Graduate School of Business
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To: NYU Accounting Summer Camp participants
Re: My talk on **Levelized Product Cost and the Market for Solar PV Modules**
From: Stefan Reichelstein

My apologies for the "double pack" in reading materials. The first paper presents a model which is then put to use in the context of the solar PV modules industry. I intend to spend at least half an hour of my presentation on the industry study.

Levelized Product Cost: Concept and Decision Relevance

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Abstract:
This paper examines a life-cycle cost concept that applies to both manufacturing and service industries in which upfront capacity investments are essential. Borrowing from the energy literature, we refer to this cost measure as the levelized product cost (LC). Per unit of output, the levelized cost aggregates a share of the initial capacity investment with periodic fixed- and variable operating costs. We relate this cost measure to the notion of full cost, as commonly calculated in managerial accounting. Our analysis identifies conditions under which the LC can be interpreted as the long-run marginal product cost. In particular, the LC is shown to be the relevant unit cost that firms should impute for investments in productive capacity.

1 Introduction

In many industries, the delivery of products and services requires upfront capacity investments. Examples include traditional manufacturing settings as well as service oriented businesses. From both a managerial accounting and a microeconomic perspective, a fundamental question is how to aggregate upfront expenditures for productive capacity with periodic operating expenditures to obtain a measure of cost for predicting product prices and capacity investment decisions.

The central concept analyzed in this article is the *Levelized Product Cost* (LC). Borrowing from the electricity literature, which coined the term Levelized Cost of Electricity, this concept is a formalization of the following verbal definition: "*the levelized cost of electricity is the constant dollar electricity price that would be required over the life of the plant to cover all operating expenses, payment of debt and accrued interest on initial project expenses, and the payment of an acceptable return to investors*" (MIT 2007).[1] The most common use of the levelized cost metric in connection with electricity is to compare the cost competitiveness of alternative generation technologies, e.g., coal-fired power plants versus wind energy. We note that the levelized cost is defined entirely in terms of cash flows and calibrated as the minimum price that investors would have to receive on average to break-even.[2]

Despite the centrality of the marginal cost concept in economics, the identification and measurement of long-run marginal cost remains controversial for industries in which firms need to make irreversible upfront capacity investments (Pittman 2009; Carlton and Perloff 2005). The principal issue is that in general, the cost of acquiring one unit of capacity is inherently a joint cost that must be apportioned among the units of output that can be produced in subsequent periods.[3] In idealized settings characterized by certainty and a stationary environment, one may postulate that the long-run marginal cost must be the price

[1]Variations of the levelized cost concept have also been used in connection with pharmaceutical products (Grabowski and Vernon 1990).

[2]The LC concept is naturally related to the notion of life cycle costing in the cost accounting literature; see, for instance, Horngren, Datar, and Rajan (2012) and Atkinson, Kaplan, Matsumura, and Young (2011). The common perspective in these textbooks is that to be profitable in the long-run, product revenues must cover all applicable costs, including the initial R&D. In contrast, our LC concept is concerned with the cost of delivering a good or service for a specific technology.

[3]In the industrial organization literature, some studies have circumvented this issue by postulating that capacity can be acquired on a rental basis in a competitive market; see, for instance, Carlton and Perloff (2005) and Rogerson (2008).

that emerges in equilibrium for a competitive industry. This criterion allows us to equate the levelized cost with the long-run marginal cost. The presence of capacity constraints will prevent prices from being bid down to the short-run marginal (variable) cost of production, even in a competitive market.

The joint cost issue that arises from a common upfront capacity expenditure becomes even more challenging under conditions of uncertainty where the available capacity may subsequently be idled in unfavorable states of the world. Given the break-even conceptualization of the levelized cost, one might expect that in a competitive market with price taking firms, the equilibrium price will "on average" equal the levelized cost. We demonstrate that in a competitive equilibrium, the present value of future expected market prices is equal to the annuity value of the levelized product cost, where the annuity is taken over the life-cycle of the productive facility. Furthermore, in a stationary environment, where market demand and production costs do not change over time, the expected equilibrium price will be equal to the levelized product cost in each period.

The aggregate capacity level in equilibrium is shown to depend on the degree of price volatility in the product market. Our notion of *limited* price volatility is that the maximal percentage deviation from the average market price (holding quantity fixed) should not exceed the ratio of the short-run marginal cost to the LC. This condition is more likely to be satisfied in industries where capacity related costs and fixed operating costs account for a relatively large share of the overall LC. With limited price volatility, firms in the industry will in equilibrium always deploy the entire available capacity, even for unfavorable shocks to market demand, and the aggregate capacity level will correspond to the expected demand at the market price corresponding to the LC.

With *significant* price volatility, the aggregate capacity in equilibrium will be *larger* than that obtained in a setting with limited volatility. While this finding may seem counterintuitive at first glance, the argument is that firms retain the option of idling parts of that capacity in subsequent periods when unfavorable market conditions prevail. Only that portion of the LC that corresponds to the capacity cost is a sunk cost. Since the market price will not fall below the short-run marginal cost, that is, the unit variable cost of production, the payoff structure associated with a capacity investment for firms effectively looks like a call option and this option becomes more valuable with significant price volatility.[4]

[4]The general idea that capacity investments have option value is also a main feature in the studies of Meyer (1975), Pindyck (1988), Isik, Coble, Hudson, and House (2003), Dangl (1999), and Göx (2002).

Managerial accounting textbooks, such as Horngren, Datar, and Rajan (2012) or Zimmerman (2010), seek to identify the costs that are relevant for particular decisions. For short-run decisions, like product pricing, these textbooks advocate the use of *incremental costs* which typically exclude fixed costs but include variable cost and applicable opportunity costs. For long-run decisions, such as investments in plant, property and equipment, accounting textbooks generally do not advocate a unit-based measure of relevant cost, but instead defer to the standard corporate finance approach of evaluating the stream of discounted cash flows associated with a particular investment.[5] We identify conditions under which the levelized product cost is the relevant unit cost for capacity investment decisions. Specifically, for a firm with monopoly power in a stationary product market, the optimal capacity level must satisfy the condition that the *expected* marginal revenue of output in each period, chosen in a sequentially optimal fashion given the initial capacity constraint, is equal to the levelized product cost.

Analogous to the competitive scenario, the optimal level of capacity will depend on whether the product market exhibits limited or significant price volatility. Ceteris paribus, a higher degree of volatility increases the option value associated with capacity, thus leading to larger investments in a monopoly setting. The capacity level at which the expected marginal revenue in each period is equal to the LC constitutes a lower bound for the optimal level of capacity investment. One obtains a corresponding upper bound by imputing the *levelized fixed cost*, defined as the LC less the unit variable cost of production. This bound again reflects that the variable cost portion of the LC is not a sunk cost in subsequent periods.

The pattern of results we obtain for competitive industries and monopolies extends to oligopolistic competition. In particular, we analyze a setting in which two firms, given their short-run marginal production costs and the constraints imposed by their initial capacity choices, choose their output levels in a standard Cournot fashion in each period. For the first-stage capacity decisions, it is then a (subgame perfect) Nash equilibrium outcome for each firm to choose a capacity level at which the expected marginal revenue of output in each subsequent period equals the LC.

The equilibria emerging in our analysis involve a single round of capacity investments.

[5]As a notable exception, Küpper (1985; 2009) advocates for cost accounting to provide cost metrics that can be used for investment decisions. To that end, Küpper (2009) demonstrates the usefulness of an accrual-based cost metric in the context of long-term decision problems, including production planning and the identification of price floors for individual products.

This stands in contrast to the recent studies by Rogerson (2008), Rajan and Reichelstein (2009), Nezlobin (2012), and Nezlobin, Rajan, and Reichelstein (2012), in which firms undertake a sequence of overlapping capacity investments in an infinite horizon setting. Furthermore, these models assume that market demand expands monotonically over time and there are no periodic price shocks. As a consequence, firms never find themselves having excess capacity. Our setting is motivated by the observation that in many settings of interest, initial capacity investments will turn out to be excessive in later periods for unfavorable realizations of market demand.[6]

From a cost accounting perspective, it is interesting to relate the levelized cost to the full cost for a product. In the context of our model, the latter unit cost measure typically comprises variable production costs, periodic fixed costs incurred on a cash basis, and depreciation charges. By construction, this measure of full cost will change over time depending on the applicable depreciation schedule. Provided the depreciation charges are properly matched with the asset's remaining productive capacity (see Rogerson 2008, 2011), the full cost in each period will also be equal to the levelized product cost. This alignment of the two cost measures, though, requires capacity related expenditures to recognize not only the depreciation expense, but also imputed interest charges on the remaining book value of the capacity generating assets.

The main issues we explore are also directly related to a branch of the managerial accounting literature that has sought to provide a rationale for full cost pricing (e.g., Banker and Hughes 1994, Balakrishnan and Sivaramakrishnan 2002, Göx 2002, Banker, Hwang, and Mishra 2002). These studies conclude that the sufficiency of full cost for product pricing depends on several conditions, including the timing of the pricing decision relative to the point in time when the firm commits to capacity resources. Other conditions include whether capacity constraints are "soft" and whether firms learn additional information about the product market after deciding on capacity levels. While our findings are broadly consistent with those in the full cost pricing literature, the focus of our analysis is on the identification of a unit cost measure that provides the relevant cost measure for capacity investments. The initial capacity choices must, of course, anticipate the pricing of the product in response to subsequent market conditions, including the overall capacity level available in the industry.

[6]Baldenius, Nezlobin, and Vaysman (2014) examine goal congruent performance measures in settings where it may be optimal to leave previously acquired capacity idle in unfavorable states of the world and managers are given incentives to do so.

Our findings show that the expected product prices are equal to the levelized product cost plus a mark-up that varies with the extent of competition in the industry. In particular, the average mark-up on levelized cost decreases with the number of competitors in the industry and converges to zero under atomistic competition.

The article proceeds as follows. Section 2 formalizes the Levelized Product Cost (LC) concept and establishes how it relates to traditional measures of full- and long-run marginal cost. Section 3 analyzes the equilibrium price and aggregate capacity level in a competitive market setting with price-taking firms. Section 4 considers a market structure with price-setting firms, in particular monopoly and duopoly. Conclusions are provided in Section 5, and proofs are relegated to the Appendix.

2 Levelized Product Cost

The levelized cost of a product or service identifies a per unit revenue figure that an investor in a particular production facility would need to obtain in order to break-even. Thus, the levelized cost of one unit of output aggregates the upfront capacity investment, the sequence of output levels generated by the facility over its useful life, the periodic operating costs required to deliver output in each period, and any tax-related cash flows.[7]

Investment in the production facility may entail economies of scale. In particular, $v(k)$ denotes the cost of installing k units capacity. We normalize units so that one unit of capacity can produce one unit of output in the initial year of operation.[8] The useful life of the output generating facility (in years) is T. In certain contexts, the output available from the initial capacity acquisition may change over time.[9] We denote by x_t the capacity decline factor, that is, the percentage of initial capacity that is functional in year t. Production in year t

[7] In the electricity literature, some authors have conceptualized the Levelized Cost as the ratio of "total lifetime cost" to "total lifetime electricity produced" (Campbell 2008). This turns out to be generally incompatible with the notion of an adequate investment return, unless both the numerator and the denominator are adjusted to properly reflect both taxes and the time value of money.

[8] A table that lists all the variables on our model can be found in the Appendix.

[9] For instance, with photovoltaic solar cells it has been observed that their efficiency diminishes over time. The corresponding decay is usually represented as a constant percentage factor, that is, $x_t = x^{t-1}$ with $x \leq 1$, where x varies with the particular technology (Reichelstein and Yorston 2013). On the other hand, production processes requiring chemical balancing frequently exhibit yield improvements over time due to learning-by-doing effects, e.g., semiconductors and biochemical production processes. We note that our model abstracts from any price level changes.

is then limited to $q_t \leq x_t \cdot k$. The analysis in this paper will pay particular attention to the "one-hoss shay" asset productivity scenario, in which the facility has undiminished capacity throughout its useful life, that is $x_t = 1$ for all $1 \leq t \leq T$ and thereafter the facility becomes obsolete (Laffont and Tirole 2000; Rogerson 2011).

The unit cost of installed capacity, $v(k)$, represents a joint cost of acquiring one unit of capacity for T years. We denote the applicable cost of capital by r and and the corresponding discount factor by $\gamma \equiv \frac{1}{1+r}$. The cost of capital can be interpreted as a weighted average of the cost of equity and debt (WACC). Throughout our analysis, r is treated as exogenous and fixed. In order to obtain *the cost of capacity for one unit of output*, the joint cost $v(k)$ will be divided by the present value term $\sum_{t=1}^{T} x_t \cdot \gamma^t$ and the units of capacity installed, k:

$$c(k) = \frac{v(k)}{k \cdot \sum_{t=1}^{T} x_t \cdot \gamma^t}. \tag{1}$$

We shall refer to $c(k)$ as the *unit cost of capacity*. Absent any other operating costs or taxes, $c(k)$ would yield the break-even price identified in the verbal definition above. To illustrate, suppose the firm makes an initial capacity investment of $v(k)$ and therefore has the capacity to deliver $q_t = x_t \cdot k$ units of product in year t. If the revenue per unit is p, then revenue in year t would be $p \cdot x_t \cdot k$ and the firm would exactly break even on its initial investment over the T-year horizon.[10]

In addition to the initial investment expenditure $v(k)$, the firm may incur periodic fixed operating costs. The notation, $F_t(k)$, indicates that the magnitude of these costs may vary with the scale of the initial capacity investment. Applicable examples here include insurance, maintenance expenditures, and property taxes. Unless otherwise indicated, we assume that the firm will incur the fixed operating cost $F_t(k)$ regardless of the output level q_t it produces in period t.[11] The initial investment in capacity triggers a stream of future fixed costs and a corresponding stream of future (expected) output levels. By taking the ratio of these, we obtain the following time-averaged fixed operating costs per unit of output:

[10]Throughout this section, it will be assumed that the available capacity is fully exhausted in each period, that is $q_t = x_t \cdot k$. This specification will no longer apply in Sections 3 and 4, where uncertainty and demand shocks are introduced.

