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Abstract:
Managerial Flexibility in Levelized Cost Measures

Many irreversible long-run capital investments entail opportunities for managers to respond flexibly to changes in the economic environment. However, common levelized cost measures designed to guide decision-making implicitly assume that the values of random economic variables are known with certainty when investment decisions are made. This assumption implies, often incorrectly, that managerial flexibility carries zero value. The levelized cost of electricity is a common example in the energy literature. We improve levelized cost measures by deriving an expansion that accounts for both uncertainties in relevant variables and the value of managerial flexibility in responding to them. We apply our method to quantify the value of flexibility in an example decision problem in which an operator of a natural gas powered electric generating facility evaluates whether to invest in carbon capture capabilities.

Keywords: Levelized cost, managerial flexibility, uncertainty, investment decision-making, operational decision-making
1 Introduction

Decision-making about irreversible long-run capital investments is an essential managerial duty in industries such as electricity generation. Such investments often entail opportunities to respond flexibly to a variety of signals. Since at least 1994, when Dixit and Pindyck published their seminal work on investments under uncertainty, managers considering such investments have had a corporate finance framework with which to evaluate such opportunities. This well-known framework recommends that managers perform a discounted cash flow (DCF) analysis whereby the value of flexibility is explicitly included. Managerial flexibility includes the ability to defer or stage investment decisions and expand or contract the scale of assets. The value of this flexibility is generally captured by the value of “real options” that are embedded in the investment opportunity.1

In certain industries, it is common to evaluate investment opportunities on the basis of their cost effectiveness. The so-called “levelized product cost” (LPC) developed by Reichelstein and Rohlfing-Bastian (2015) provides decision-makers in these contexts with a relevant cash-based cost measure (i.e., defined entirely in terms of cashflows) that can guide long-run investment decision-making. The LPC is the average unit price that a facility must earn over all of its output for the investment. In the energy literature, this concept is known as the levelized cost of electricity (LCOE), which is defined as “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). Generally, an investment is deemed cost-competitive with respect to other facilities when it produces the same output (e.g., electricity) at the lowest LPC (e.g., LCOE). Since the LPC ensures that the facility would cover all expenses and provide an acceptable return to investors, the measure is generally consistent with guidance from corporate finance that investors pursue opportunities with a net present value (NPV) at least equal to zero. When managerial flexibility exists, however, a wedge will remain between the guidance provided by the LPC and DCF analyses. This is because the latter metric accounts for managerial flexibility while the former does not.

The main contribution of this paper is the derivation of a cost measure that can guide

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1 For example, if a manager has the ability to invest today in a factory capable of producing 300 widgets per annum but designed to facilitate an expansion next year to produce 500 widgets, her appraisal of investment opportunity for the 300-widget factory should account for the embedded call option to expand in the future period.
long-run investment decision-making *in the presence of managerial flexibility*. We propose an expanded LPC for firms in competitive markets that allows managers to fully incorporate the value of capital and operational flexibility, which we subsequently define in greater detail. Reichelstein and Rohlfing-Bastian (2015) recognize the importance of uncertainty and include price volatility and a specific type of operational flexibility, namely, the ability to idle capacity when prices are low. In this work, we include the most general set of uncertainty within the LPC metric. This expanded LPC thus complements and expands the concepts developed by Reichelstein and Rohlfing-Bastian. The comprehensive and compact expanded LPC can guide practical decision-making for electricity generating facilities.

The expanded LPC includes two new terms relative to the conventional LPC. First, a weighting term, reflects the probabilities that certain states of the world obtain and that the manager employs a strategic option. Second, a scaling term, discounts cash flows generated by the exercise of these options in future time periods. We show that this expanded LPC is fully compatible with expanded NPV calculations that account for managerial flexibility, thereby extending the agreement between corporate finance recommendations and cash-based cost measures. While expanded NPV metrics are already widely used to guide managerial decision-making, the expanded LPC measure allows for the comparison of projects of different time horizons and capital intensities. We show that the expanded LPC is an appropriate cost measure for long-term decisions in environments with uncertainty and flexibility. We demonstrate that a productive asset is cost competitive in expectation if and only if the expected total LPC-based contribution margin is positive.

The expanded LPC can accommodate a range of uncertainties and can be applied to a variety of investment settings where the parameters characterizing decision variables are uncertain. In Section 4, we provide a brief illustration in the context of electricity generation. Our example studies the decision to invest in carbon capture technology by an operator of a natural gas power plant (NGCC). The decision to invest in carbon capture capabilities is likely to become increasingly relevant to power plant operators as efforts to curb carbon dioxide (CO$_2$) emissions increase. While regulatory actions have been taken across the EU and US, larger efforts to decrease emissions, could prompt current and future power plant owners to reduce the emissions of CO$_2$. Though carbon capture technologies could meet increasingly stringent constraints on CO$_2$ emissions, *a priori* uncertainty in the cost of CO$_2$ emissions is high.

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2The “expanded NPV” term is attributable to Trigeorgis (1996).
emissions endows the operator of NGCCs with the managerial flexibility that motivates our example.

The remainder of the paper is organized as follows. Section 2 introduces the expanded levelized product cost. It outlines the base LPC measure and develops the intuition motivating our expansion to account for managerial flexibility, i.e., capital and operational flexibility. Section 3 expands the LPC measure to account for both capital and operational flexibility. Section 4 demonstrates these methods with an illustration from the carbon capture decision context. Section 5 concludes. The Appendix provides background information and proofs.

2 The Levelized Product Cost

2.1 The Base Measure

Reichelstein and Rohlfing-Bastian (2015) define the levelized product cost (LPC) as a life-cycle cost concept relevant to decision-making in long-run capacity investments. To estimate the LPC, the manager apportions capital costs across all units of output and, upon combining these with ongoing fixed and variable costs, arrives at a full cost estimate to inform the investment decision. The LPC is defined by:

\[ \text{LPC} = w + f + c \]  

where \( w \) captures time-averaged variable operating costs, \( f \) represents fixed operating costs, and \( c \) is the cost of capacity. Equations (2) and (3) introduce \( w \) and \( f \) formally:

\[
w = \frac{\sum_{t=1}^{T} W_t \cdot a_t \cdot x_t \cdot \gamma^t}{m \sum_{t=1}^{T} CF_t \cdot x_t \cdot \gamma^t}
\]  

\[ f = \sum_{t=1}^{T} CF_t \cdot x_t \cdot \gamma^t \]  

\[ c = \sum_{t=1}^{T} C_t \cdot x_t \cdot \gamma^t \]

Note that the general formulation of the LPC includes a tax factor that accounts for the depreciation tax shield. We abstract from depreciation tax shield considerations here in the interest of simplifying our narrative.

Constant returns-to-scale technologies are assumed for \( w \) and \( c \), meaning that these values are constant in each period up to the capacity limit. For additional detail, the reader is referred to Reichelstein and Yorston (2013) and Reichelstein and Rohlfing-Bastian (2015).
\[
    f = \frac{\sum_{t=1}^{T} F_t \cdot \gamma^t}{m \sum_{t=1}^{T} CF_t \cdot a_t \cdot x_t \cdot \gamma^t}
\]

The first two terms reflect the allocation of ongoing variable and fixed operating costs, \(W_t\) and \(F_t\), respectively, over all output. The term \(\gamma\) is equal to \(\frac{1}{1+d}\), where \(d\) is the cost of capital and is taken as exogenous. In the case in which the project keeps the firm’s leverage ratio constant and matches the risk characteristics of the firm, the appropriate discount rate is the weighted average cost of capital (WACC). \(T\) represents the operational life of the facility in years. Finally, in the case where output is to be measured on the basis of production per unit time (rather than on a unit product basis), \(m\) represents hours in the year.\(^5\) For example \(m = 8,760\) in the case of electricity production, so as to levelize the cost component of the LPC to \$/kWh.

