)
Sharpe ratio S&P500	h_S	0.64	`curveo.eu` (accessed 16/6/23)
Construction delay	δ	1 year	assumed

Table 1: Parameter values for base-case analysis. [Note: the risk-free rate is taken to be the yield on a 1-year UK Government Bond.]

Market prices and time-to-build

The market price at which capacity is expanded is given in terms of *pledged* capacity. That is, the firm predicts the price it gets at the time that the new capacity becomes productive. Hence, there is a cap on the price commanded by pledged capacity. This does not, of course, imply that there is a cap on the price commanded by *active* capacity. This is clearly visible in Figure 1.

In fact, the actual market price can increase unboundedly during the time-to-build of newly-pledged capacity. For example, suppose that the barrier P^* is hit at a time t at which $C_t = K_t$. This implies that no new capacity will become active during the interval $[t, t+\delta)$. Consequently, $\mathrm{d}P = \mathrm{d}X$ on this time interval. From the general properties of the log-normal distribution it then follows that at time t for $h \in [t, t+\delta)$, a 95% prediction interval of the electricity spot price is given by

$$P^* e^{\alpha h} \pm 1.96 P^* e^{\alpha h} \sqrt{\exp(\sigma^2 h) - 1}.$$

For the base-case parameters these "worst-case" prediction intervals are plotted in Figure 3. As can

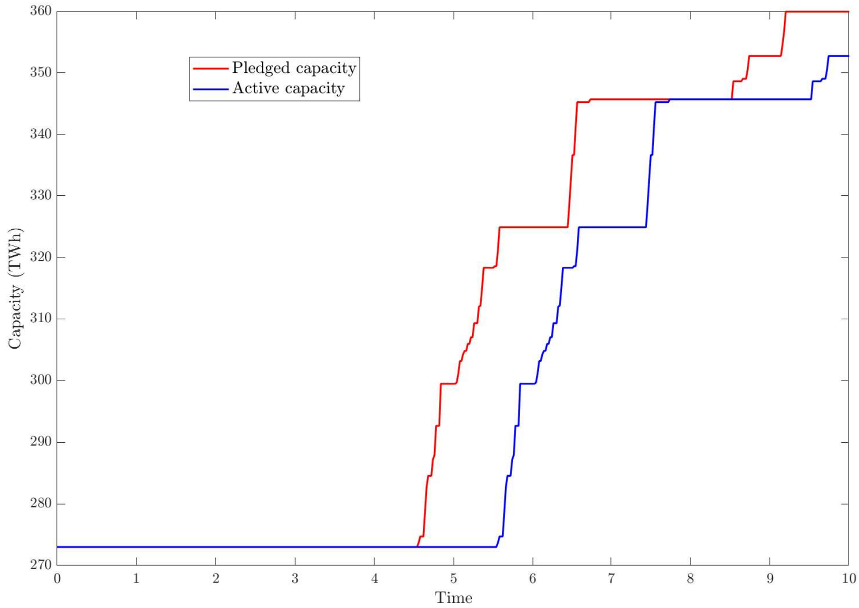

Figure 2: Simulated sample paths of active capacity (blue line) and pledged capacity (red line).

be seen, *actual* prices can continue to rise substantially even after new capacity has been pledged.

Investment and taxes

Finally, corporate tax rates have no influence on the optimal policy, as long as investment costs and losses can be offset against (future) revenues. Suppose that corporate income is taxed at a rate $\tau \in [0,1)$. Then the firm's value problem becomes

$$\begin{aligned} J^*(x,c) &= \sup_I \tilde{\mathsf{E}}_x \left[\int_0^\infty e^{-rt} \left\{ (1-\tau) e^{-\eta\delta} R(X_t, C_t) \mathrm{d}t - (1-\tau)\kappa \mathrm{d}I_t \right\} \right] \\ &= (1-\tau) \sup_I \tilde{\mathsf{E}}_x \left[\int_0^\infty e^{-rt} \left\{ e^{-\eta\delta} R(X_t, C_t) \mathrm{d}t - \kappa \mathrm{d}I_t \right\} \right]. \end{aligned}$$

So, while taxes reduce the firm's value, it does not influence its investment decisions. This result only holds, of course, for all-equity firms. With (part-) debt financing, a tax shield is created, which would make the optimal investment schedule tax-dependent.

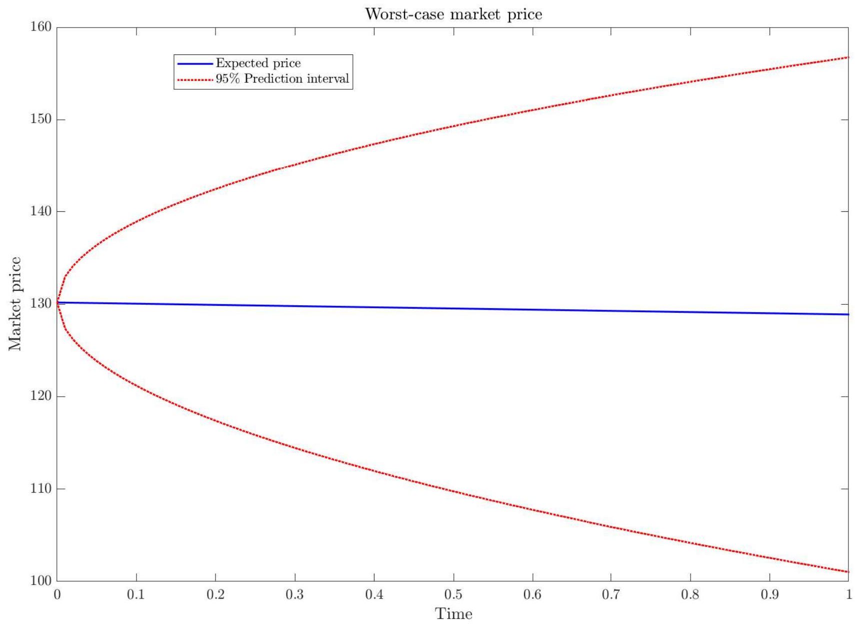

Figure 3: 95% prediction intervals of market prices over the time-to-build when $K_0 = C_0$ and $P_0 = P^*$ for the base-case parameter values.

4 Concluding Remarks

In order to keep electricity prices low under increasing demand, more capacity is obviously needed. Under uncertain future demand and construction lead times, firms are more cautious and invest in additional capacity later. Another consequence of construction lead times is that during the lag prices can increase substantially.

Another potential problem with capacity investment is that such is only optimal if demand is sufficiently elastic. Electricity demand is, however, typically inelastic and this suggests that there is room for welfare enhancing policy interventions. Such interventions could take the form of a subsidy on the investment cost, although these would have to be unrealistically high. The most effective measures would make the firm *as if* demand is, in fact, elastic.

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