[11]We will also consider an alternative scenario wherein the cost $F_t(k)$ is incurred only if $q_t > 0$. Thus, the firm can *avoid* the fixed operating cost $F_t(k)$ in period t if it idles the production facility in that period.

$$f(k) \equiv \frac{\sum_{t=1}^{T} F_t(k) \cdot \gamma^t}{k \cdot \sum_{t=1}^{T} x_t \cdot \gamma^t}. \tag{2}$$

With regard to variable production costs, we assume a constant returns to scale technology in the short run, so that the variable costs per unit of production up to the capacity limit are constant in each period, though they may vary over time. The periodic variable costs are denoted by w_t. We again define the time-averaged unit variable cost by:

$$w \equiv \frac{\sum_{t=1}^{T} w_t \cdot x_t \cdot k \cdot \gamma^t}{k \cdot \sum_{t=1}^{T} x_t \cdot \gamma^t}. \tag{3}$$

Corporate income taxes affect the levelized cost measure through depreciation tax shields and debt tax shields, as both interest payments on debt and depreciation charges reduce the firm's taxable income. Following the usual corporate finance approach, we assume that the debt related tax shield is already incorporated into the calculation of the firm's (weighted average) cost of debt.[12]

The depreciation tax shield is determined jointly by the effective corporate income tax rate, denoted by α, and the depreciation schedule allowable for tax purposes, which we denote by $\hat{d}_t$ for $1 \leq t \leq T$. Thus the depreciation expense for tax purposes is given by $\hat{d}_t \cdot v(k)$ in period t.[13] For the purposes of calculating the levelized product cost, the effect of income taxes can be summarized by a *tax factor* which amounts to a "mark-up" on the unit cost of capacity, $c(k)$.

$$\Delta = \frac{1 - \alpha \cdot \sum_{t=1}^{T} \hat{d}_t \cdot \gamma^t}{1 - \alpha}. \tag{4}$$

The tax factor Δ exceeds 1 and reflects that for tax purposes the amortization charges

[12]In reference to the quote from the MIT coal study in the Introduction, we note that if the firm's leverage ratio is held constant, equity holders will receive an *"acceptable return"* and debt holders will receive *"accrued interest on initial project expenses"* provided the project achieves a zero Net Present Value (NPV) when evaluated at the Weighted Average Cost of Capital (WACC); see, for instance, Ross, Westerfield, and Jaffe (2005).

[13]Since the useful life for tax purposes is generally less than the economic useful life, T, we will simply assume that $\hat{d}_t = 0$ for any $t < T$ that exceeds the useful life of the asset for tax purposes.

lag behind the initial investment expenditure.[14] It is readily verified that Δ is increasing and convex in the tax rate α. Holding α constant, a more accelerated tax depreciation schedule corresponds to a higher depreciation tax shield which would lower Δ. In particular, Δ would be equal to 1 if the tax code were to allow for full expensing of the investment immediately, that is, $\hat{d}_0 = 1$ and $\hat{d}_t = 0$ for $t > 0$.

The formal expression for the levelized product cost then becomes:

$$LC(k) = w + f(k) + c(k) \cdot \Delta, \tag{5}$$

where $c(k), w, f(k)$ and Δ are as given in (1) - (4). To see that the expression in (5) does indeed satisfy the verbal break-even definition provided in the Introduction, let p denote the unit sales price. Figure 1 illustrates the sequence of annual pre-tax cash flows and annual operating incomes subject to taxation.

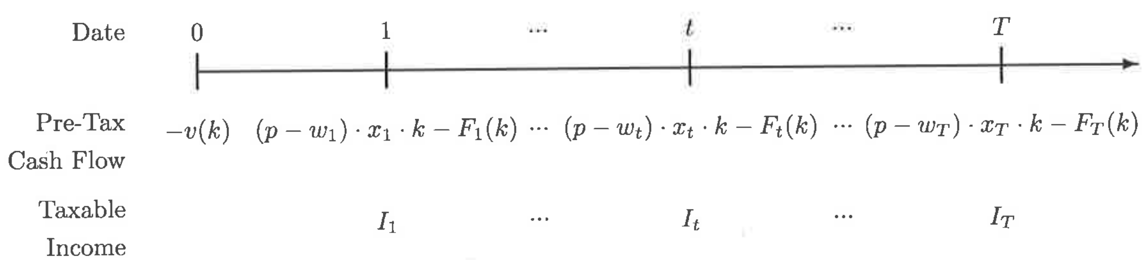

Figure 1: *Cash Flows and Taxable Income*

Taxable income in period t is given by the contribution margin in the respective period minus fixed operating costs minus the depreciation expense allowable for tax purposes:

$$I_t = (p - w_t) \cdot x_t \cdot k - F_t(k) - \hat{d}_t \cdot v(k).$$

As the firm pays an α share of its taxable income as corporate income tax, the annual *after-tax* cash flows are $CF_0 = -v(k)$, and:

$$CF_t = (p - w_t) \cdot x_t \cdot k - F_t(k) - \alpha \cdot I_t.$$

[14] To illustrate, for a corporate income tax rate of 35%, and a tax depreciation schedule corresponding to the 150% declining balance rule over 20 years, the tax factor would amount to approximately $\Delta = 1.3$.

In order for the firm to break even on this investment, the product price p must be such that the present value of all after-tax cash flows is zero. Solving the corresponding linear equation yields $p = LC$. In conclusion, the levelized product cost includes three principal components: the (time-averaged) fixed operating cost per unit of output produced, $f(k)$, the (time-averaged) unit variable cost, w, and the unit cost of capacity, $c(k)$, marked-up by the tax factor Δ.

A natural question at this stage is how the levelized product cost relates to a product's *full cost*, as conceptualized in cost accounting textbooks, for instance, Horngren, Datar, and Rajan (2012) and Zimmerman (2010). Full cost is usually articulated as a unit cost that comprises direct variable production costs plus indirect costs. Indirect (overhead) costs, in turn, include both fixed and variable components. These components usually contain accruals that arise due to cash expenditures being allocated cross-sectionally across products or inter-temporally across time periods, e.g., depreciation charges. Let d_t denote the depreciation charge in period t that the company applies for internal accounting purposes to the amount initially capitalized in connection with the capacity investment. We consider the following "expanded" measure of *full cost*:

$$FC_t(k) = \frac{w_t \cdot q_t + F_t(k) + [d_t + r \cdot (1 - \sum_{i=1}^{t-1} d_i)] \cdot v(k) \cdot \Delta}{q_t}. \tag{6}$$

The measure in (6) exceeds the usual representation of full cost on two accounts: the amount initially capitalized is marked-up by the tax factor Δ and the capacity related charges include an imputed interest charge on the remaining book value, i.e., the term $r \cdot (1 - \sum_{i=1}^{t-1} d_i) \cdot v(k) \cdot \Delta$.

Observation 1 *Suppose the asset's productivity profile conforms to the one-hoss shay scenario ($x_t = 1$), $w_t = w$, and $F_t(k) = f \cdot k$. With full capacity utilization, that is, $q_t = k$, full cost is equal to the levelized product cost in each period, that is,*

$$FC_t(k) = LC(k),$$

provided depreciation is calculated according to the annuity method, that is, the depreciation schedule $\{d_t\}$ satisfies $d_{t+1} = d_t \cdot (1 + r)$.

The claim in Observation 1 relies on the well-known observation that with annuity depreciation:

$$d_t + r \cdot (1 - \sum_{i=1}^{t-1} d_i) = \frac{1}{\sum_{i=1}^{T} \gamma^i}.$$

As a consequence, the last term in the numerator of (6) is equal to $c(k) \cdot \Delta$, establishing the claim.

While the conditions for Observation 1 appear rather restrictive, a more general result can be obtained provided full cost is calculated on the basis of additional accrual accounting concepts. First, suppose that either the unit variable costs w_t or the unit fixed operating costs $\frac{F_t(k)}{k}$ change over time. In order for full cost FC_t, as defined in (6), to align with $LC(k)$, variable and fixed operating costs can no longer be recognized on a cash basis but instead their overall present value must be prorated across time periods through appropriate accruals.[15]

Secondly, the one hoss-shay assumption in Observation 1 can be relaxed, provided depreciation is calculated according to the so-called *Relative Practical Capacity* rule (Rogerson 2008). In particular, there exists a unique depreciation rule, $(d_1, ..., d_T)$, such that for any productivity profile $(x_1, ..., x_T)$:

$$x_t \cdot c(k) \equiv \frac{x_t}{\sum_{i=1}^{T} x_i \cdot \gamma^i} \cdot v(k) = [d_t + r \cdot (1 - \sum_{i=1}^{t-1} d_i)] \cdot v(k),$$

and therefore again $LC(k) = FC_t(k)$ for all $1 \leq t \leq T$, if $q_t = x_t \cdot k$.

Regardless of the depreciation schedule used internally, the measure of full cost in (6) will still be equal to $LC(k)$ *on average* in the sense that the present value of the two cost measures will be identical.[16] Third, given the assumptions in Observation 1, suppose the firm uses straight-line depreciation for internal accounting purposes. The traditional measure of full cost, which does not include an imputed capital charge on the remaining book value, would then be consistently below $LC(k)$ in each period. This follows because a traditional full cost calculation based on straight-line depreciation entails a depreciation charge of $\frac{v(k)}{T}$ per unit of capacity. In contrast, the levelized cost requires the capacity charge (depreciation

[15]In their chapter on life cycle costing, Ewert and Wagenhofer (2008) also rely on accruals to assign an appropriate share of cash expenditures to the product costs reported at different stages.

[16]This follows directly from the fundamental identity:

$$\sum_{t=1}^{T} [d_t + r \cdot (1 - \sum_{i=1}^{t-1} d_i)] \cdot \gamma^t = 1,$$

showing the equivalence between discounted cash flows and discounted residual incomes (Preinreich 1938).

plus imputed interest) to be $\frac{v(k)}{\sum \gamma^t}$. But since $T > \sum_{t=1}^{T} \gamma^t$ for any $\gamma < 1$, we find that the traditional full cost measure based on straight-line depreciation is smaller than $LC(k)$.

We conclude this section by relating the levelized product cost to the representation of marginal cost in the industrial organization literature.[17] One approach to side-stepping the joint cost issue inherent in long-term capacity investments is to assume that productive capacity can be procured in a rental market. Rental capacity then effectively becomes a consumable input, like labor and raw materials. In our notation, Carlton and Perloff (2005, p. 254) conceptualize marginal cost as:

$$MC = w + (r + \delta) \cdot v, \tag{7}$$

where δ denotes "economic depreciation." Carlton and Perloff (2005) posit that with a competitive market for capacity services, one unit of capacity rented for one period of time should trade for $(r + \delta) \cdot v$, if v is the price per unit of capacity (that is, $v(k) = v \cdot k$) and δ reflects the physical decay rate of capacity. This specification is compatible with the LC formulation under the assumptions that assets are infinitely lived ($T = \infty$) and the decline in capacity follows a geometric pattern, that is, $x_t = x^{t-1}$. The denominator in the expression for the unit cost of capacity $c(k)$ in (1) then amounts to:

$$\sum_{t=1}^{\infty} x^{t-1} \cdot \gamma^t = 1 - x + r.$$

Therefore, the unit cost of capacity c in (1) coincides with the marginal cost of capital, that is $(r + \delta) \cdot v$, provided the economic depreciation rate δ is equated with $1 - x$, the capacity 'survival' factor. We note that Carlton and Perloff (2005) include neither the tax factor Δ nor fixed operating costs in their measure of marginal cost. This can be justified by assuming that the provider of the rental capacity services bears these costs and therefore they are included in the competitive rental rates.[18]

Aside from postulating a rental market for capacity, the long-run marginal cost can also be identified in settings where firms make an infinite sequence of overlapping capacity

[17]Pittman (2009) notes that it is common in microeconomic studies to use variable production cost as a proxy for marginal cost. Pittman succinctly summarizes the resulting tension as follows: *"It is difficult to understand how a firm that sets prices at true marginal cost is able to survive as a going concern unless that true marginal cost includes the marginal cost of capital."*

[18]In particular, the marginal cost of capacity would then be $(r + \delta) \cdot v \cdot \Delta + f$, provided the fixed operating costs $F_t(k)$ also decline geometrically, that is, $F_t(k) = f \cdot k \cdot \gamma^t$.

investments; see, for example, Rogerson (2008, 2011), Rajan and Reichelstein (2009), and Nezlobin (2012). Provided the firm invests a positive amount in each period, it becomes possible to construct a "variation" in the infinite investment trajectory so as to determine the marginal cost of one unit of capacity made available *for one period of time.* If $v(k) = v \cdot k$, the resulting unit cost of capacity is precisely equal to $c(k)$, as given in (1).