Our treatment differs from that by Reichelstein and Rohlfing-Bastian in its use of a capacity factor term, \(CF\), which reflects the ratio of actual output to its full nameplate output. While Reichelstein and Rohlfing-Bastian (2015) implicitly assume that \(CF\) equals one (i.e., production occurs continually at the maximum rate, net of degradation in productive capacity, without any downtime), this condition is violated in some applications of the LPC, such as that in the power sector. We generalize the LPC by reflecting time-dependent changes in capacity utilization. The capacity factor \(CF_t\) reflects economic characteristics of the asset with respect to substitutes that can generate the same output.\(^6\) The capacity factor term differs from the system degradation factor term, \(x_t\), in that the latter reflects physical characteristics of a unit. For example, expected changes in process yield would be described by \(x_t\), which will appropriately adjust the volume of output anticipated in any period \(t\). \(x_t\) represents the decay in the ability of a system to produce its output and usually takes the form of a constant percentage factor, which varies with the particular technology (Reichelstein and Yorston, 2013). In contrast, \(CF_t\) can represent uncertain variable costs over time, a changing grid composition (i.e., as capacity is added or retired), and other endogenous market characteristics. The term \(a_t\) refers to the actual capacity of the facility, which is

\(^5\)In the case that the levelize product does not have a time component, then \(m\) is removed from the equations.

\(^6\)For example, in the power generation context changes in utilization can be interpreted as changes in dispatch; these changes are partially attributable to the cost competitiveness of the unit relative to other generators on the electrical grid.
independent of the $CF_t$ as it refers to the physical capacity, rather than such capacity’s availability. The physical capacity, in the absence of any subsequent managerial decision, is typically fixed at the magnitude of initial build. Importantly, quantity produced in any period $t$ is the product of capacity factor, capacity of the facility, and degradation factor (i.e., $CF_t \cdot a_t \cdot x_t$). In the case of electricity – where the product is electricity measured in kWh, the quantity is calculated as $m \cdot CF_t \cdot a_t \cdot x_t$.

The third term of Equation (1) levelizes up-front capital costs of the amount $SP$ (system price in dollars) over all output from the productive asset. This levelization of the initial investment follows the approaches by Arrow (1964) and Rogerson (2008) and is known as the unit cost of capacity. We introduce this term as:

$$c = \frac{SP}{m \sum_{t=1}^{T} CF_t \cdot a_t \cdot x_t \cdot \gamma_t}$$  \hspace{1cm} (4)

### 2.2 Defining Managerial Flexibility

Figure 1 illustrates two types of managerial flexibility – namely, capital and operational flexibility. The simplified two-stage diagram represents a decision context in which managerial flexibility includes first-stage capital flexibility (at time $\tau_1$) and then second-stage operational flexibility if adjustable capital is installed (at time $\tau_2$). Capital flexibility refers to an embedded real option in which a manager can make capital budgeting decisions (e.g., adjust capacity or build new facilities) in response to a realized or anticipated event that materially impacts economy viability. For instance, owners of a fossil fuel power plant may install capture equipment if a carbon pricing policy is enacted during the asset’s lifetime. Conditional on this investment, operational flexibility allows asset owners to switch between operating modes in reaction to, or in anticipation of, events that can change expected cash flows. $^7$ Flexibility of switching between operating modes can be valuable, for instance, for firms that adjust environmental control equipment to comply with a volatile regulatory environment (e.g., a power plant with carbon capture can adjust equipment to comply with a carbon pricing policy that has a fluctuating stringency). For both types of managerial flexibility, the manager is assumed to enumerate potential discrete outcomes, quantify associated probabilities, and make decisions over time in response to available information.

$^7$Operational flexibility is not generally conditional on new capital investments. Rather, it may be embedded in the incumbent capital investment made by a firm.
Upon accounting for managerial flexibility, the expanded LPC is interpreted as the *expected* average price the facility would have to receive for its output to cover operating expenses and compensate investors. We distinguish the expanded LPC from attempts to incorporate uncertainty into levelized cost calculations. Though these efforts acknowledge uncertainty, they implicitly assume that the manager’s actions will be the same regardless of the realized value of the unknown parameters. To account for uncertainty, Darling et al. (2011) derive a distribution of LCOE measures from input parameter distributions feeding a Monte Carlo simulation. While this method illustrates the sensitivity of the LCOE to uncertainties in underlying parameters, measures of distribution central tendency of LCOEs are not generally consistent with a zero net present value condition. Said otherwise, the LCOE derived from the expectation of underlying parameter values is not generally equal to the expected LCOE derived from distributions on underlying parameter values.

### 2.3 Generalizing the LPC to Account for Managerial Flexibility

We develop the intuition behind our generalization of the LPC. From Equation 1, the LPC does not consider uncertainty in costs or the potential for flexible managerial responses. Figure 2 introduces the concepts of uncertainty and flexibility separately, and we update
both the NPV and LPC metrics in two steps to show how both measures can account for uncertainty and flexibility. We update the measures in parallel to highlight the continued congruence between the guidance from the NPV metric and that from the LPC. The market setting in this paper assumes competitive and complete markets and that all firms are risk-neutral with access to capital.8

![Figure 2: Taxonomy of LPC metrics based on their treatment of uncertainty and flexibility.](image)

The traditional NPV and LPC measures are appropriate to the context of Quadrant 1 of Figure 2. If variables describing the economic environment evolve stochastically and the manager is unable to respond flexibly, the metrics must be updated to provide measures in expectation. Accordingly, we state stochastic, passive NPV and LPC measures in Equations 5 and 6, respectively.9 These equations reflect the context of Quadrant 2 of Figure 2.10 Through the distribution $g(\omega)$, the stochastic, passive NPV and LPC measures reflect the probabilities particular states of the world, $\omega$, are realized.

$$
\mathbb{E}[NPV] = \sum_{\omega \in \Omega} g(\omega) \cdot NPV_\omega 
$$

\footnote{8The general framework presented in this paper can be extended to accommodate alternate market settings. For instance, Reichelstein and Rohlifing-Bastian (2015) examine the impact of market structure on LPC calculations and derive a mark-up term that depends on the number of competitors in a given industry.}

\footnote{9The expressions assume that the state space has finite support.}

\footnote{10These equations also hold for Quadrant 3, since the manager is unable to capitalize on uncertainty under these conditions.}

7
\[ \mathbb{E}[LPC] = \sum_{\omega \in \Omega} g(\omega) \cdot (w_{\omega} + f_{\omega} + c_{\omega}) \] (6)

If the manager is able to change her strategy as economic random variables are revealed, we must account for both the uncertainty and changes in cash flows. Equation 7 and the expression in Proposition 1 are still NPV and LPC measures in expectation, but they additionally reflect the value of a manager’s strategic flexibility. We term the appropriate measures as stochastic, expanded NPV and LPC metrics. Equation 7 presents the stochastic, expanded NPV, which governs Quadrant 4 of Figure 2:

\[ \mathbb{E}[NPV] = \left[ \sum_{\omega \in \Omega} g(\omega) \cdot NPV_{\omega} \right] + \Phi \] (7)

The stochastic, expanded NPV is the sum of the stochastic, passive NPV (first term on the right) and the option premium (second term on the right), which captures the value of flexible responses. While the stochastic, passive NPV reflects an investment opportunity in an uncertain environment with a baseline capital and operational strategy, \( \Phi \) captures the incremental value from changes in the capital or operational profile that the manager makes as the economic environment evolves. The term reflects the probabilities associated with states of the world and value of strategic changes. The stochastic, expanded LPC correspondingly includes a new term, \( \phi_{\omega} \), that is interpreted as the levelized option premium. While the levelized option premium reflects a single value of managerial flexibility (i.e., \( \Phi \)), the subscript on the option premium accounts for possible differences in the volume of output in different states of the world. Proposition 1 introduces the stochastic, expanded LPC.