3 Price Taking Firms

This section examines the role of levelized product costs in a market setting with a large number of identical firms who act as price-takers. All firms are assumed to have the same cost structures and there are no barriers to entry. For expositional simplicity, we suppose that the market for the product in question opens at date 0 (initially there are no market incumbents) and effectively closes at date T, possibly because the current product or production technology will be replaced by a superior one at that point in time.

The standard textbook description of equilibrium in a competitive industry posits that the market price will be equal to both marginal- and average cost. If a firm is to cover its periodic operating fixed costs so as to obtain zero economic profits, marginal cost must then be below the market price for some range of output levels to the left of the equilibrium output level.[19] In the context of our model, suppliers make irreversible capacity investments at date 0 on the terms described in the previous section. In each subsequent period, firms adjust prices and output to current demand conditions subject to their current capacity constraints. This gives rise to competitive equilibria even though firms incur fixed operating costs and have a positive marginal cost that is constant up to the capacity limit.

The expected aggregate market demand in period t is given by $Q_t = D_t^o(p_t)$. The functions $D_t^o(\cdot)$ are assumed to be decreasing and we denote by $P_t^o(\cdot)$ the inverse of $D_t^o(\cdot)$. The actual price in period t is a function of the aggregate supply Q_t and the realization of a random shock $\tilde{\epsilon}_t$:

$$P_t(Q_t, \tilde{\epsilon}_t) = \tilde{\epsilon}_t \cdot P_t^o(Q_t). \tag{8}$$

[19]Borenstein (2000) articulates this point as follows: "*It is important to understand that a price-taking firm does not sell its output at a price equal to the marginal cost of each unit of output it produces. It sells all of its output at the market price, which is set by the interaction of demand and all supply in the market. The price-taking firm is willing to sell at the market price any output that it can produce at a marginal cost less than that market price.*"

The specification of multiplicatively separable shocks will be convenient in order to quantify a threshold value for the magnitude of the periodic uncertainty.[20] The random variables $\tilde{\epsilon}_t$ are assumed to be serially uncorrelated and to have the common density $h(\cdot)$ whose support is contained in the interval $[\underline{\epsilon}, \bar{\epsilon}]$ with $\bar{\epsilon} > 1 > \underline{\epsilon} > 0$. In order for $P_t^o(\cdot)$ to be interpreted as the *expected* inverse demand curve, we also normalize the periodic random fluctuations such that:

$$E[\tilde{\epsilon}_t] \equiv \int_{\underline{\epsilon}}^{\bar{\epsilon}} \epsilon_t \cdot \ h(\epsilon_t) \ d\epsilon_t = 1.$$

Firms in the industry are assumed to be risk neutral and to have the same information regarding future demand.[21] In particular, they anticipate that $\tilde{\epsilon}_t$ will be realized at the beginning of period t, prior to each supplier deciding its current level of output, less than or equal to its capacity level. Provided firms are price-takers, a firm will exhaust its full capacity in period t whenever the market price covers at least the short-run marginal cost w_t.

The initial results in this section rely on the assumption of a long-run constant returns to scale technology. Thus $v(k) = v \cdot k$ (and therefore $c(k) = c \cdot k$) and $F_t(k) = f_t \cdot k$. As a consequence, the levelized product cost $LC(k)$ is independent of k and will be denoted simply by LC.[22] Initially, we shall also focus on a time-invariant cost- and capacity structure such that $x_t = 1$, $w_t = w$, $h_t(\cdot) = h(\cdot)$, and $F_t(k) = f \cdot k$ for $1 \leq t \leq T$. Furthermore, we consider first a setting where the expected aggregate demand is unchanged over the T-period horizon, that is $P_t^o(\cdot)$=$P^o(\cdot)$. We refer to the combination of these assumptions as a *stationary constant returns to scale environment.*

Since the levelized product cost is the threshold price at which firms break-even on their capacity investments, one would expect that the competitive equilibrium price will on average be equal to the LC, at least if firms always exhaust the available capacity. The following

[20]In contrast, the body of work reviewed by Balakrishnan and Sivaramakrishnan (2002) on capacity choice and full cost pricing exclusively considers an additive error term for the aggregate demand function.

[21]We do not consider inventory in our model. In some industries, holding inventory is impossible (e.g., transportation services), while in others it is not a viable option because of high inventory holding costs (e.g., electricity). The general effect of low inventory holding costs will be to smooth out demand fluctuations. As a consequence, we would then expect the equilibrium prices and capacity levels to approach those obtained under conditions of demand certainty.

[22]The assumption that fixed operating costs are unavoidable (even if $q_t = 0$) is of obvious importance here.

result characterizes the expected equilibrium prices and the aggregate level of capacity in equilibrium. We denote by $P(w, \epsilon_t, K)$ the equilibrium price in period t, contingent on the unit variable cost w, the aggregate industry capacity level K, and the realization of the periodic shock ϵ_t:

$$P(w, \epsilon_t, K) = \begin{cases} \epsilon_t \cdot P^o(K) & \text{if} \quad \epsilon_t \geq \epsilon(K, w) \\ w & \text{if} \quad \epsilon_t < \epsilon(K, w). \end{cases}$$

Here, $\epsilon(K, w)$ denotes the cut-off level for the periodic shock ϵ_t below which the available capacity will no longer be fully exhausted. Thus, $\epsilon(K, w) \cdot P^o(K) = w$ for values of ϵ in the range $[\underline{\epsilon}, \overline{\epsilon}]$. The following condition relates the volatility in market prices to the short-run marginal cost of production as a percentage of the overall levelized cost.

Definition 1 *Market demand is said to exhibit limited price volatility if*

$$\text{Prob } [\tilde{\epsilon} \geq \frac{w}{LC}] = 1. \tag{9}$$

This condition is more likely to be satisfied in industries where capacity- and fixed operating costs, taken together, comprise a relatively high share of the overall levelized cost.[23] If condition (9) is not met, we shall refer to the setting as one of *significant price volatility.*

In stating the following result, we define the *Levelized Fixed Cost* (LFC) as the levelized product cost minus the unit variable cost. Thus, $LFC \equiv LC - w \equiv f + c \cdot \Delta$. It will also be useful to define:

$$LC^- \equiv \max\left\{\frac{LC}{\overline{\epsilon}}, LFC\right\}.$$

Proposition 1 *Given a stationary constant returns to scale environment, a competitive equilibrium entails a unique aggregate capacity level K^* such that the expected product price satisfies:*

$$E[P(w, \tilde{\epsilon}_t, K^*)] = LC.$$

The equilibrium capacity level K^* is bounded by:

$$D^o(LC^-) \geq K^* \geq D^o(LC), \tag{10}$$

with $K^* = D^o(LC)$ if and only if price volatility is limited.

[23] Applicable examples include semiconductors, electricity generation, and airlines.

As discussed in the Introduction, upfront capacity investments inherently represent a joint cost and this jointness creates an indeterminacy for the long-run marginal cost of producing one unit of output in a particular period. To the extent that microeconomic theory generally postulates that prices are equal to long-run marginal cost in a competitive equilibrium, Proposition 1 supports the interpretation of the levelized product cost as the long-run marginal cost. The result also provides a rationale for full cost pricing, provided full cost is conceptualized as in (6).[24]

To explain the arguments underlying Proposition 1, suppose first that there are no shocks to price, that is, $P(Q_t, \tilde{\epsilon}_t) = P^o(Q_t)$ for sure. Firms will then produce at full capacity in each period provided $P_t^o(K^*) \geq w$. The capacity constraint prevents the industry from bidding the market price down to w. At the investment stage, the condition of zero economic profits for all participants dictates that the aggregate capacity level must satisfy $P^o(K^*) = LC$. Furthermore, the stationarity of the environment implies that in equilibrium, all capacity investments will be made at the initial stage. In other words, in equilibrium, all firms move in lock-step with their investments at date zero and effectively foreclose the possibility of entry in the remaining $T-1$ periods.

When market prices are subject to periodic shocks, the discounted value of expected future cash flows for a firm that has invested k units of capacity, in an industry with aggregate capacity K, becomes:

$$\Gamma(k|K) = \sum_{t=1}^{T} \left\{ E\left[[P(w, \tilde{\epsilon}_t, K) - w] \cdot q^*(w, \tilde{\epsilon}_t, k) - f \cdot k - \alpha \cdot \tilde{I}_t \right] \right\} \gamma^t - v \cdot k, \tag{11}$$

where $q^*(w, \epsilon_t, k)$ denotes the firm's optimal quantity in period t. Thus $q^*(w, \epsilon_t, k) = k$ whenever $P(w, \epsilon_t, K) > w$, while $q^*(\cdot)$ is indeterminate if $P(w, \epsilon_t, K) = w$. Individual firms are indifferent about idling any part of their capacity once the market price drops down to w and, as a consequence, $P(w, \epsilon_t, K) \geq w$.[25]

In equilibrium, the aggregate capacity level, K^*, must be chosen such that $\Gamma(k|K^*) = 0$ and furthermore:

[24] If full cost is measured in the more restrictive sense that imputed interested charges and tax related expenses are excluded, Proposition 1 provides a justification for cost-plus pricing such that the expected competitive mark-up yields a product price equal to the levelized cost.

[25] An implicit assumption here is that $\underline{\epsilon} \cdot P^o(0) \geq w$.

$$E\left[\tilde{\epsilon}_t \cdot P^o(Q_t^*(w, \tilde{\epsilon}_t, K^*)\right] = LC, \tag{12}$$

where $Q_t^*(w, \epsilon_t, K^*)$ denotes the optimal aggregate output level, given K^* and the realization of the current shock ϵ_t. In particular, $Q_t^*(w, \epsilon_t, K^*) = K^*$ if and only if $\epsilon_t \cdot P^o(K^*) \geq w$, and $Q_t^*(w, \epsilon_t, K^*)$ is given as the solution to $\tilde{\epsilon}_t \cdot P^o(Q_t^*(w, \tilde{\epsilon}_t, K^*) = w$ otherwise, reflecting again that the market price will not drop below w, as some firms would idle their capacity. With limited price volatility in the sense of condition (9), the zero-profit condition in (12) is met at $K = K^o$ because:

$$\underline{\epsilon} \cdot P^o(K^o) \equiv \underline{\epsilon} \cdot LC \geq w,$$

and therefore $Q_t^*(\epsilon_t, K^o) = K^o$.

Intuitively, one might expect that higher price volatility results in a lower aggregate capacity level than $K^o \equiv D^o(LC)$, because if condition (9) is not met, some of the industry's aggregate capacity will be idle with positive probability. However, as $P^o(\cdot)$ is decreasing, the zero economic profit condition in (12) can only be met for some $K^* > K^o$. In effect, the aggregate investment in capacity will be larger than under conditions of limited volatility because there is no need to commit the entire LC at the investment stage. Firms have a *call option* to idle parts of their capacity in subsequent periods which allows them to avoid the short-run marginal cost, w, in case of unfavorable demand realizations. [26] Figure 2 illustrates the equilibrium capacity levels identified in Proposition 1.

The upper bound on capacity, K^+, is readily explained for the case where $LFC = LC^-$. If hypothetically the variable production costs were to be zero, firms would always use their entire available capacity and the expected market price would be equal to $LFC = LC - w$. As a consequence the aggregate capacity level would be $D^o(LFC)$. With positive variable production costs, the aggregate capacity level must in equilibrium be correspondingly lower than $D^o(LFC)$ in order for firms to earn zero economic profits.[27]

The distribution of equilibrium prices for two volatility scenarios is illustrated in Figure 3. With limited price volatility, the support of $\tilde{\epsilon}^1$ is given by $[\underline{\epsilon}^1, \bar{\epsilon}^1]$ and the market price will

[26] Isik et al. (2003) also identify an option value associated with capacity investments. In contrast to our setting, though, their model assumes that if a firm idles its capacity in any given period, it must also do so in all subsequent periods, that is, the asset is effectively abandoned.

[27] As shown in the proof of Proposition 1, the upper bound on K^* can be tightened further by considering the alternative capacity level $D^o(\frac{LC}{\bar{\epsilon}})$. For that reason, LC^- was defined as $\max\{\frac{LC}{\bar{\epsilon}}, LFC\}$.