**Proposition 1** The stochastic, expanded LPC is given by (8) and is the appropriate cost measure for long-term decision-making when the economic environment is characterized by uncertainty and the manager can respond flexibly.

\[ \mathbb{E}[LPC] = \sum_{\omega \in \Omega} g(\omega) \cdot (w_{\omega} + f_{\omega} + c_{\omega}) - \sum_{\omega \in \Omega} h(\omega) \cdot \phi_{\omega} \] (8)

Above, the term \( \phi_{\omega} \) is given by:

\[ \phi_{\omega} = \frac{\Phi}{m \sum_{t} CF_{t,\omega} \cdot a_{t,\omega} \cdot x_{t,\omega} \cdot \kappa^{t}} \] (9)
The expression in Proposition 1 includes a distribution $h$ with the same support as $g$. As explained in Section 3, $h(\omega)$ reflects risk-adjusted probabilities with which states of the world obtain. We emphasize that while Equations 2, 3, and 4 apply the discount factor $\gamma$, Equation 9 uses the discount factor $\kappa$. The latter value is based on the risk-free rate (i.e., $\kappa = \frac{1}{1+r}$, where $r$ is the risk-free rate), while the former uses a rate such as the WACC. The WACC is appropriate in the former case, as it reflects the risk profile of the firm’s operations and is used in concert with probabilities that do not account for these risks. In contrast, the risk-free rate is justified when using the distribution $h$, which already reflects the risks stemming from stochastic processes that almost certainly differ from those characterizing the firm’s operational risk profile.

Appendix A provides proof of Proposition 1. By emphasizing the interpretation of the expanded, stochastic LPC as the measure implying a break-even condition for an investor, the proof extends the agreement between the LPC and NPV demonstrated by Reichelstein and Rohlfing-Bastian.

In direct analogue to the decision relevance of the traditional passive LPC, Proposition 2 asserts the applicability of the expanded, stochastic LPC to decision-making in the presence of uncertainty and managerial flexibility.

**Proposition 2** *A facility is cost competitive in expectation if and only if* $\mathbb{E}[CM] > 0$, *where* $CM$ *is the total-LPC based contribution margin.*

Appendix A presents the proof for this proposition. Proposition 2 applies broadly to situations in which the firm faces uncertainty, regardless of whether it exercises managerial flexibility. If the firm does not employ managerial flexibility, $\phi_\omega = 0 \forall \omega$, and the stochastic, expanded LPC collapses to the stochastic, passive LPC. This implies an immediate observation: in accounting for managerial flexibility, the stochastic, expanded LPC will always be weakly lower than the stochastic, passive LPC. This follows from the sign on $\phi_\omega$.

### 3 Incorporating Flexibility in the LPC

Section 2 motivates the expanded levelized product cost metric to account for managerial flexibility and offers a general derivation of this measure. We now illustrate sources of managerial flexibility and the incorporation of individual capital and operational flexibility into
the LPC (Sections 3.1 and 3.2, respectively). Section 3.3 briefly discusses the simultaneous consideration of both types of managerial flexibility in LPC calculations.

### 3.1 Capital Flexibility

Facility owners may adjust capacity in response to circumstances that materially affects operation, economic viability, or both. This *capital flexibility* is one type of real option embedded in capital budgeting contexts, and its representation in metrics like the LPC is critical in accurately depicting long-run investment decisions. Examples of such capital options include the ability to expand a manufacturing facility if favorable market conditions obtain or to install carbon capture equipment on a fossil-fueled generator if a carbon pricing policy is enacted. In such situations, the firm’s decision to exercise the option depends on factors like the option’s strike price (i.e., the irreversible investment outlay), associated asset expected volatility, and other context-specific dimensions of project valuation.

To explore the incorporation of capital flexibility into the LPC measure from Section 2.3, this section introduces an example of a growth option with binary uncertain outcomes. It offers a transparent illustration of a simple form of capital flexibility, which provides a foundation for the structurally similar application to power plant investments in Section 4. In this example, Scenario 1 refers to the high-value state of the world for the firm’s asset, and Scenario 2 refers to the low-value outcome. We introduce the following parameters to guide the derivation of LPC with capital flexibility:

- $SP_0$ initial outlay to build capacity at $t = 0$; product of system price and capacity
- $V_H$ future value of cash flows under Scenario 1
- $V_L$ future value of cash flows under Scenario 2
- $q$ probability of occurrence of Scenario 1; $Pr(V_H)$
- $1 - q$ probability of occurrence of Scenario 2; $Pr(V_L)$
- $Z$ price of twin security traded in financial markets
- $k$ expected return of twin security

Our definition of $SP$ assumes a constant returns to scale technology. We define the twin security as an instrument traded in financial markets with the same risk characteristics with

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11Capacity growth options are a common type of real option but are only one potential source of capital flexibility. For other varieties of capital flexibility (e.g., time-to-build options, options to defer), cash flows structures may be different, but the formulation of the LPC measure is general enough to encapsulate these options (Trigeorgis, 1996).
the real project under consideration (Trigeorgis, 1996). Finally, the probabilities $q$ and $1 - q$ are specific manifestations in the two-scenario case of the general probability measure $g(\omega)$ introduced in Section 2.

### 3.1.1 NPV and LPC without Growth Option

The passive NPV, which maps to Quadrant 2 of Figure 2, can be expressed as the difference between the present value of the post-investment cash flows (represented by the random variable $\tilde{V}$) and the initial capital investment:

$$E[NPV] = E[\tilde{V}] - SP_0 = E \left[ \sum_{t=1}^{T} CFL_t \cdot \gamma^t \right] - SP_0$$

(10)

$CFL_t$ denotes the cash flows at time $t$.$^{13}$ Importantly, the cash flows represented by $\tilde{V}$ are in the absence of any managerial flexibility.

The expression in (10) must be evaluated in expectation, using $g(\omega)$, because the cash flows depend on the scenario, $\omega$, that obtains in each time period. Even if the passive NPV is negative, a project can be economically desirable once the managerial flexibility is taken into account. When such options are unavailable, the expanded NPV is equal to the passive NPV.

To prepare ourselves for an expanded NPV calculation, we switch from using the “real-world” probabilities $q$ and expected return of twin security to risk-adjusted (i.e., risk-neutral) probabilities $q'$ and the riskless rate of return.$^{14}$ In general, one derives $q'$, or the risk-neutral probability that Scenario 1 obtains, by using characteristics of the twin security, as shown in Trigeorgis (1996).

$$q' = \frac{(1 + r)Z - Z_H}{Z_L - Z_H}$$

(11)

Above, $Z_H$ is the high value of the twin security in Scenario 1 and $Z_L$ is the low value of the twin security in Scenario 2. Once again describing the scenario without flexibility, we

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12Rose (1998) points out that, in the absence of a twin security in the capital markets, Rubinstein (1976) and Brennan (1979) restrict investors’ risk preferences so as to allow risk-neutral valuation.

13Note that in this case we set the discount rate $d$ equal to $k$.

14We switch to the riskless rate of return since the appropriate discount rate in the face of managerial flexibility changes as the value of economic variables change.
re-write the passive NPV of the two-scenario case from Equation 10 as:

\[
\mathbb{E} [NPV] = q' \cdot \left[ \sum_{t=1}^{T} CFL_t(V_H) \cdot \kappa^t \right] + (1 - q') \cdot \left[ \sum_{t=1}^{T} CFL_t(V_L) \cdot \kappa^t \right]
\]  

(12)

where \( CFL_t(\tilde{V}) \) indicates that cash flows are a function of \( \tilde{V} \).

In discussing scenario-contingent capital and operating decisions, we distinguish between decision stages (indexed by \( s \in S \)) and time periods (indexed by \( t \in T \)). Periods are intervals in the time horizon, and stages are sets of consecutive periods that divide the time horizon based on the ability of decision-makers to revise strategies given new information. The function \( u: S \rightarrow T \) links consecutively numbered decision stages to time periods. In general, \( S \neq T \), but these sets could be identical, which gives \( u(s) = s \).

### 3.1.2 NPV and LPC with Growth Option

Assume that an owner has a growth option to install capital equipment on the facility at time \( \tau_1 \), as illustrated in Figure 3. This setting is interpreted as the initial project plus a call option on a future market opportunity. Upon exercising the option, the firm will bear new capital costs, with an equipment outlay \( SP_{\tau_1} \) at \( \tau_1 \) for an expanded facility that will be available immediately.

![Timeline of the firm’s growth option for investing in new capital equipment at time \( \tau_1 \).](image_url)

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The new plant will generally imply changes in fixed and variable costs after \( \tau_1 \). For instance, new carbon capture equipment will cause added operational costs due to parasitic energy losses in the power plant. We reflect these changes in fixed and variable costs with the term \( \xi^c \), where \( c \) denotes capital flexibility, and \( \xi^c = j(dw, df) \omega \). The function \( j \) can be expressed as:

\[
j(dw, df) \omega = (w + f)^{EF} - (w + f)^{IF}
\]

\( EF \) denotes the “extended facility” (i.e., post capital investment), while \( IF \) denotes the “incumbent facility” (i.e., prior to capital investment). The \( \xi^c \) term includes a subscript \( \omega \) because the change in cash flows will depend on the scenario.\(^\text{15}\)

Since cash flows related to a potential expansion occur in future periods, they must be scaled to reflect the time value of money. Since cash flows are not deterministic, they must be weighted by the probabilities associated with these possible states of the world. As described earlier, these probabilities also must be adjusted to appropriately account for risk.

Let the random variable \( \tilde{E} \) denote the value of post-initial capacity investment cash flows in the case of managerial flexibility. Since these cash flows are at least equal to those implied by \( \tilde{V} \), we represent \( \tilde{E} \) as:

\[
\tilde{E} = \text{max} [\tilde{V}, \tilde{V} + (\sum_{t=\tau_1}^{T} E[\xi^c_t] \cdot \gamma^{t-\tau_1} - SP_{\tau_1}) \cdot \kappa^{\tau_1}] = \tilde{V} + \text{max} [0, (\sum_{t=\tau_1}^{T} E[\xi^c_t] \cdot \gamma^{t-\tau_1} - SP_{\tau_1}) \cdot \kappa^{\tau_1}].
\]

Without loss of generality, our assumption is that market conditions are favorable for capital deployment only in Scenario 2. Thus, if Scenario 1 occurs, the firm will not invest in new capacity and will have a gross project value of \( E_H = V_H \). Alternatively, if Scenario 2 occurs, management will install the equipment and have a gross project value of \( E_L = V_L + (\sum_{t=\tau_1}^{T} \xi^c_t \cdot \gamma^{t-\tau_1} - SP_{\tau_1}) \cdot \kappa^{\tau_1} \). The flexibility to wait before investing allows firms to observe whether they would be adequately compensated for the expected increase in costs of capacity and subsequent changes in cash flows before making these expenditures.

The value of the investment opportunity including the expansion option becomes:

\[
E[NPV] = E \left[ \sum_{t=1}^{T} CFL_t \cdot \kappa^t \right] - SP_0 = E \left[ \tilde{E} \right] - SP_0
\]

This equation gives the general expression for the stochastic, expanded NPV, which pertains

\(^{15}\text{An investment at } \tau_1 \text{ may imply an extension of the facility’s economic lifetime, which is a straightforward extension of the analysis.}\)
to Quadrant 4 of Figure 2. We use $\kappa$ instead of $\gamma$ to discount as the risk characteristics of the project change as the underlying uncertain economic variable (e.g., price on carbon emissions or manufacturing input price) changes, and the manager possibly invests in new capital equipment.

In the two-scenario example, this equation is expressed as:

$$\mathbb{E}[NPV] = q' \cdot V_H + (1 - q') \cdot \left[ V_L + \left( \sum_{t=\tau_1}^{T} \xi_{t,L}^c \cdot \gamma^{t-\tau_1} - SP_{\tau_1} \right) \cdot \kappa^{\tau_1} \right]$$  \hspace{1cm} (15)$$

The value of the growth option is called the option premium for capital flexibility ($\Phi^c$) and represents the difference between the expanded and passive NPV measures. In our two-scenario example, $\Phi^c$ assumes the value:

$$\Phi^c = (1 - q') \cdot \left( \sum_{t=\tau_1}^{T} \xi_{t,L}^c \cdot \gamma^{t-\tau_1} - SP_{\tau_1} \right) \cdot \kappa^{\tau_1}$$  \hspace{1cm} (16)$$

For the calculation of $\phi^c$ in the stochastic, expanded LPC in (9), the bounds on time are $0$ to $T$ to reflect the appropriate time horizon for the expansion investment.

It is straightforward to extend this analysis to account for additional states of the world. The following expression captures the more general, multiple-scenario setting:

$$\Phi^c = \sum_{\omega \in \Omega} h(\omega) \cdot \left( \sum_{t=\tau_1}^{T} \xi_{t,\omega}^c \cdot \gamma^{t-\tau_1} - SP_{\tau_1} \right) \cdot \kappa^{\tau_1}$$  \hspace{1cm} (17)$$

The index $\omega$ on $\xi_{t,\omega}^c$ allows for the representation of the different cash flows that accrue in different scenarios. Finding 1 summarizes our development of the value of capital flexibility by re-expressing the above as an expectation.

**Finding 1** In the general setting with multiple scenarios, the value of capital flexibility, $\Phi^c$, is given by (18).

$$\Phi^c = \mathbb{E} \left( \sum_{t=\tau_1}^{T} \xi_{t}^c \cdot \gamma^{t-\tau_1} - SP_{\tau_1} \right) \cdot \kappa^{\tau_1}$$  \hspace{1cm} (18)$$

This expression quantifies the option premium in the stochastic, expanded NPV from Equation (7). Common levelized cost measures implicitly assume that such managerial flexibility carries zero value, so this added term reflects the error in the passive NPV when capital
optionality is excluded. Though the expression in Finding 1 is a generalization of (16), we emphasize that the finding is appropriate to contexts in which the investment opportunity entails only one capital investment stage subsequent to the initial investment period. The expression can be extended to account for scenarios in which the investment opportunity entails multiple investment stages.