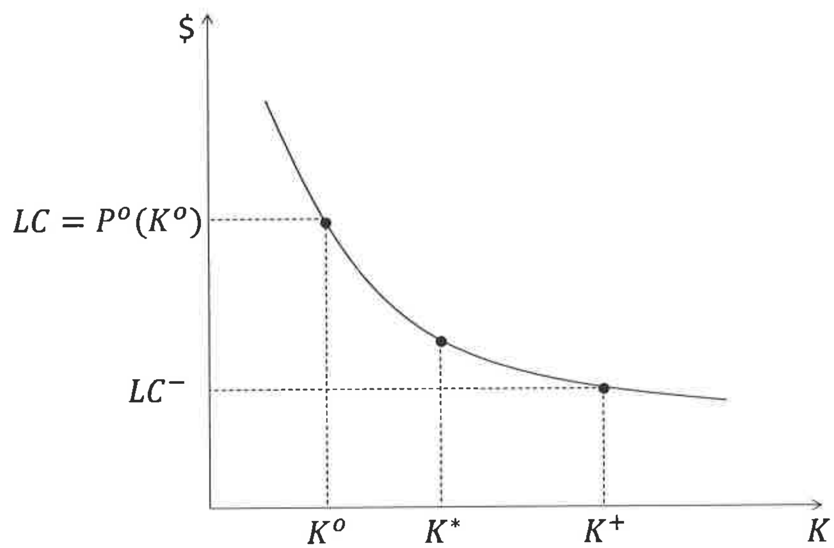

Figure 2: *Equilibrium Capacity Levels*

vary proportionally with $\tilde{\epsilon}$ at the rate $P^o(K_1^*)$. With significant volatility, the support of $\tilde{\epsilon}^2$ broadens to $[\underline{\epsilon}^2, \bar{\epsilon}^2]$ and equilibrium prices will be a piecewise linear function of $\tilde{\epsilon}^2$. The effects of higher price volatility on the option value of capacity investments can effectively be summarized by the following relations:

$$P^o(K_1^*) = E\left[P(w, \tilde{\epsilon}^1, K_1^*)\right] = LC = E\left[P(w, \tilde{\epsilon}^2, K_2^*)\right] > P^o(K_2^*).$$

Another way of interpreting the convexity of the price function corresponding to $\tilde{\epsilon}^2$ is that, without loss of generality, an atomistic firm anticipates to exhaust its entire capacity, since its own supply decision has no impact on the market price which, in turn, is protected on the downside by w. But if the firm earns zero economic profits in the $\tilde{\epsilon}^1$ environment, the convexity of the price curve would yield positive profits in the $\tilde{\epsilon}^2$ environment, unless $P^o(K_1^*) > P^o(K_2^*)$.

The remainder of this section extends the benchmark result in Proposition 1 by relaxing several of the assumptions invoked thus far. The benchmark result has assumed that the fixed operating costs, f, are *unavoidable*. If one supposes alternatively that the firm will not incur the unit cost f if it were to idle its entire capacity in period t, Proposition 1 remains valid as stated, except that the aggregate level of capacity may increase. Once the fixed cost f are "in play," the relevant price floor for capacity utilization in each period increases to

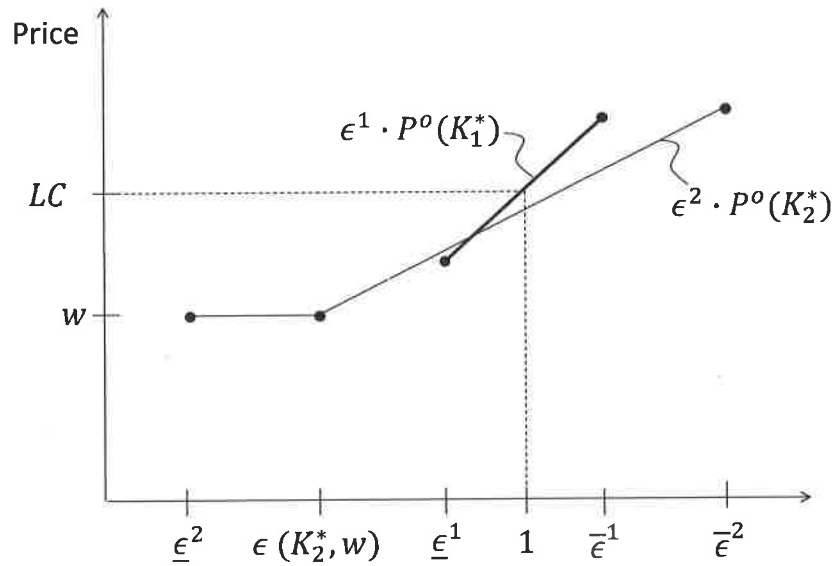

Figure 3: *Distribution of Equilibrium Prices*

$w + f$ because suppliers would be better off withholding their capacity if the price were to drop below $w + f$.

Corollary 1 *If the periodic operating fixed costs per unit of capacity, f, are avoidable, the expected equilibrium price remains equal to the levelized product cost. The equilibrium level of aggregate capacity increases relative to the scenario where f is unavoidable if and only if*

$$\text{Prob}\ [\tilde{\epsilon} \geq \frac{w+f}{LC}] < 1.$$

Consistent with the intuition developed above, the option value of capacity increases to the extent that a larger share of the LC becomes avoidable.

One consequence of the assumed long-run constant returns to scale technology in our model has been that the efficient scale of operation for individual firms, that is the individual k, remains indeterminate. If the cost of acquiring capacity, $v(k)$, and the periodic fixed operating costs, $F_t(k)$, are non-linear, the condition of zero expected economic profits dictates that the efficient scale of operation must be chosen such that the LC per unit of output is minimized. Referring back to the generalized definition of $LC(k)$ in Section 2, we define the efficient scale of operation by:

$$k^* \in \text{argmin}\{LC(k)\}.$$

The capacity level k^* effectively determines the efficient size of firms in the industry. The expected equilibrium price in Proposition 1 then becomes $LC(k^*)$, while the aggregate capacity level in equilibrium, K^*, is determined as in Proposition 1 after replacing LC by $LC(k^*)$.[28]

Finally, we relax some of our stationarity assumptions and consider changes in the aggregate market demand over time. In particular, suppose that $P_t^o(\cdot)=\lambda_t \cdot P^o(\cdot)$ for all $1 \leq t \leq T$ such that $\lambda_{t+1} < \lambda_t < 1$ for all $1 \leq t \leq T$. We refer to such a scenario as a *declining product market*. We introduce the notation $\boldsymbol{\lambda} = (\lambda_1, ..., \lambda_T)$ and define:

$$m(\boldsymbol{\lambda}) = \frac{\sum_{t=1}^{T} \gamma^t}{\sum_{t=1}^{T} \lambda_t \cdot \gamma^t}.$$

Intuitively, one would expect the equilibrium capacity in a declining product to be lower compared to a stationary market. The following result confirms this intuition and shows that on average, the expected equilibrium market price will also be higher in a declining product market. We also allow the short-run marginal cost to change over time. Consistent with the notion of a declining product market, the restriction imposed is that $w_{t+1} \geq w_t$. The importance of that restriction is that in a competitive equilibrium all capacity investments will be made initially.

Let $P_t(w_t, \epsilon_t, \lambda_t, K)$ denote the equilibrium market price in period t when aggregate market demand is given by $\lambda_t \cdot P^o(\cdot)$ and the current demand shock is realized. By construction,

$$P_t(w_t, \epsilon_t, \lambda_t, K) = \begin{cases} \epsilon_t \cdot \lambda_t \cdot P^o(K) & \text{if} \quad \epsilon_t \geq \epsilon(w_t, K, \lambda_t) \\ w_t & \text{if} \quad \epsilon_t < \epsilon(w_t, K, \lambda_t), \end{cases}$$

with

$$\epsilon(w_t, K, \lambda_t) \cdot \lambda_t \cdot P^o(K) \equiv w_t.$$[29]

Proposition 2 *With a declining product market and a constant returns to scale technology, a competitive equilibrium entails a unique aggregate capacity level K^* such that the expected equilibrium prices satisfy:*

$$\sum_{t=1}^{T} E[\lambda_t \cdot P_t(w_t, \tilde{\epsilon}_t, \lambda_t, K)] \cdot \gamma^t = LC \cdot \sum_{t=1}^{T} \gamma^t.$$

[28]Non-linearities in $v(k)$ and $F_t(k)$ can give rise to a U-shaped $LC(\cdot)$ curve.

[29]As before, $\epsilon(w, K, \lambda_t)$ is bounded by $\underline{\epsilon}$ and $\bar{\epsilon}$.

The capacity level K^* is bounded by:

$$D^o(LC^- \cdot m(\boldsymbol{\lambda})) \geq K^* \geq D^o(LC \cdot m(\boldsymbol{\lambda})) \tag{13}$$

with $K^* = D^o(LC \cdot m(\boldsymbol{\lambda}))$ if and only if:

$$\text{Prob}\left[\tilde{\epsilon} \cdot \lambda_T \geq \frac{w_t}{LC \cdot m(\boldsymbol{\lambda})}\right] = 1. \tag{14}$$

For a declining product market, the zero-profit condition applies over the entire planning horizon rather than on a period-by-period basis.[30] In particular, the annuity value of the levelized cost must then be equal to the present value of future expected market prices. With a declining product market and weakly increasing variable costs, it becomes ceteris paribus more likely that market demand exhibits significant volatility, at least in later time periods. Formally, this can be seen from the fact that the inequality in (14) is more stringent than (9) because $m(\boldsymbol{\lambda}) \cdot \lambda_T < 1$.

Proposition 2 can be extended to a growing product market, where $\lambda_{t+1} > \lambda_t > 1$, provided the growth rates are"sufficiently small." Once demand grows too quickly, it will no longer be an equilibrium for all capacity investments to be undertaken at the initial date. The resulting scenario of sequential and overlapping investments would be similar to that in the earlier studies by Rogerson (2008, 2011), Rajan and Reichelstein (2009), and Nezlobin (2012). In particular, the main finding of Proposition 1, namely that the expected market price in each period is equal to the levelized product cost, will continue to hold provided (i) there is an infinite planning horizon, (ii) the product market expands monotonically over time, and (iii) price volatility is limited so that firms never have excess capacity.[31]

4 Price Setting Firms

4.1 Monopoly

We now turn to a monopolistic firm that faces the same stationary constant returns to scale environment posited in connection with Proposition 1. We take it as exogenously given that

[30]The proof of Proposition 2 is omitted since it is analogous to the one for Proposition 1.

[31]The transfer pricing model of Dutta and Reichelstein (2010) allows for unfavorable shocks to market demand. Nonetheless, it is sequentially optimal to always use the existing capacity and to expand capacity over time. In contrast, the recent work of Baldenius, Nezlobin, and Vaysman (2014) examines managerial performance measures in settings where it may be sequentially optimal to idle previously acquired capacity.

the firm has monopoly power. One common reason is proprietary product technology due to intellectual property rights. The expected aggregate market demand in period t is given by $q_t = D^o(p_t)$. The function $D^o(\cdot)$ is assumed to be decreasing and we denote by $P^o(\cdot)$ again the inverse of $D^o(\cdot)$. The actual price in period t is a function of the quantity supplied q_t and the realization of the random shock $\tilde{\epsilon}_t$:

$$P(q_t, \tilde{\epsilon}_t) = \tilde{\epsilon}_t \cdot P^o(q_t). \tag{15}$$

Similar to our assumptions in Section 3, the monopolist observes the realization of $\tilde{\epsilon}_t$ before deciding on the quantity supplied in that period. Let $MR^o(q)$ denote the marginal revenue, with

$$MR^o(q) \equiv \frac{d}{dq}[P^o(q) \cdot q].$$

Throughout this section, we assume that marginal revenue is decreasing in q. Assuming the short-run variable costs are again constant over time and equal to w and fixed operating costs in each period are unavoidable and equal to f per unit of capacity, we obtain the following result.

Proposition 3 *Given a stationary constant returns to scale environment, the optimal capacity investment, k^*, for a monopolist satisfies $k^* \in [k^o, k^+]$, where k^o and k^+ are given by:*

$$MR^o(k^o) = LC \text{ and } MR^o(k^+) \equiv LC^-. \tag{16}$$

Furthermore, $k^* = k^o$ if and only if the condition of limited price volatility in (9) is satisfied.

Proposition 3 identifies a setting where the levelized cost is effectively the relevant unit cost for capacity investment decisions. Specifically, the first-order condition for the optimal k^* is:

$$E\left[\tilde{\epsilon}_t \cdot MR^o(q_t^*(\tilde{\epsilon}_t, w, k^*))\right] = LC, \tag{17}$$

where $q_t^*(w, \epsilon_t, K^*)$ denotes the optimal monopoly output level in period t, given the initial capacity choice and the realization of the current shock ϵ_t. We note that $MR^o(q_t^*(w, \epsilon_t, k^*)) = w$ if the capacity constraint does not bind for a particular ϵ_t, while $MR^o(q_t^*(w, \epsilon_t, k^*)) = MR^o(k^*)$ in case $\epsilon_t \cdot MR^o(k^*) \geq w$. If the limited price volatility condition in (9) holds and therefore

$$\epsilon_t \cdot MR^o(k^o) = \epsilon_t \cdot LC \geq w$$

for all realizations of ϵ_t, the first-order condition in (17) implies $k^* = k^o$.

Once price volatility becomes *significant*, in the sense that condition (9) no longer holds and the maximal percentage deviation from the expected market price exceeds the ratio of variable- to levelized costs, the monopolist will withhold capacity in unfavorable states of the world. Like in the competitive setting, this has the effect of driving up the amount of initial capacity investment, because the short-run marginal cost is not yet sunk. An upper bound on the optimal capacity level is obtained by equating marginal revenue with the levelized fixed cost. LFC would be the relevant cost of capacity for a hypothetical firm that has no incremental short-run costs and therefore always produces at capacity. The claim in Proposition 3 then follows, because the marginal return on capacity investments in the hypothetical setting ($w = 0$) is always at least as large as the marginal return on investment in the actual problem with positive short-run marginal costs.

A qualitatively similar prediction is derived in Proposition 3 of Göx (2002) in the context of capacity planning and product pricing. In particular, Göx (2002) finds that the optimal capacity level chosen by a firm that faces a downward sloping demand curve exceeds the optimal capacity level that the firm would choose under conditions of demand certainty.