3.2 Operational Flexibility

Operational flexibility allows the switching between operating modes in reaction to, or in anticipation of, events that may alter expected cash flows. The flexibility of switching between operating modes can be a potential source of value. This type of flexibility is embedded in many applications, including manufacturers that can adjust output levels for products based on uncertain demand or firms that adjust environmental control equipment to comply with a volatile regulatory environment. Examples of such options include the ability to switch production lines within a manufacturing facility if favorable market conditions obtain, or to ramp the use of carbon capture equipment to comply with a carbon pricing policy that has fluctuating stringency over time.

We begin by considering a case in which the manager can choose between only two operational modes. Figure 1 depicts this setting. Imagine that after having installed new capital equipment, the manager is evaluating whether to operate such equipment. We define three technologies that allow the equipment to operate in one of two modes:

1. $\hat{F}$ = The component can switch between “on” and “off” modes
2. $\hat{A}$ = The component must operate in the “on” mode only
3. $\hat{B}$ = The component must operate in the “off” mode only

This simplified example includes only one decision stage (i.e., $s_2$ at time $\tau_2$) but, as we show, it can be extended to any number of decision stages.

Let $(w + f_x)^\omega$ represent the cost of operating with technology $x$ under scenario $\omega$, where $x = \{F, A, B\}$. Assume that switching between modes of operation with flexible technology

---

16To provide a concrete example, consider a power plant with carbon capture capabilities. Then, $F$ would represent flexibility to capture at full capture capacity or nothing; $A$ would represent rigid operation with full capture capacity only; and, $B$ would represent no capture capability.
Since the operator has the ability to alter the equipment operational mode, the present value of the flexible technology is greater than the present value of either of the two inflexible technologies. Specifically, the present value of the flexible technology exceeds that of technology \( A \) by the value of being able to switch from the mode enabled by technology \( A \) (i.e., “on”) to that entailed by technology \( B \) (i.e., “off”), which we represent by \( F(A \rightarrow B) \). Since the value of this flexibility depends on an uncertain underlying economic variable (e.g., carbon price), the value is itself a random variable, \( \tilde{M} \). We evaluate \( \tilde{M} \) as follows:

\[
\mathbb{E} \left[ \tilde{M} \right] = PV_A + F(A \rightarrow B) = \mathbb{E} \left[ \sum_{t=\tau_1}^T CFL_t \cdot k^t \right] + F(A \rightarrow B)
\] 

The time bounds reflect the timing of the completed capital investment decision at \( \tau_1 \).

The value of the flexible technology derives from the incremental cash flows implied by the use of technology \( F \) (i.e., that which allows switching between modes) in scenario \( \omega \) relative to the use of technology \( A \). Let \( \xi_\omega \) represent this incremental cash flow. Then, the value of \( \xi_\omega \) is the difference between cash flows (including fixed and variable costs, and incremental changes in revenue) entailed in using technology \( B \) (i.e., that permitting only the “off” mode) and those in using technology \( A \) (i.e., that allowing only the “on” mode). The manager would switch between the operational modes only if the value of doing so were weakly positive. We define \( \xi_\omega \) as follows:

\[
\xi_\omega = \max \left[ j(dw, df)_\omega^B, 0 \right]
\]

Since the cash flows associated with the use of technology \( A \) comprise the baseline scenario, \( j(dw, df)_\omega^B \) is defined as:

\[
j(dw, df)_\omega^B = (w + f)_\omega^B - (w + f)_\omega^A
\]
These cash flows accrue in all time periods between that of stage two, \( \tau_2 \), and the end of life for the facility, \( T \). We can thus express the value of the flexible technology as:

\[
\mathbb{E} \left[ \tilde{M} \right] = \mathbb{E} \left[ \sum_{t=\tau_1}^{T} CFL_t \cdot \kappa^t \right] + F(A \rightarrow B) = \mathbb{E} \left[ \sum_{t=\tau_1}^{T} CFL_t \cdot \kappa^t \right] + \mathbb{E} \left[ \sum_{t=\tau_2}^{T} \xi^o_t \cdot \kappa^t \right]
\]  

(22)

Both expectation terms of (22) are assessed over all scenarios, \( \omega \), using the risk-adjusted probability measure, \( h(\omega) \). Note the subscript on the \( \xi^o \) terms has shifted from \( \omega \) to \( t \). This is because the incremental cash flows at each time period need to be assessed across all scenarios. Given our assumption that a capital investment is made at time \( \tau_1 \), the present value of the investment opportunity, including the operational flexibility option, becomes:

\[
\mathbb{E}[NPV] = \mathbb{E} \left[ \tilde{M} \right] - SP_0 - SP_{\tau_1} \cdot \gamma^{\tau_1}
\]  

(23)

This equation gives the general expression for the stochastic, expanded NPV with operational flexibility only.

Equation (22) also implies the value of operational flexibility in the context of one operational decision stage and two operational modes:

\[
\Phi^o = F(A \rightarrow B) = \mathbb{E} \left[ \sum_{t=\tau_2}^{T} \xi^o_t \cdot \kappa^t \right]
\]  

(24)

The value of operational flexibility is affected by the number of decision stages and duration over which it would be optimal to exercise this flexibility. As the number of decision stages increases \textit{ceteris paribus}, the value of operational flexibility increases. It is advantageous to match decision stage frequency with the timescale of the underlying stochastic variable (e.g., cost of emissions). We can relax the assumption that the decision-maker has only one decision stage. Upon doing so, we update (22) such that it captures the present value of the ability to switch from mode \( A \) to \( B \) at other decision stages, should that operational change be warranted. Formally, we update (22):

\[\text{That is, } \mathbb{E} \text{ denotes } \mathbb{E}_\omega.\]

\[\text{20In the most general treatment of operational flexibility with two operational modes, a capital investment at } \tau_1 \text{ does not gate the operational flexibility. Consequently, the time bounds on } CFL_t \text{ can range from 0 to } T, \text{ and the assessment of operational flexibility can begin from the first decision stage available to the manager.}\]
\[ \mathbb{E} \left[ \hat{M} \right] = \mathbb{E} \left[ \sum_{t=\tau_1}^{T} C_{FL_t} \cdot \kappa^t \right] + \mathbb{E} \left[ \sum_{t=\tau_2}^{\tau_3} \xi^o \cdot \kappa^t \right] + \cdots + \mathbb{E} \left[ \sum_{t=\tau_{(S-1)}}^{\tau_S} \xi^o \cdot \kappa^t \right] \] (25)

Above, \( S \) denotes the number of decision stages available.\(^{21}\) Equation (25) implies that the value of operational flexibility in the context of two modes is:

\[ \Phi^o = F(A \rightarrow B) = \mathbb{E} \left[ \sum_{t=\tau_2}^{\tau_3} \xi^o \cdot \kappa^t \right] + \cdots + \mathbb{E} \left[ \sum_{t=\tau_{(S-1)}}^{\tau_S} \xi^o \cdot \kappa^t \right] \] (26)

Finally, we can relax the assumption that there are only two operational modes. In general, the manager may be able to use a technology \( X \) that permits switching from a default mode to one of \( n \) alternative modes. Retaining for convenience an assumption that technology \( A \) permits only the default operational mode, we introduce the \( n \) alternative modes by redefining \( \xi^o \) from (20):

\[ \xi^o = \max \left[ j(dw, df)^B_1, \ldots, j(dw, df)^B_n, 0 \right] \] (27)

\( B_1 \) through \( B_n \) denote \( n \) alternative technologies that permit only alternative operational modes 1 through \( n \), respectively. Finding 2 summarizes our development of the value of operational flexibility.