Combining our findings in Propositions 1 and 2, we conclude that with limited price volatility, the monopolist's capacity investment is lower than the aggregate capacity level that obtains under competition, since $MR^o(k^o) = LC = P^o(K^o)$ and $MR^o(\cdot) < P^o(\cdot)$. With limited price volatility, the monopoly price entails a mark-up on the levelized cost, such that:

$$p^*(k^o, \epsilon_t) = \epsilon_t \cdot LC \cdot \frac{E(k^o)}{E(k^o) - 1},$$

and $E(k^o) > 1$ denotes the price elasticity of demand. In contrast to the customary micro-economic textbook representation, we submit that the basis for the mark-up is LC rather than the short-run marginal cost.[32]

Holding other parameters fixed, Proposition 3 suggests that the monopoly capacity investment will be higher for firms operating in environments with high price volatility. To formalize this comparative static result, we rely on the usual metric of calling one proba-

[32]Related to our finding here, Lengsfeld and Schiller (1998) derive a monopoly mark-up which reflects the opportunity cost associated with capacity constraints.

bility distribution as "riskier" than another distribution if the first one can be expressed as a compound lottery of the second. Formally, the distribution $h_2(\cdot)$ is obtained by a mean-preserving spread of $h_1(\cdot)$, if:

$$\tilde{\epsilon}_2 = \mu + \tilde{\epsilon}_1,$$

where μ is a random variable distributed on some interval $[\underline{\mu}, \bar{\mu}]$, such that the conditional probability distributions $g(\mu|\epsilon_1)$ satisfy:

$$\int_{\underline{\mu}}^{\bar{\mu}} \mu \, g(\mu|\epsilon_1) \, d\mu = 0,$$

for all ϵ_1.[33] Thus, $\tilde{\epsilon}_2$ is obtained from $\tilde{\epsilon}_1$ by adding a second lottery which preserves the original mean of $\tilde{\epsilon}_1$.

Corollary 2 *Higher price volatility results ceteris paribus in a larger capacity investment by the monopolist.*

As noted in Section 2, our analysis has treated the cost of capital as exogenous and fixed. One implicit assumption for the comparative statics result in Corollary 2 therefore is that an increase in price volatility in the product market is not assumed to alter any risk premium embedded in the cost of capital. This specification is plausible if the investment decision under consideration is small relative to the firm's overall investment portfolio.

It should be noted that the prediction of a larger capacity investment due to more volatility does not necessarily translate into a prediction of lower monopoly prices on average. Holding the distribution $h(\cdot)$ fixed, the quantity supplied to the market is, of course, weakly increasing in the amount of capacity available. Yet, this higher variance distribution does generally not translate into a higher average monopoly price. For the special case of uniform distributions, it turns out that the expected monopoly price will indeed be lower as volatility increases. Suppose $h(\epsilon) = \frac{1}{2 \cdot \bar{h}}$. Higher values of $\bar{h}$ then correspond to higher volatility in the sense of a mean-preserving spread. Assuming in addition a constant price elasticity of demand, numerical simulations show that the expected monopoly price is monotonically decreasing in $\bar{h}$.

[33]Our definition of mean-preserving spreads here follows Mas-Colell, Whinston, and Green (1995).

4.2 Duopoly

Our findings in the previous two sections have demonstrated that the levelized poduct cost is the relevant cost for capacity investments both in a monopoly and a competitive setting. These findings strongly suggest that this attribute of the LC also carries over to oligopolistic settings in which the incumbent firms make initial capacity investments and subsequently compete subject to their capacity limitations. To model the interactions of the oligopolists, we focus on quantity games in the sense of Cournot competition.[34]

Suppose two firms, identical in their products and cost structure, first make simultaneous capacity decisions and then in each subsequent period choose production quantities simultaneously. These choices then determine the market price in that period. In the simplest setting, the two identical firms i and j face a *stationary environment* as described in Section 3. If the firms choose the production quantities $\boldsymbol{q_t} = (q_t^1, q_t^2)$ the product price in period t is given by:

$$P(q_t^1 + q_t^2, \tilde{\epsilon}_t) = \tilde{\epsilon}_t \cdot P^o(q_t^1 + q_t^2). \tag{18}$$

The initial capacity investments are denoted by $\boldsymbol{k} = (k^1, k^2)$ and thus $K(\boldsymbol{k}) = k^1 + k^2$ becomes the aggregate capacity level. Given the quantity and capacity choice of firm j, the marginal revenue for firm i is given by:

$$MR^o(q^i|q^j) \equiv \frac{d}{dq^i}[P^o(q^1 + q^2) \cdot q^i].$$

We assume that the marginal revenue of firm i is decreasing in both q^i and q^j. Clearly, that condition will be met for "standard" willingness to pay curves, including the special case of a linear function.

Proposition 4 *Given a stationary environment, suppose the limited price volatility condition in (9) holds. The following then constitutes a subgame perfect equilibrium outcome:*
i) At date 0, both firms choose identical capacity investments, $k^{1*} = k^{2*} = k^*$ which satisfy the equation:

$$MR^o(k^*|k^*) = LC. \tag{19}$$

ii) In subsequent periods $1 \leq t \leq T$, each firm supplies the maximal production quantity $q_t^1 = q_t^2 = k^*$.

[34] For ease of notation, we rely on the duopoly setting for the derivation of our results.

The proof of the Proposition exploits that, regardless of the initial capacity choices and regardless of the realization of the noise term $\tilde{\epsilon}_t$, there is a unique Nash-equilibrium in the output quantities chosen at stage t. The restriction imposed by subgame perfection therefore requires that the initial capacity choices constitute an equilibrium if followed by the subsequent output levels corresponding to the unique equilibrium in each stage game. In particular, these equilibrium output levels call for the firm with the lower capacity level to exhaust its capacity provided the marginal revenue at the capacity limit still covers the unit variable cost w. With limited price volatility, firm j will therefore anticipate full capacity utilization whenever $k^j \leq k^*$. Finally, it is shown in the proof that k^* is indeed a best response to the same capacity level chosen by the other firm.[35]

There are several promising directions for extending the baseline result in Proposition 4. First, it would be desirable to characterize the entire set of equilibrium outcomes. Absent any price volatility, the first-order conditions for a Nash-equilibrium immediately show that the capacity levels identified in Proposition 4 constitute the unique equilibrium. Second, it would be natural to consider a scenario where one of the firms has a first-mover advantage with its capacity choice. Once both firms have entered the market, albeit sequentially, they decide their output levels simultaneously in each subsequent period. At the initial investment stages, the Stackelberg leader can then credibly preempt capacity investments by the follower to the extent that the price of the output to be produced still exceeds the unit variable cost. Third, beginning with the work of Kreps and Scheinkman (1983) earlier industrial organization literature has established an equivalence between Cournot quantity competition and Bertrand price competition subject to capacity constraints. In future work, it would be useful to establish this equivalence for the model examined in this paper.[36] Finally, Proposition 4 strongly suggests that with n symmetric competing firms there exists a (subgame-perfect) equilibrium such that the resulting market price will converge to the levelized cost as n grows large.

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[35] Kloock (1997) also establishes a symmetric Cournot-equilibrium for duopolists choosing capacity levels. Kloock does not seek to identify the relevant unit cost for the initial investment choices. Furthermore, an apparent simplification in the analysis by Kloock (1997) is that firms can pre-commit to exhaust their available capacity in subsequent periods regardless of the initial decisions. Put differently, there does not seem to be a sequential rationality requirement.

[36] See, in particular, Davidson and Deneckere (1986) and Grant and Quiggin (1996).

5 Concluding Remarks

A central feature of many manufacturing and service industries is that irreversible upfront capacity investments are required in order for firms to deliver products and services. This paper has examined the economic relevance of the so-called levelized product cost (LC), a concept widely used in the electricity literature under the label Levelized Cost of Electricity. This life-cycle cost is based entirely on discounted cash flows and is calibrated as the minimum average price that would have to be received in order to justify investment in a particular production facility, assuming full capacity utilization. The levelized cost can be viewed as a full cost, provided depreciation is calculated in a manner that reflects the decline in productive capacity over time. In addition, this alignment requires full cost to include imputed interest charges on the outstanding book value of the productive asset and the amount initially capitalized to be marked up by a tax factor that reflects the delay in depreciation tax shields.

Our analysis also demonstrates that the levelized cost can be interpreted as the long-run marginal product cost since the expected equilibrium price in a competitive setting is shown to be equal to the levelized cost. For a range of alternative market settings, we show that the LC is the relevant unit cost in the sense that firms equate the levelized product cost with the expected marginal revenue that is obtained through output levels that are sequentially optimally in subsequent periods, given the initial capacity choice. Taken together, our analysis of the LC provides a desired connection between the accountant's notion of full cost and the economist's notion of long-run marginal cost in the context of industries that require upfront capacity investments (Pittman 2009).

Our classification of limited versus significant volatility hinges on the proportion of the short-run marginal cost relative to the levelized cost. This ratio tends to be small in capital intensive industries. In general, the optimal capacity level is such that the corresponding marginal revenue is below the LC. At the investment stage firms do not need to commit to use their entire capacity in future periods but retain a call option to idle parts of their installed capacity in future periods in response to unfavorable market conditions. This call option becomes more valuable with higher volatility, resulting ceteris paribus in higher capacity investments.

The analysis in this paper has confined attention to single product environments. In contrast, much of the existing work on product costing has focused on settings where capacity installations and their attendant fixed costs are shared among multiple products (Cooper and Kaplan 1988; Lengsfeld and Schiller 1998). In those settings, particular cost allocation rules, like activity-based costing, are usually justified by the need to identify the long-run cost of individual products, even though capacity investments are treated as exogenous. Our model lends itself to extending the literature on alternative product costing systems to environments in which multiple products share the same capacity installations and relevant costs are determined by means of both intertemporal and cross-sectional cost allocations. With uncertain market demand, there will be a natural diversification effect that arises when multiple products use the same scarce capacity resources.

6 Appendix

6.1 Appendix A – List of Variables

$c(k)$	Unit cost of capacity	$p^*(\cdot)$	Mark-up on marginal cost
CF_t	After-tax cash flow in year t	p_t	Market price in year t
d_t	Depreciation in year t	$P_t(\cdot)$	Equilibrium price in year t
$\hat{d}_t$	Allowable tax depreciation in year t	$P_t^o(\cdot)$	Inverse aggregate demand in year t
$D_t^o(\cdot)$	Aggregate demand in year t	q_t	Production quantity in year t
$f(k)$	Time-averaged unit fixed operating costs	q_t^i	Production quantity of firm i in year t
$F_t(k)$	Fixed operating costs in year t	$\mathbf{q_t}$	Vector of individual production quantities q_t^i
$FC_t(k)$	Full cost in year t	Q_t	Aggregate supply in year t
$h_t(\cdot)$	Density function	Q_t^*	Optimal aggregate supply in year t
I_t	Taxable income in year t	r	Cost of capital
k	Unit of capacity	T	Useful life of capacity investment
k^i	Initial capacity investment by firm i	$v(k)$	Cost of installing k units capacity
k^*	Individual equilibrium capacity level	w	Time-averaged unit variable cost
k^o	Individual capacity level at which $MR^o(k^o) \equiv LC$	w_t	Unit variable costs in year t
k^+	Individual capacity level at which $MR^o(k^+) \equiv LC^-$	x_t	Capacity decline factor in year t
K	Aggregate industry capacity level	α	Effective corporate income tax rate in %
K^*	Equilibrium aggregate capacity level	γ	Discount factor
K^o	Aggregate capacity level at which $P^o(K^o) \equiv LC$	δ	Economic depreciation
K^+	Aggregate capacity level at which $P^o(K^+) \equiv LC^-$	Δ	Tax factor
$LC(\cdot)$	Levelized cost	$\tilde{\epsilon}_t$	Random shock in year t
LC^-	Lower bound on expected price	$\bar{\epsilon}$	Upper bound for the random fluctuation
LFC	Levelized fixed cost	$\underline{\epsilon}$	Lower bound for the random fluctuation
$m(\boldsymbol{\lambda})$	Product market decline factor	λ_t	Growth factor
$MR^o(\cdot)$	Marginal revenue	$\boldsymbol{\lambda}$	Vector of growth factors λ_t

6.2 Appendix B – Proofs

Proof of Proposition 1.

Denote the aggregate capacity investment at date 0 by K. We first characterize the equilibrium level of K^* and the expected equilibrium prices, $E[P(w, \tilde{\epsilon}_t, K^*)]$, under the assumption that no firm makes additional capacity investments at any date t, $1 \leq t < T$. We subsequently confirm that in equilibrium there are indeed no capacity investments after date 0.

If the aggregate capacity level is K at date 0, the equilibrium price in period t is given by:

$$P(w, \epsilon_t, K) = \begin{cases} \epsilon_t \cdot P^o(K) & \text{if} \quad \epsilon_t \geq \epsilon(K, w) \\ w & \text{if} \quad \epsilon_t < \epsilon(K, w). \end{cases}$$

Here $\epsilon(K,w)$ denotes the unique cut-off level defined as follows:

$$\epsilon(K,w) = \begin{cases} \bar{\epsilon} & \text{if} \quad \bar{\epsilon} \cdot P^o(K) \leq w \\ \frac{w}{P^o(K)} & \text{if} \quad \bar{\epsilon} \cdot P^o(K) > w > \underline{\epsilon} \cdot P^o(K) \\ \underline{\epsilon} & \text{if} \quad \underline{\epsilon} \cdot P^o(K) \geq w \end{cases}$$

Clearly, $\epsilon(K,w)$ is weakly increasing in K.