**Finding 2** In the general setting with multiple operational modes and decision stages, the value of operational flexibility, \( \Phi^o \), retains the form given in (26), but the \( \xi^o \) terms must be defined as in (27).

Equations (26) and (27) define the option premium in the expanded NPV from Equation (7) for decision contexts where operational flexibility is present. Passive NPV calculations that neglect these sources of managerial flexibility may be omitting critical decision-relevant dynamics.

\(^{21}\)Note that we assume that switching costs can be neglected. The presence of switching costs invalidates the additivity property in (25). However, the expanded LPC framework can be modified to account for these more complicated dynamics.
3.3 Combined Managerial Flexibility

The previous two subsections have added independent capital and operational flexibility considerations to the LPC. In general, managerial flexibility is the combination of capital and operational flexibility, but the value of this combination is not immediately obvious. The value of an option in the presence of other options may differ from its value in isolation (Trigeorgis, 1993).

\[
\Phi \leq \Phi^o + \Phi^c
\]

Interactions between options depend on the type, temporal separation, extent to which options are “in or out of the money,” and order of the options involved. All of these factors impact the joint probability of exercising these options (Trigeorgis, 1993).

In the next section, we present an example of managerial flexibility for a natural gas power plant owner who can respond with capital investments and operational changes to an uncertain climate policy. We will see in this context that the value of managerial flexibility is less than the sum of the two types of flexibility.

4 Illustration: Natural Gas Power Plant with Carbon Capture

We provide an example of a NGCC that may need to comply with policies penalizing CO\(_2\) emissions. The nature of these policies, however, is uncertain. We assume a carbon policy that places a cost on each unit of CO\(_2\) emitted. That is, the underlying economic variable that introduces uncertainty into the manager’s investment decision-making is the cost of CO\(_2\) emissions. In response, the owner has the option, but not the obligation, to invest in carbon capture capabilities. Carbon capture is a broad set of technologies employed to capture CO\(_2\) from industrial processes and fossil-fuel powered electricity generation.

Applying carbon capture to a NGCC entails high capital investment, in addition to operational costs (refer to Table 1). If CO\(_2\) emissions costs are currently low, an immediate investment in capture technology would be uneconomic. If carbon costs were to rise in the future, the manager could retrofit the plant with carbon capture capabilities.\(^{22}\) This endows

\(^{22}\)It is assumed the incumbent natural gas power plant is able to accommodate such additional equipment, and be so-called “carbon-capture ready.”
the manager with capital flexibility. Since carbon costs are assumed to be stochastic, once the manager installs capture capabilities, switching off the unit to avoid higher operational costs is possible. This would be warranted if carbon prices were to drop. The ability to switch operational modes provides the manager with operational flexibility.

We apply our analytical development to answer two questions. First, what is the value of the capital and operational flexibility entailed in the manager’s investment opportunity? Second, with what belief about carbon prices does the managerial flexibility appear to be valuable? To answer these questions, we determine the expanded of a NGCC. The LCOE in this example is a specific formulation of the LPC, where the “product” in this case is one kilowatt hour (kWh) of electricity.\textsuperscript{23}

As shown in Table 1, the critical cost component of carbon capture is the capital investment. Non-fuel operational costs (fixed and variable) also contribute substantially to the LCOE, mainly due to increases in labor, consumables, and material. The overall net output of facility with carbon capture suffers from what is known as “parasitic losses,” which are the energy requirements for the carbon capture process. In the absence of carbon capture technology, this energy would have otherwise been converted into electrical power and sold. The compound effect of higher costs and lower output is a substantial increase in the LCOE of a plant equipped with carbon capture, relative to one without such capability.

Using the input values in Table 1, we calculate the LCOE of NGCC power plant without carbon capture to be $0.066/kWh.\textsuperscript{24} Further, assuming a retrofit that adds capture capability in the 10th year of the facility’s operational life, the LCOE rises to $0.080/kWh.\textsuperscript{25} A change of this magnitude (20%) could have a material effect on the competitiveness of the facility, as the electricity generation industry is characterized by thin margins (i.e., typically 3–5%).

To illustrate the value of capital flexibility, we assume a 50% probability of a zero-valued carbon price (i.e., low cost of emissions), and some \textit{a priori} unknown variable high-cost

\textsuperscript{23}The LCOE is a break-even price for electricity that investors would have to receive \textit{on average} in order to be willing to invest in the facility. Thus, if a new plant were to sell its electricity output under a power purchasing agreement, the LCOE would be the minimum average price per kWh that would allow the investors in the plant to break even.

\textsuperscript{24}Calculations make the following assumptions: Operation life = 30 years; Discount Rate = 8%; Tax Rate = 40%; Gas Price = $6.13/mmBtu; (initial) Cost of Emissions = $0/tCO\textsubscript{2}, no operational life extension from addition of carbon capture capabilities.

\textsuperscript{25}If retrofit were to occur immediately, then the LCOE is $0.106/kWh, representing approximately 9% “retrofit premium” compared to an identical new build natural gas plant with carbon capture system ($0.097/kWh).
Table 1: Baseline Cost Estimates

<table>
<thead>
<tr>
<th>Stage</th>
<th>Element</th>
<th>Unit</th>
<th>NGCC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Net Capacity</td>
<td>MWe-net</td>
<td>632</td>
</tr>
<tr>
<td>1</td>
<td>CAPEX</td>
<td>$/kW</td>
<td>830.3</td>
</tr>
<tr>
<td>1</td>
<td>Fixed OPEX</td>
<td>$/kW-yr</td>
<td>25.08</td>
</tr>
<tr>
<td>1</td>
<td>Variable OPEX</td>
<td>$/kWh</td>
<td>0.00205</td>
</tr>
<tr>
<td>1</td>
<td>Fuel Cost</td>
<td>$/kWh</td>
<td>0.0476</td>
</tr>
<tr>
<td>1</td>
<td>Efficiency</td>
<td>%</td>
<td>51.6</td>
</tr>
<tr>
<td>1</td>
<td>Emissions</td>
<td>kg/kWh</td>
<td>0.355</td>
</tr>
<tr>
<td>1</td>
<td>LCOE</td>
<td>$/kWh</td>
<td>0.066</td>
</tr>
<tr>
<td>2</td>
<td>Net Capacity</td>
<td>MWe-net</td>
<td>546</td>
</tr>
<tr>
<td>2</td>
<td>CAPEX (capture eq. only)</td>
<td>$/kW</td>
<td>1,210.1</td>
</tr>
<tr>
<td>2</td>
<td>Fixed OPEX</td>
<td>$/kW-yr</td>
<td>56.08</td>
</tr>
<tr>
<td>2</td>
<td>Variable OPEX</td>
<td>$/kWh</td>
<td>0.00441</td>
</tr>
<tr>
<td>2</td>
<td>Fuel Cost</td>
<td>$/kWh</td>
<td>0.0551</td>
</tr>
<tr>
<td>2</td>
<td>Efficiency</td>
<td>%</td>
<td>44.6</td>
</tr>
<tr>
<td>2</td>
<td>Emissions</td>
<td>kg/kWh</td>
<td>0.041</td>
</tr>
<tr>
<td>2</td>
<td>LCOE</td>
<td>$/kWh</td>
<td>0.080</td>
</tr>
</tbody>
</table>

emissions price after the base plant begins operation. As shown in Figure 4, the option to install carbon capture becomes valuable provided a (probabilistic) sufficiently high cost of emissions. If emissions costs arise five years from the beginning of the base facility operation, the threshold cost for a non-zero value of capital flexibility is $70/tCO₂. Further, as this cost of emissions rises, the value of the option, in turn, rises linearly. The value of this option is material; for example, at a 50% probability of a zero cost of emission and $100/tCO₂, the option holds 7% of the value of the baseline LCOE.

We note that the threshold cost of emissions rises to about $80/tCO₂ in the case of a ten-year delay in emissions cost implementation. Moreover, for every possible value of the high emissions cost above the threshold, the value of the option is strictly less than that of the scenario where capital expansion occurred after only a five-year delay. This intuitively makes sense, owing to the combined effects of fewer years to depreciate the carbon capture unit and fewer years of constrained revenue due to the new operating conditions.

Next, we turn to the value of operating flexibility. We assume a 50% probability of a zero-cost emissions, and some a priori unknown high-cost state one year after the carbon capture has been installed. This scenario reflects a cap-and-trade emissions regime, where the cost of emissions could vary stochastically.²⁶ Provided the ability to “switch off” the

²⁶We acknowledge that price ceilings and floors could be incorporated into such a regime (e.g., California);
capture unit while still generating electricity, Figure 5 represents the value of operational flexibility. Specifically, Figure 5 shows the value of the option to shut off the carbon capture unit, should the cost of emissions fall below a threshold. In the case of switching off the unit one year after the five year scenario described above in relation to capital flexibility, the threshold value for the high emissions price is $115/tCO\textsubscript{2} ($110/tCO\textsubscript{2} in the ten year scenario). We note that a 50% probability of zero and $50/tCO\textsubscript{2} realized one year after the five-year-delayed capital expansion (shown as the six-year plot in Figure 5) is worth 10% of the baseline LCOE value.

5 Conclusion

Irreversible long-run capital investment options often include opportunities for managers to respond flexibly to the economic environment. This realization has spawned a set of updates to traditional guidance for investment decision-making in the corporate finance literature. Corporate finance suggests that managers append DCF analyses with the assessment of so-called “real options” that capture the value of managerial flexibility. While these updates have enriched the ability of NPV-based analyses to capture the dynamics of investment opportunities, the NPV is not the only metric used to assess the attractiveness of such investment opportunities. It is common in several industries, such as electricity generation, to compare the life-cycle cost of production with expected prices and to gauge whether the investment is likely to be economical.

however, this simplified exposition does not include such boundaries.
Reichelstein and Rohlfing-Bastian (2015) provide a general formulation for the calculation of life-cycle costs and demonstrate that guidance from their metric, the levelized product cost (LPC), is fully compatible with that from NPV-based analyses. However, many LPC-based applications (e.g., LCOE) assume a deterministic economic environment, which means that a wedge between NPV- and LPC-based analyses remains in contexts with uncertainty and managerial flexibility. This paper expands the LPC metric and thereby extends the agreement between the NPV and LPC metrics.

Our extension of the LPC concept borrows from the intuition developed by real options analysis. Reflecting the cash-basis of the LPC, our strategy to include managerial flexibility entails three fundamental steps. First, we determine the incremental capital, fixed, and variable costs associated with the exercise of managerial flexibility. Second, since cash flows occur in future periods, we scale them to reflect the time value of money. Third, since these cash flows occur in only some states of the world, we weigh them by the probabilities associated with whether they do or do not obtain. As with the deterministic LPC, an investment opportunity with a stochastic, expanded LPC that is weakly lower than the expected price for the asset’s output is deemed to be cost competitive. We show that this guidance is consistent with a weakly positive NPV requirement. Our analytical development considers separately two forms of managerial flexibility—namely, capital and operational flexibility. Though these two classes capture the broad set of strategies available to managers, our analysis focuses on two particular sources of managerial flexibility. Specifically, we analyze a capital growth option and a costless switching operational option. Our general three-step method applies to other forms of capital and operational flexibility.

We illustrate our analytic development with an example from the electricity generation context. Managers of NGCC may need to consider adding carbon capture equipment. The attractiveness of such additions will depend on the evolution of the cost of emitting carbon dioxide, and a priori uncertainty about these costs implies that investments in such facilities include embedded managerial flexibility. While the value of flexibility will vary greatly across investment opportunities, we find that its inclusion reduces the LPC of NGCCs. With our assumptions, we find that capital flexibility alone, or the option to invest in carbon capture technology only if the cost of emissions is sufficiently high, implies a 7% reduction. When we add operational flexibility (i.e., the ability to turn on and off the carbon capture equipment), we find that total managerial flexibility reduces the LPC by approximately 17%.
An immediate implication of our work is that common applications of the LPC should reflect the managerial flexibility entailed by alternative investments. The LPC has been prominently applied in the power generation sector, where it is known as the levelized cost of electricity. As society attempts to reduce its emissions of carbon dioxide, projects should be evaluated on the basis of their ability to respond flexibly to changes in emissions prices. In this regard, technologies that seem prohibitively expensive when considered and in the absence of an emissions price, may approach cost competitiveness when evaluated as part of flexible managerial responses to higher emissions prices.
6 Proof of Proposition 1

Claim: The general, stochastic LPC is given by:

\[
\mathbb{E}[LPC] = \sum_{\omega \in \Omega} g(\omega) \cdot (w_\omega + f_\omega + c_\omega) - \sum_{\omega \in \Omega} h(\omega) \cdot \phi_\omega
\]  

(1)

where \( \phi_\omega = \frac{\Phi}{m \sum_t CF_{t,\omega} \cdot a_{t,\omega} \cdot x_{t,\omega} \cdot \kappa^t} \).

The proof shows that the stochastic LPC is the correct cost measure under uncertainty. In particular, the stochastic, expanded LPC is the correct cost measure upon accounting for the value of managerial flexibility; with a passive strategy, the correct measure is the passive, expanded LPC.

Recall that, under uncertainty, the probability distribution \( g(\omega) \) describes the probability with which state \( \omega \) obtains, where \( \omega \in \Omega \), the space of all possible states of the world. We assume without loss of generality that the support of \( \omega \) is finite. \( h(\omega) \) reflects risk-adjusted probabilities with which the states of the world obtain. We note too that \( h(\omega) \) and \( g(\omega) \) have the same support.

In state \( \omega \), the firm receives a sales price \( p_\omega \) per unit of output. Assume in the following that state \( \omega \) implies that the manager will play a strategy requiring incremental cash flows relative to the passive scenario.\(^{27}\) As discussed in the main exposition, these incremental cash flows could include either or both incremental non-capital expenditure and non-depreciation related cash flows, \( \xi^C = j(dw, df)_\omega \), or incremental capital costs that occur at time \( \tau_1 \), \( SP_{\tau_1} \).\(^{28}\)

Since managers respond flexibly to the state of the world, we write \( \xi_{t,\omega} \) and \( SP_{t,\omega} \).