Consider now an individual firm that has invested a capacity level k. The present value of expected future cash flows for this firm is:

$$\Gamma(k|K) = \sum_{t=1}^{T} \left\{ E\left[[P(w,\tilde{\epsilon}_t,K) - w] \cdot q^*(w,\tilde{\epsilon}_t,k) - f \cdot k - \alpha \cdot \tilde{I}_t \right] \right\} \gamma^t - v \cdot k,$$

where taxable income $\tilde{I}_t$ is given by:

$$\tilde{I}_t = [P(w,\tilde{\epsilon}_t,K) - w] \cdot q^*(w,\tilde{\epsilon}_t,k) - f \cdot k - \hat{d}_t \cdot v \cdot k,$$

and $q^*(w,\epsilon_t,k)$ denotes the firm's optimal quantity in period t. Thus $q^*(w,\epsilon_t,k) = k$ whenever $P(w,\epsilon_t,K) > w$, while $q^*(\cdot)$ is indeterminate in the range $[0,k]$ if $P(w,\epsilon_t,K) = w$. Individual firms are indifferent about idling any part of their capacity once the market price drops down to w and, as a consequence, $P(w,\epsilon_t,K) \geq w$. This market-clearing condition can always be met provided $\underline{\epsilon} \cdot P^o(0) \geq w$.

In a competitive equilibrium, the aggregate capacity level must be chosen such that for each atomistic firm: $\Gamma(k|K^*) = 0$. By construction,

$$[P(w,\tilde{\epsilon}_t,K) - w] \cdot q^*(w,\tilde{\epsilon}_t) = [P(w,\tilde{\epsilon}_t,K) - w] \cdot k,$$

for all $\tilde{\epsilon}_t$. Solving the equation $\Gamma(k|K^*) = 0$ therefore yields:

$$(1-\alpha) \sum_{t=1}^{T} E[P(w,\tilde{\epsilon}_t,K^*)] \cdot \gamma^t = \qquad (20)$$

$$v \cdot \left[1 - \alpha \cdot \sum_{t=1}^{T} \hat{d}_t \cdot \gamma^t \right] + (1-\alpha) \cdot \sum_{t=1}^{T} \{f + w\} \cdot \gamma^t.$$

Dividing by $(1-\alpha)$ in (20) and recalling the definition of the tax factor, Δ:

$$\Delta = \frac{1 - \alpha \sum_{t=1}^{T} \hat{d}_t \cdot \gamma^t}{1-\alpha}$$

we conclude that the right-hand side of (20) is exactly equal to $LC \cdot \sum_{t=1}^{T} \gamma^t$ and therefore:

$$E\left[P(w, \tilde{\epsilon}_t, K^*)\right] = LC. \tag{21}$$

The expected equilibrium price in period t is equal to::

$$E\left[P(w, \tilde{\epsilon}, K^*)\right] = \int_{\underline{\epsilon}}^{\epsilon(K^*,w)} w\ h(\epsilon)\ d\epsilon + \int_{\epsilon(K^*,w)}^{\bar{\epsilon}} \epsilon \cdot P^o(K^*)\ h(\epsilon)\ d\epsilon. \tag{22}$$

We next demonstrate that $E\left[P(w, \tilde{\epsilon}, \cdot)\right]$ is decreasing in K. For any $K_1 < K_2$, we can write $E\left[P(w, \tilde{\epsilon}, K_1)\right]$ as:

$$\int_{\underline{\epsilon}}^{\epsilon(K_1,w)} w\ h(\epsilon)\ d\epsilon + \int_{\epsilon(K_1,w)}^{\epsilon(K_2,w)} \epsilon \cdot P^o(K_1)\ h(\epsilon)\ d\epsilon + \int_{\epsilon(K_2,w)}^{\bar{\epsilon}} \epsilon \cdot P^o(K_1)\ h(\epsilon)\ d\epsilon \tag{23}$$

and similarly $E\left[P(w, \tilde{\epsilon}_t, K_2)\right]$ can be expressed as:

$$\int_{\underline{\epsilon}}^{\epsilon(K_1,w)} w\ h(\epsilon)\ d\epsilon + \int_{\epsilon(K_1,w)}^{\epsilon(K_2,w)} w\ h(\epsilon)\ d\epsilon + \int_{\epsilon(K_2,w)}^{\bar{\epsilon}} \epsilon \cdot P^o(K_2)\ h(\epsilon)\ d\epsilon. \tag{24}$$

Since $\epsilon \cdot P^o(K_1) \geq w$ for $\epsilon(K_1, w)$ and $P^o(K_1) > P^o(K_2)$, we conclude that each of the three integrals in (23) is respectively equal to or larger than its counterpart in (24).

Suppose the condition

$$\text{Prob}\left[\tilde{\epsilon} \geq \frac{w}{LC}\right] = 1 \tag{25}$$

is met. By construction, we then have $\epsilon(K^*, w) = \underline{\epsilon}$ and therefore

$$E\left[P(w, \tilde{\epsilon}, K^*)\right] = P^o(K^*).$$

Equation (21) yields that $K^* = K^o$, with K^o defined as $P^o(K^o) \equiv LC$. Conversely, if (25) is not met, then the equilibrium capacity level must satisfy $K^* > K^o$. To see this, assume to the contrary that $K^o \geq K^*$. That would lead to a contradiction since by (22) :

$$\begin{aligned} E[P(w, \tilde{\epsilon}_t, K^*)] &\geq E[P(w, \tilde{\epsilon}_t, K^o)] \\ &> P^o(K^o) \\ &\equiv LC. \end{aligned} \tag{26}$$

The strict inequality in (26) follows from the fact that if the condition in (25) is not met, then $\underline{\epsilon} < \epsilon(K^o, w) \leq \bar{\epsilon}$. We thus conclude that $K^* > K^o$.

To show the upper bound on K^* claimed in Proposition 1, we note that the zero-profit condition again stipulates that:

$$E[P(w, \tilde{\epsilon}_t, K^*)] = w + f + c \cdot \Delta.$$

It follows from (22) that

$$E[P(w, \tilde{\epsilon}_t, K^*)] \leq \bar{\epsilon}\,(1 - H(\epsilon(K^*, w))) \cdot P^o(K^*) + w \cdot H(\epsilon(K^*, w))$$

where $H(\cdot)$ is the cumulative distribution function of the density $h(\cdot)$. Thus

$$[\bar{\epsilon} \cdot P^o(K^*) - w] \cdot [1 - H(\epsilon(K^*, w))] \geq f + c \cdot \Delta$$

and therefore

$$P^o(K^*) \geq \frac{LC}{\bar{\epsilon}},$$

which is equivalent to $K^* \leq D^o\left(\frac{LC}{\bar{\epsilon}}\right)$.

To demonstrate that $K^* \leq D^o(LFC)$ is another bound on the aggregate capacity in equilibrium, let K^+ denote the capacity level that would emerge if $w = 0$ and thus $LC = LFC$. Since firms would then always produce at capacity, we have:

$$E\left[P(w = 0, \tilde{\epsilon}_t, K^{**})\right] = P^o(K^{**}) = LFC.$$

At the same time,

$$E\left[P(w, \tilde{\epsilon}_t, K^*)\right] = LC,$$

or equivalently

$$E\left[P(w, \tilde{\epsilon}_t, K^*)\right] = \int_{\underline{\epsilon}}^{\epsilon(K^*,w)} w\; h(\epsilon)\; d\epsilon + \int_{\epsilon(K^*,w)}^{\bar{\epsilon}} \epsilon \cdot P^o(K^*)\; h(\epsilon)\; d\epsilon = w + LFC.$$

It follows that

$$P^o(K^{**}) = \int_{\epsilon(K^*,w)}^{\bar{\epsilon}} [\epsilon \cdot P^o(K^*) - w]\; h(\epsilon)\; d\epsilon. \tag{27}$$

If $w = 0$, (27) would require $K^* = K^{**}$. The right-hand side of (27) is decreasing in w since its derivative–by Leibniz' rule–is given by: $-[1 - H(\epsilon(K^*, w))]$. At the same time, the right-hand side of (27) is decreasing in K^*. Thus for any $w > 0$, (27) can only hold if $K^* < K^{**}$.

It remains to show that in equilibrium all investments will occur initially, that is, no firm will make capacity investments at a date $t \geq 1$. Assume to the contrary, that some firms will invest at date $t = 0$ and others (or the same firm) will possibly add additional capacity at subsequent dates. The resulting sequence of aggregate capacity levels $\mathbf{K} = (K_1, ..., K_T)$ will therefore be weakly increasing. The condition of zero economic profits dictates that in equilibrium both an investment at date 0 and an investment at date 1 have expected future cash flows with zero present values. Without loss of generality, we can normalize each one of these investments to one unit of capacity. Thus:

$$\Gamma_0(1|\mathbf{K}) = \sum_{t=1}^{T} \left\{ E\left[P(w, \tilde{\epsilon}_t, K_t) - w - f - \alpha \cdot \tilde{I}_t \right] \right\} \gamma^t - v = 0, \tag{28}$$

with $\tilde{I}_t = P(w, \tilde{\epsilon}_t, K_t) - w - f - \hat{d}_t \cdot v$ and

$$\Gamma_1(1|\mathbf{K}) = \sum_{t=2}^{T} \left\{ E\left[P(w, \tilde{\epsilon}_t, K_t) - w - f - \alpha \cdot \tilde{I}_t \right] \right\} \gamma^{t-1} - v = 0, \tag{29}$$

with $\tilde{I}_t = P(w, \tilde{\epsilon}_t, K_t) - w - f - \hat{d}_{t-1} \cdot v$ for $2 \leq t \leq T-1$ and

$$\tilde{I}_T = P(w, \tilde{\epsilon}_T, K_T) - w - f - (\hat{d}_{T-1} + \hat{d}_T) \cdot v$$

The investment undertaken at date $t = 1$ has a useful life of T periods and can thus be used until $t = T + 1$. However, since we effectively assume that the market closes at $t = T$ and firms will earn no revenue beyond that date, the asset is effectively impaired and therefore can be written off at $t = T$. As shown above, the zero-profit condition for the investment at date 0 requires that:

$$\sum_{t=1}^{T} E\left[P(w, \tilde{\epsilon}_t, \mathbf{K})\right] \cdot \gamma^t = LC \cdot \sum_{t=1}^{T} \gamma^t.$$

Since $K_1 \leq K_2 \leq ... \leq K_T$, the expected equilibrium prices are weekly decreasing over time and

$$\sum_{t=2}^{T} E[P(w, \tilde{\epsilon}_t, K_t)]\gamma^{t-1} \leq LC \cdot \sum_{t=2}^{T} \gamma^{t-1}.$$

Recalling that $LC = w + \gamma + c \cdot \Delta$, we find that:

$$\Gamma_1(1 \mid \mathbf{K}) \leq \sum_{t=2}^{T-1} \{(1-\alpha) \cdot \Delta \cdot c + \alpha \cdot \hat{d}_{t-1} \cdot v\} \cdot \gamma^{t-1} + \{(1-\alpha) \cdot \Delta \cdot c + \alpha\ (\hat{d}_{T-1} + \hat{d}_T) \cdot v\} \gamma^{T-1} - v. \tag{30}$$

By definition of Δ and c,

$$\sum_{t=2}^{T+1}\{(1-\alpha)\cdot\Delta\cdot c+\alpha\cdot\hat{d}_{t-1}\cdot v\}\gamma^{t-1}=v.$$

Therefore (30) can be expressed as:

$$\Gamma_1(1\mid \mathbf{K})\leq \alpha\cdot\hat{d}_T\cdot\gamma^{T-1}-[(1-\alpha)\cdot\Delta\cdot c+\alpha\cdot\hat{d}_T\cdot v]\gamma^T. \tag{31}$$

Thus it remains to show that the right-hand side of (31) is strictly negative, or equivalently,

$$\alpha\cdot\hat{d}_T<[(1-\alpha)\cdot\Delta\cdot c+\alpha\cdot\hat{d}_T\cdot v]\cdot\gamma. \tag{32}$$

Since

$$\begin{aligned}\Delta &= \frac{1-\alpha\cdot\sum_{t=1}^{T}\hat{d}_t\cdot\gamma^t}{1-\alpha},\\ c &= \frac{v}{\sum_{i=1}^{T}\gamma^i},\end{aligned}$$

and $(1-\gamma)=r\cdot\gamma$, the inequality in (32) becomes:

$$\frac{1}{\sum\gamma^i}\,[1-\alpha\sum_{i=1}^{T}\hat{d}_i\cdot\gamma^i]>\alpha\cdot d_T\cdot r\cdot\sum_{i=1}^{T}\gamma^i,$$

or equivalently:

$$1-\alpha\,[\hat{d}_1\cdot\gamma+...+\hat{d}_T[\gamma^T+r\sum_{i=1}^{T}\gamma^i]]>0.$$

This last inequality indeed holds because for any T,

$$\gamma^T+r\cdot\sum_{i=1}^{T}\gamma^i=1,$$

and $d_1\cdot\gamma+d_2\cdot\gamma^2+...d_{T-1}\cdot\gamma^{T-1}+d_T<1.$ ■

Proof of Corollary 1.