We ignore tax, depreciation, and tax incentive effects, though these nuances can be readily incorporated into the derivations presented using straightforward managerial accounting concepts. For one unit of capacity installed, cash flows in period \( t \) are given by \( CFL_{t,\omega} \), or the difference between operating revenues and costs:

\[
CFL_{t,\omega} = m \cdot x_{t,\omega} \cdot CF_{t,\omega} \cdot a_{t,\omega} \cdot (p_\omega - w_{t,\omega}) - F_{t,\omega} + \xi^C_{t,\omega} + \xi^O_{t,\omega}
\]  

(2)

\( dCFL_{t,\omega} \) represents the change in cash flows that result from the changes incumbent with

\(^{27}\)This subsumes scenarios in which an active manager’s optimal strategy does not require any incremental cash flows.

\(^{28}\)Without loss of generality, we provide a proof that considers only one incremental capital investment. The logic can be immediately extended to settings with more than one investment after time 0.
an expansion (i.e., use or otherwise of the expanded facility):

\[
I_{t,\omega} = \begin{cases} 
CFL_{t,\omega} - SP & : t < \tau_1 \\
CFL_{t,\omega} - dCFL_{t,\omega} - SP - SP_{\tau_1,\omega} & : \tau_1 \leq t < \tau_2 \\
CFL_{t,\omega} - dCFL_{t,\omega} & : t \geq \tau_2 
\end{cases}
\]

The cash flows are given by \( CFL_{t,\omega} \):

\[ CFL_{t,\omega} - dCFL_{t,\omega} - I_{t,\omega} = 0 \quad (3) \]

For the firm to just break even (per the definition of the LPC), the discounted cash flows realized must sum exactly to zero:

\[
\sum_{t=1}^{T} CFL_{t,\omega} \cdot \gamma^t - dCFL_{t,\omega} \cdot \kappa^t - SP - SP_{\omega} \cdot \gamma^\tau = 0 \quad (4)
\]

Directly substituting for \( CFL_{t,\omega} \), we have:

\[
\sum_{t=1}^{T} m \cdot \gamma^t x_{t,\omega} CF_{t,\omega} \cdot (p_{\omega} - w_{t,\omega}) - F_{t,\omega} \cdot \gamma^t \\
- \sum_{t=1}^{T} m \cdot \gamma^t x_{t,\omega} CF_{t,\omega} \cdot a_{t,\omega} \cdot (p_{\omega} - dw_{t,\omega}) - dF_{t,\omega} \cdot \kappa^t = SP + SP_{\omega} \gamma^\tau \quad (5)
\]

The expression above can be collapsed to:

\[ p_{\omega} = w_{\omega} + f_{\omega} + c_{\omega} + dw_{\omega} + df_{\omega} + c_{\tau_1,\omega} \quad (6) \]

By definition, the price \( p_{\omega} \) that solves the above equation is the LPC if state \( \omega \) obtains. Recalling the definitions of \( w, f, \) and \( c \):

\[ LPC_{\omega} = w_{\omega} + f_{\omega} + c_{\omega} + dw_{\omega} + df_{\omega} + c_{\tau_1,\omega} \quad (7) \]

If the manager had not responded flexibly to the realization of state \( \omega \), the expression above would not have included \( dw_{\omega} + df_{\omega} + c_{\tau_1,\omega} \). This difference reflects the value of managerial flexibility in state \( \omega \). Since we expect that state \( \omega \) will entail the exercise of such flexibility only if \( dw_{\omega} + df_{\omega} + c_{\tau_1,\omega} < 0 \), we can summarize these by \( \phi_{\omega} \), where \( \phi_{\omega} = |dw_{\omega} + df_{\omega} + c_{\tau_1,\omega}| \), and express the LPC as follows:
\[ LPC_\omega = w_\omega + f_\omega + c_\omega \cdot \Delta_\omega - \phi_\omega \] (8)

\( \phi_\omega \) reflects the incremental cash flows levelized over all units of output, as given by 
\[ \sum_{t=1}^{T} m \cdot x_{t,\omega} CF_{t,\omega} a_{t,\omega} \cdot k^t \].
Recall that formulating \( \phi_\omega \) with the risk-free rate \( r \) and \( h(\omega) \), is equivalent to \( \phi_\omega \) with the discount rate of the matching security, \( k \) and \( g(\omega) \). Taking the expectation over all states of both sides of the above equation, we have:

\[ \sum_{\omega \in \Omega} g(\omega) \cdot p_\omega = \sum_{\omega \in \Omega} g(\omega) \cdot (w_\omega + f_\omega + c_\omega \cdot \Delta_\omega) - \sum_{\omega \in \Omega} h(\omega) \cdot \phi_\omega \]
\[ \quad \rightarrow \mathbb{E}[LPC] = \sum_{\omega \in \Omega} g(\omega) \cdot (w_\omega + f_\omega + c_\omega \cdot \Delta_\omega) - \sum_{\omega \in \Omega} h(\omega) \cdot \phi_\omega \] (9)

By omitting the tax factor in all cases, the result is the general stochastic LPC expression:

\[ \mathbb{E}[LPC] = \sum_{\omega \in \Omega} g(\omega) \cdot (w_\omega + f_\omega + c_\omega) - \sum_{\omega \in \Omega} h(\omega) \cdot \phi_\omega \] (10)

Note that in the absence of managerial flexibility, \( \phi_\omega = 0 \) and the cash flows realized by the firm are determined purely by the realized state, \( \omega \). Since no incremental cash flows obtain, the stochastic, passive LPC will always be weakly higher than the stochastic, expanded LPC.

Note that the above proof applies equally to operational and capital flexibility. The former case will not entail incremental capital investments, but the value of operational flexibility would be reflected in \( \xi^O \) instead of \( \xi^C \), as used here; this is further discussed in the main exposition.
7 Proof of Proposition 2

A productive asset is cost competitive in expectation if and only if:

\[ \mathbb{E}[CM] > 0 \]  \hspace{1cm} (11)

where \( CM \) is the total-LPC based contribution margin.

The standard, static contribution margin is given as:

\[ p - LPC \]  \hspace{1cm} (12)

which reflects the average revenue per kWh less the average cost per kWh. Clearly, this quantity must be greater than zero in order to motivate investment and/or operation of a productive asset. This would be true if the quantity of produced items was static across time and situation. Now, given \( \mathbb{E}[p] \) and \( \mathbb{E}[LPC] \), by definition of the expectation operator the previous equation becomes:

\[ \sum_{\omega \in \Omega} g(\omega) \cdot p_\omega - \sum_{\omega \in \Omega} g(\omega) \cdot LPC_\omega \]  \hspace{1cm} (13)

Provided that output from the productive asset now varies across states of the world, quantity must be included in the decision-making process. Only if the total-LPC based contribution margin is greater than zero, will a productive asset be cost-competitive in expectation. Put formally:

\[ \mathbb{E}[CM] = \sum_{\omega \in \Omega} g(\omega) \cdot (p_\omega - LPC_\omega) \cdot m \cdot x_{t,\omega} \cdot CF_{t,\omega} \cdot a_{t,\omega} > 0 \]  \hspace{1cm} (14)

The expression above shows that, in expectation, the asset at least breaks even, the requirement for cost competitiveness.

Assume now that the facility is cost competitive in expectation. By definition, we have that \( \mathbb{E}[p - LPC] \geq 0 \), and the required inequality follows trivially from the linearity of the expectation operator.
References