If fixed operating costs are avoidable and the aggregate capacity level is equal to K, the expected equilibrium price in period t is equal to:

$$E\left[P(w',\tilde{\epsilon},K)\right]=\int_{\underline{\epsilon}}^{\epsilon(K,w')}w'\,h(\epsilon)\,d\epsilon+\int_{\epsilon(K,w')}^{\bar{\epsilon}}\epsilon\cdot P^o(K)\,h(\epsilon)\,d\epsilon,$$

where $w' \equiv w+f$. We note that $\epsilon(K,w')$ is weakly increasing in w'. Similar to the argument in the proof of Proposition 1, we next demonstrate that $E[P(w',\tilde{\epsilon},\cdot)]$ is increasing in w'. For any $w_1' < w_2'$, we can write $E[P(w_1',\tilde{\epsilon},K)]$ as:

$$\int_{\underline{\epsilon}}^{\epsilon(K,w_1')} w_1' \cdot h(\epsilon)\, d\epsilon + \int_{\epsilon(K,w_1')}^{\epsilon(K,w_2')} \epsilon \cdot P^o(K)\, h(\epsilon)\, d\epsilon + \int_{\epsilon(K,w_2')}^{\bar{\epsilon}} \epsilon \cdot P^o(K)\, h(\epsilon)\, d\epsilon. \tag{33}$$

Similarly $E[P(w,\tilde{\epsilon},K_2)]$ can be expressed as:

$$\int_{\underline{\epsilon}}^{\epsilon(K,w_1')} w_2'\, h(\epsilon)\, d\epsilon + \int_{\epsilon(K,w_1')}^{\epsilon(K,w_2')} w_2'\, h(\epsilon)\, d\epsilon + \int_{\epsilon(K,w_2')}^{\bar{\epsilon}} \epsilon \cdot P^o(K)\, h(\epsilon)\, d\epsilon. \tag{34}$$

Since $\epsilon \cdot P^o(K) \geq w$ for $\epsilon > \epsilon(K,w)$ and $w_1' < w_2'$, we conclude that each of the three integrals in (33) is respectively at least as large as its counterpart in (34). It should be noted that the claimed monotonicity here is strict whenever $\epsilon(K,w_2') > \underline{\epsilon}$.

Denoting the equilibrium capacity levels with avoidable and unavoidable fixed costs by K^* and K^{**} respectively, it follows directly from the arguments in Proposition 1 that:

$$E[P(w,\tilde{\epsilon},K^*)] = E[P(w+f,\tilde{\epsilon},K^{**})] = LC.$$

Since $E[P(w,\tilde{\epsilon},K)]$ is decreasing in K and strictly increasing in w whenever $\epsilon(K,w+f) > \underline{\epsilon}$, we conclude that $K^{**} > K^*$ whenever

$$\text{Prob}[\tilde{\epsilon} \geq \frac{w+f}{LC}] < 1,$$

as claimed in Corollary 1. ■

Proof of Proposition 3.

Given any capacity investment k at date 0, the monopolist will choose the optimal quantity in period t as

$$q^*(w,\epsilon_t,k) = \begin{cases} k & \text{if} \quad \epsilon_t \geq \epsilon(k,w) \\ q(w,\epsilon_t) & \text{if} \quad \epsilon_t < \epsilon(k,w), \end{cases}$$

where $q(w,\epsilon)$ solves the equation: $\epsilon \cdot MR^o(q(w,\epsilon)) = w$, and

$$\epsilon(k,w) = \begin{cases} \bar{\epsilon} & \text{if} \quad \bar{\epsilon} \cdot MR^o(k) \leq w \\ \frac{w}{MR^o(k)} & \text{if} \quad \bar{\epsilon} \cdot MR^o(k) \geq w \geq \underline{\epsilon} \cdot MR^o(k) \\ \underline{\epsilon} & \text{if} \quad \underline{\epsilon} \cdot MR^o(k) \geq w. \end{cases}$$

We note that $\epsilon(k, w)$ is increasing in k and that $q(w, \epsilon) < k$ whenever $\epsilon < \epsilon(k, w)$.

For any capacity level k, the present value of expected cash flows becomes:

$$\Gamma(k) = \sum_{t=1}^{T}\{E\left[\tilde{\epsilon}_t \cdot R^o(q^*(w, \tilde{\epsilon}_t, k)) - w \cdot q^*(w, \tilde{\epsilon}_t, k) - f \cdot k - \alpha \cdot \tilde{I}_t\right]\} \cdot \gamma^t - v \cdot k,$$

where

$$\tilde{I}_t = \tilde{\epsilon}_t \cdot R^o(q^*(\cdot)) - w \cdot q^*(\cdot) - f \cdot k - \hat{d}_t \cdot v \cdot k.$$

Define

$$\hat{\Gamma}(k) = \frac{\Gamma(k)}{(1-\alpha) \cdot \sum_{t=1}^{T} \gamma^t}.$$

Recalling the definition of the unit capacity cost, c, the tax factor, Δ, and the levelized fixed cost, LFC, the monopolist's objective is to maximize:

$$\hat{\Gamma}(k) = E[\tilde{\epsilon} \cdot R^o(q^*(w, \tilde{\epsilon}, k)) - w \cdot q^*(w, \tilde{\epsilon}, k)] - LFC \cdot k.$$

Thus,

$$\hat{\Gamma}'(k) = \int_{\epsilon(k,w)}^{\bar{\epsilon}} [\epsilon \cdot MR^o(k) - w]\, h(\epsilon)\, d\epsilon - LFC, \tag{35}$$

where $MR^o(k) = \frac{d}{dk}R^o(\cdot)$. Since for any random variable X, $E[f(X)] \leq E[\max\{0, f(X)\}]$, it follows that

$$\begin{aligned}
\hat{\Gamma}'(k) &\geq \int_{\underline{\epsilon}}^{\bar{\epsilon}} [\epsilon \cdot MR^o(k) - w]\, h(\epsilon)\, d\epsilon - LFC \\
&= MR^o(k) - w - LFC \quad (36)\\
&= MR^o(k) - LC. \quad (37)
\end{aligned}$$

By definition $MR^o(k^o) \equiv LC$. Therefore $k^* \geq k^o$. We next demonstrate that $k^* = k^o$ if and only if the condition

$$\text{Prob}\left[\tilde{\epsilon} \geq \frac{w}{LC}\right] = 1 \tag{38}$$

holds. This condition is equivalent to $\epsilon(k^o, w) = \underline{\epsilon}$, because $\epsilon(k^o, w) > \underline{\epsilon}$ if and only if $\underline{\epsilon} \cdot MR^o(k^o) < w$. Referring back to (35), we obtain:

$$\hat{\Gamma}'(k^o) = MR^o(k^o) - LC = 0$$

if and only if condition (38) is met. To demonstrate the upper bound on k^* claimed in Proposition 3, we note that

$$\begin{aligned}\hat{\Gamma}'(k) &\leq [MR^o(k)\cdot\bar{\epsilon} - w]\cdot[1 - H(\epsilon(k,w))] - LFC.\\ &\leq \bar{\epsilon}\cdot MR^o(k) - LC.\end{aligned}$$

Therefore $\hat{\Gamma}'(k) < 0$ for any $k > k^+$ with k^+ given by $MR^o(k^+) = \frac{LC}{\bar{\epsilon}}$.

To show that an upper bound on capacity is also provided by k^+ defined by the requirement that $MR^o(k^+) = LFC \equiv LC - w$, we first state an auxiliary result which ranks the maximizers of two functions, $\Gamma_1(k)$ and $\Gamma_2(k)$. Suppose both functions are differentiable on the positive real line.

Auxiliary Lemma: *If k_1^* is the unique maximizer of $\Gamma_1(k)$ and k_2^* is the unique maximizer of $\Gamma_2(k)$, then $k_2^* \geq k_1^*$ provided $\Gamma_2'(k) \geq \Gamma_1'(k)$ for all k.*

Proof of Auxiliary Lemma: Suppose to the contrary that $k_1^* > k_2^*$. By definition:

$$\Gamma_1(k_1^*) > \Gamma_1(k_2^*) \text{ and } \Gamma_2(k_2^*) > \Gamma_2(k_1^*).$$

Adding these two inequalities yields:

$$\Gamma_1(k_1^*) - \Gamma_1(k_2^*) > \Gamma_2(k_1^*) - \Gamma_2(k_2^*),$$

or

$$\int_{k_2^*}^{k_1^*} [\Gamma_1'(u) - \Gamma_2'(u)]\,du > 0.$$

Since $\Gamma_1'(u) \leq \Gamma_2'(u)$, we obtain a contradiction. ■

To complete the proof of Proposition 3, we identify $\Gamma_1(\cdot)$ in the Auxiliary Lemma with the monopolist's problem, that is, $\Gamma_1(k) = \hat{\Gamma}(k)$. Let $\Gamma_2(k)$ be given by the corresponding function when $w = 0$. Thus $\Gamma_2(k) = \hat{\Gamma}(k|w = 0)$. If $w = 0$, the firm always produces at capacity and therefore k_2^* is such that $MR^o(k_2^*) = LFC$. To invoke the Auxiliary Lemma, we verify that

$$\begin{aligned}\Gamma_2'(k) &= MR^o(k) - LFC\\ &\leq \Gamma_1'(k) = \int_{\epsilon(k,w)}^{\bar{\epsilon}} [\epsilon\cdot MR^o(k) - w]\,h(\epsilon)\,d\epsilon - LFC.\end{aligned}$$

This inequality indeed holds because

$$\frac{\partial}{\partial w}\int_{\epsilon(k,w)}^{\bar{\epsilon}} [\epsilon\cdot MR^o(k) - w]\,h(\epsilon)\,d\epsilon = -\left[1 - H\left(\epsilon(k,w)\right)\right] \leq 0,$$

and

$$MR^o(k) = \int_{\epsilon(k,w=0)}^{\bar{\epsilon}} \epsilon \cdot MR^o(k) \cdot h(\epsilon)\, d\epsilon.$$

Thus the monopolist's optimal capacity choice satisfies $k^* \le k_2^*$, where $MR^o(k_2^*) = LFC$.

Combining the two upper bounds on capacity, we conclude that $k^* \le k^+$, where

$$MR^o(k^+) = LC^- = \max\left\{LFC, \frac{LC}{\bar{\epsilon}}\right\}.$$

■

Proof of Corollary 4.

To show that the monopolist will choose a higher level of capacity if market volatility increases in the sense of a mean-preserving spread, we again invoke the Auxiliary Lemma in the Proof of Proposition 3. Specifically, we show that

$$\hat{\Gamma}'(k|h_2(\cdot)) \ge \hat{\Gamma}'(k|h_1(\cdot))$$

for all k. As shown in connection with Proposition 3:

$$\begin{aligned}\Gamma'(k|h_1(\cdot)) &= \int_{\epsilon(k,w)}^{\bar{\epsilon}} [\epsilon \cdot MR^o(k) - w] h_1(\epsilon_1)\, d\epsilon_1 - LFC \\ &= \int_{\underline{\epsilon}}^{\bar{\epsilon}} V(\epsilon_1) \cdot h_1(\epsilon_1)\, d\epsilon_1 - LFC\end{aligned}$$

where[37]

$$V(\epsilon) \equiv \begin{cases} 0 & \text{if } \epsilon(k,w) \cdot MR^o(k) < w \\ \epsilon \cdot MR^o(k) - w & \text{if } \epsilon(k,w) \cdot MR^o(k) \ge w. \end{cases}$$

If $\tilde{\epsilon}_2$ is obtained by a mean-preserving spread of $\tilde{\epsilon}_1$, then $\tilde{\epsilon}_2 = \tilde{\epsilon}_1 + \tilde{\mu}$ where $\tilde{\mu}$ is an unbiased random variable such that

$$\int_{\underline{\mu}}^{\bar{\mu}} \mu \cdot g(\mu|\epsilon_1)\, d\mu = 0$$

for all ϵ_1. Since $h_2(\epsilon_2) = g(\mu|\epsilon_1) \cdot h_1(\epsilon_1)$, we obtain:

$$\begin{aligned}\hat{\Gamma}'(k|h_2(\cdot)) &= \int_{\underline{\epsilon_1}}^{\bar{\epsilon}_1} \int_{\underline{\mu}}^{\bar{\mu}} V(\epsilon_1 + \mu) \cdot g(\mu|\epsilon_1) \cdot h_1(\epsilon_1) d\mu d\epsilon_1 - LFC \\ &\ge \int_{\underline{\epsilon_1}}^{\bar{\epsilon}_1} V\left(\epsilon_1 + \int_{\underline{\mu}}^{\bar{\mu}} \mu \cdot g(\mu|\epsilon_1)\, d\mu\right) h_1(\epsilon_1) d\epsilon_1 - LFC \\ &= \int_{\underline{\epsilon_1}}^{\bar{\epsilon}_1} V(\epsilon_1)\, h_1(\epsilon_1)\, d\epsilon_1 - LFC \\ &= \hat{\Gamma}'(k|h_1(\cdot)).\end{aligned}$$

[37] For notational simplicity, we suppress the dependence of $V(\cdot)$ on k and w.

The preceding inequality follows from Jensen's inequality and the convexity of $V(\cdot)$ in ϵ. Thus, $k_2^* \geq k_1^*$.[38] ■

Proof of Proposition 4.

Claim 1: *For every pair of capacity investments* (k^1, k^2) *and every realization of* ϵ_t, *there exists a unique Nash equilibrium*

$$(q_t^1(k^1, k^2, \epsilon_t), q_t^2(k^1, k^2, \epsilon_t))$$

in period t.

Proof of Claim 1: Define $q(\epsilon_t)$ by the requirement that

$$\epsilon_t \cdot MR^o(q(\epsilon_t)|q(\epsilon_t)) = w.$$

Thus $q(\epsilon_t)$ denotes the equilibrium quantities the parties would supply in a symmetric, capacity-unconstrained equilibrium. We distinguish three scenarios.

Scenario 1: $k^i > q(\epsilon_t)$ for $1 \leq i \leq 2$. In this scenario, both firms will supply $q_t = q(\epsilon_t)$ in equilibrium. To see that this equilibrium is unique, suppose, to the contrary, that another pair (q^1, q^2) constitutes a Nash equilibrium in period t. Then, if $q^i < k^i$, it must be that

$$\epsilon_t \cdot MR^o(q^1|q^2) = w = \epsilon_t \cdot MR^o(q^2|q^1)$$

which implies $q^i = q(\epsilon_t)$. Similarly, there cannot be an equilibrium in which either $q^i = k^i$ or both.

Scenario 2: $k^i \leq q(\epsilon_t)$ for $1 \leq i \leq 2$. In this case, the unique equilibrium is for both firms to supply $q_t^i = k^i$ in period t because

$$\epsilon_t \cdot MR^o(q^i|k^j) \geq w$$

for all $q^i \leq k^i$.

Scenario 3: $k^i > q(\epsilon_t)$ and $k^j \leq q(\epsilon_t)$. It is then a Nash equilibrium for firm j to supply k^j and for firm i to choose:

$$q_t^i \in \underset{q \leq k^i}{\operatorname{argmax}} \{\epsilon_t \cdot R^o(q|k^j) - w \cdot q\}.$$

[38] The Auxiliary Lemma requires unique maximizers which follows from the fact that $\Gamma'(\cdot|h_i(\cdot))$ is strictly decreasing.

Clearly, there cannot be an equilibrium in which $q^j < k^j$, regardless of whether firm i exhausts its available capacity or not.

Claim 2: *Given the limited price volatility condition, suppose that firm j chooses the capacity level $k^j = k^*$. In equilibrium, firm j will then supply $q_t^j = k^*$ for all ϵ_t and any capacity level k^i.*

Proof of Claim 2: If $k^i \leq k^*$, the condition of limited price volatility ensures that

$$\begin{aligned} & \epsilon_t \cdot MR^o(k^*|k^i) - w \\ \geq\ & \epsilon_t \cdot MR^o(k^*|k^*) - w \\ =\ & \epsilon_t \cdot LC - w \geq 0. \end{aligned}$$

Thus firm j will supply $k^j = k^*$ for any ϵ_t and any q^i which satisfies $q^i \leq k^i \leq k^*$.

If $k^i > k^*$ and $k^j = k^*$, the unique Nash equilibrium $(q_t^1(k^1, k^2, \epsilon_t), q_t^2(k^1, k^2, \epsilon_t))$, given ϵ_t, must correspond to either Scenario 2 or 3 in the proof of Claim 1. To see this, we note that in Scenario 1:

$$k^i > k^j = k^* > q(\epsilon_t),$$

and

$$\epsilon_t \cdot MR^o(q(\epsilon_t)|q(\epsilon_t)) = w.$$

Yet that would lead to a contradiction on account of the inequalities:

$$\epsilon_t \cdot MR^o(q(\epsilon_t)|q(\epsilon_t)) > \epsilon_t \cdot MR^o(k^*|k^*) = \epsilon_t \cdot LC > w.$$

Thus, either Scenario 2 or 3 applies if $k^j = k^*$ and, as shown in Claim 1, in either one of these $q_t^j(k^i, k^j = k^*, \epsilon_t) = k^*$.

Claim 3: *Given $k^j = k^*$, it is a best response for firm i to choose the initial capacity level $k^i = k^*$.*

Proof of Claim 3: The argument adapts the notation in the proof of Proposition 3. Given any k^i and $q^i(k^i, k^j = k^*, \epsilon_t)$, firm i's Nash equilibrium quantity in period t is given by

$$q^i(k^i, k^*, \epsilon_t) = \begin{cases} k^i & \text{if } \epsilon_t \geq \epsilon(k^i|k^*) \\ q(k^*, \epsilon_t) & \text{if } \epsilon_t \leq \epsilon(k^i|k^*) \end{cases}$$

where $q(k^*, \epsilon_t)$ is uniquely determined by

$$\epsilon_t \cdot MR^o(q(k^*, \epsilon_t)|k^*) = w,$$

and

$$\epsilon(k^i|k^*) = \begin{cases} \bar{\epsilon} & \text{if } \bar{\epsilon} \cdot MR^o(k^i|k^*) \leq w \\ \frac{w}{MR^o(k^i|k^*)} & \text{if } \bar{\epsilon} \cdot MR^o(k^i|k^*) \geq w \geq \underline{\epsilon} \cdot MR^o(k^i|k^*) \\ \underline{\epsilon} & \text{if } \underline{\epsilon} \cdot MR^o(k^i|k^*) \geq w. \end{cases}$$

It follows that $\epsilon(k^i|k^*)$ is increasing in k^i and $q(k^*, \epsilon_t) < k^i$ if and only if $\epsilon_t < \epsilon(k^i|k^*)$. Given $k^j = k^*$, firm i's objective function can then be expressed as

$$\Gamma(k^i|k^*) =$$
$$\sum_{t=1}^{T} \left\{ E\left[\tilde{\epsilon}_t \cdot R^o(q^i(k^i, k^*, \epsilon_t)|k^*) - w \cdot q^i(k^i, k^*, \epsilon_t) - f \cdot k^i - \alpha \cdot \tilde{I}_t\right]\right\} \gamma^t - v \cdot k^i,$$

where

$$\tilde{I}_t = \epsilon_t \cdot R^o(q^i(\cdot)|k^*) - w \cdot q^i(\cdot) - f \cdot k^i - d_t \cdot v \cdot k^i.$$

Using the same normalization as in the proof of Proposition 3, we define:

$$\hat{\Gamma}(k^i|k^*) = \Gamma(k^i|k^*) \cdot \frac{1}{(1-\alpha) \cdot \sum_{t=1}^{T} \gamma^t},$$

with

$$\hat{\Gamma}(k^i|k^*) = E\left[\tilde{\epsilon} \cdot R^o(q^i(k^i, k^*, \tilde{\epsilon})|k^*) - w \cdot q^i(k^i, k^*, \tilde{\epsilon})\right] - LFC \cdot k^i.$$

It follows that

$$\frac{\partial}{\partial k^i}\hat{\Gamma}(k^i|k^*) = \int_{\epsilon(k^i|k^*)}^{\bar{\epsilon}} \left[\epsilon \cdot MR^o(k^i|k^*) - w\right] h(\epsilon)\, d\epsilon - LFC. \tag{39}$$

The right-hand side of (39) is decreasing in k^i. Furthermore, the limited price volatility condition implies $\epsilon(k^*|k^*) = \underline{\epsilon}$. Since, by definition, $MR^o(k^*|k^*) = LC$, it follows that:

$$\frac{\partial}{\partial k^i}\hat{\Gamma}(k^i|k^*)\Big|_{k^i=k^*} = 0,$$

which shows that $k^i = k^*$ is a best response to $k^j = k^*$. Thus, $(k^1, k^2) = (k^*, k^*)$ followed by $(q_t^1, q_t^2) = (k^*, k^*)$ in each period is a subgame perfect equilibrium outcome. ∎

References

Atkinson, A. A., R. S. Kaplan, E. M. Matsumura, and S. M. Young (2011), *Management Accounting: Information for Decision-Making and Strategy Execution.*, 6th ed., Prentice Hall, New York.

Balakrishnan, R., and K. Sivaramakrishnan (2002), "A Critical Overview of Full-Cost Data for Planning and Pricing." *Journal of Management Accounting Research*, 14, 3–31.

Baldenius, T., A. Nezlobin, and I. Vaysman (2014), "Managerial Performance Evaluation Under Uncertain Demand." *Working paper, U.C. Berkeley.*

Banker, R. D., and J. S. Hughes (1994), "Product Costing and Pricing." *The Accounting Review*, 69, 479–494.

Banker, R. D., I. Hwang, and B. K. Mishra (2002), "Product Costing and Pricing under Long-Term Capacity Commitment." *Journal of Management Accounting Research*, 14, 79–97.

Borenstein, S. (2000), "Understanding Competitive Pricing and Market Power in Wholesale Electricity Markets." *The Electricity Journal*, 13, 49–57.

Campbell, M. (2008), "The Drivers of the Levelized Cost of Electricity for Utility-Scale Photovoltaics." *White Paper: SunPower Corporation.*

Carlton, D. W., and J. M. Perloff (2005), *Modern Industrial Organization.*, 4th ed., Pearson/Addison Wesley, New York.

Cooper, R., and R. S. Kaplan (1988), "How Cost Accounting Distorts Product Costs." *Management Accounting*, 69, 20–28.

Dangl, T. (1999), "Investment and Capacity Choice under Uncertain Demand." *Journal of Operational Research*, 117, 415–428.

Davidson, C., and R. Deneckere (1986), "Long-Run Competition in Capacity, Short-Run Competition in Price, and the Cournot Model." *RAND Journal of Economics*, 17, 404–415.

Dutta, S., and S. Reichelstein (2010), "Decentralized Capacity Management and Internal Pricing." *Review of Accounting Studies*, 15, 442–478.

Ewert, R., and A. Wagenhofer (2008), *Interne Unternehmensrechnung.*, 7th ed., Springer, Heidelberg.

Göx, R. (2002), "Capacity Planning and Pricing under Uncertainty." *Journal of Management Accounting Research*, 14, 59–78.

Grabowski, H., and J. Vernon (1990), "A New Look at the Returns and Risks to Pharmaceutical R&D." *Management Science*, 36, 804–821.

Grant, S., and J. Quiggin (1996), "Capital Precommitment and Competition in Supply Schedules." *Journal of Industrial Economics*, XLIV, 427–441.

Horngren, C. T., S. M. Datar, and M. V. Rajan (2012), *Cost Accounting - A Managerial Emphasis.*, 14th ed., Prentice Hall, Boston New York San Francisco.

Isik, M., K. H. Coble, D. Hudson, and L. O. House (2003), "A Model of Entry-Exit Decisions and Capacity Choice under Demand Uncertainty." *Agricultural Economics*, 28, 215–224.

Kloock, J. (1997), *Betriebliches Rechnungswesen*, 2nd ed., Lohmar/Köln.

Kreps, D. M., and J. A. Scheinkman (1983), "Quantity Precommitment and Bertrand Competition Yield Cournot Outcomes." *Bell Journal of Economics*, 14, 326–337.

Küpper, H.-U. (1985), "Investitionstheoretische Fundierung der Kostenrechnung." *Zeitschrift für betriebswirtschaftliche Forschung*, 37, 26–46.

Küpper, H.-U. (2009), "Investment-Based Cost Accounting as a Fundamental Basis of Decision-Oriented Management Accounting." *Abacus*, 45, 249–274.

Laffont, J. J., and J. Tirole (2000), *Competition in Telecommunications.*, MIT Press, Cambridge, MA.

Lengsfeld, S., and U. Schiller (1998), "Strategische und operative Planung mit der Prozesskostenrechnung." *Zeitschrift für Betriebswirtschaft*, 68, 525–547.

Mas-Colell, A., M. D. Whinston, and J. R. Green (1995), *Microeconomic Theory.*, Oxford University Press.

Meyer, R. A. (1975), "Monopoly Pricing and Capacity Choice under Uncertainty." *American Economic Review*, 65, 326–337.

MIT (2007), "The Future of Coal." `http://web.mit.edu/coal`.

Nezlobin, A. (2012), "Accrual Accounting, Informational Sufficiency, and Equity Valuation." *Journal of Accounting Research*, 50, 233–273.

Nezlobin, A., M. V. Rajan, and S. Reichelstein (2012), "Dynamics of Rate-of-Return Regulation." *Management Science*, 58, 980–995.

Pindyck, R. S. (1988), "Irreversible Investment, Capacity Choice, and the Value of the Firm." *American Economic Review*, 78, 969–985.

Pittman, B. (2009), "Whom Are You Calling Irrational? Marginal Costs, Variable Costs, and the Pricing Practices of Firms." *Working Paper, Department Of Justice, Washington DC.*

Preinreich, G. A. D. (1938), "Annual Survey of Economic Theory: The Theory of Depreciation." *Econometrica*, 6, 219–241.

Rajan, M., and S. Reichelstein (2009), "Depreciation Rules and The Relation Between Marginal and Historical Cost." *Journal of Accounting Research*, 47, 1–43.

Reichelstein, S., and M. Yorston (2013), "The Prospects for Cost Competitive Solar PV Power." *Energy Policy*, 55, 117–127.

Rogerson, W. (2008), "Inter-Temporal Cost Allocation and Investment Decisions." *Journal of Political Economy*, 116, 931–950.

Rogerson, W. (2011), "On the Relationship Between Historic Cost, Forward Looking Cost and Long Run Marginal Cost." *Review of Network Economics*, 10, Article 2.

Ross, S., R. Westerfield, and J. Jaffe (2005), *Corporate Finance.*, McGrawHill Publishers, New York, N.Y.

Zimmerman, J. (2010), *Accounting for Decision Making and Control.*, 7th ed., McGraw-Hill/Irwin, New York.