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Coal-Power Plants Rejuvenated With Biomass: An Economic, Social, and Environmentally Sustainable Transition to Clean Power

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Foreword

For decades, the U.S. coal industry has experienced declining production, due to high costs from stricter environmental regulations, safety issues, and competition from other energy sources, especially natural gas. In spite of these challenges, U.S. coal is still an important component of our Nation's energy portfolio, accounting for approximately 30 percent of U.S. electricity generation. U.S. coal is vital to some rural coal mining communities where few alternative job opportunities exist and job growth is stagnating. The economic plight of these communities recently captured the attention of the public and policymakers when revitalizing the U.S. coal industry became a key issue in the 2016 Presidential campaign. Rejuvenating the U.S. coal industry would not be easy, however, and would require creative public policies to help reverse the decline and move it forward on a sustainable path.

While the coal industry is losing market share to other sources of power, stricter environmental regulations are making it even more difficult for coal power to remain cost competitive. Environmental regulations causing abrupt technological change to coal plants could not only increase the economic instability of coal mining communities, but expected cost spikes could ultimately be passed on to U.S. consumers through higher energy prices. Therefore, adopting policies that promote a smooth transition of the U.S. coal industry from a high- to a low-emission system may have merit.

One transition approach is adopting BIOmass CO-firing (BIOCO), which can extend the life of some existing coal-fired plants by retrofitting them with a technology allowing co-firing coal with biomass. BIOCO can extend a coal plant's life by helping to meet more stringent Environmental Protection Agency air emissions regulations while delaying the full costs of adopting cleaner conversion technologies. The purpose of this report is to study the conditions under which the rejuvenation of coal-power plants with BIOCO could become an economically efficient path for society to transition from a high- to a low-emission power system. A dynamic theoretical model is developed for a coal plant using biopellets to evaluate the effect relative costs of each transition phase has on choosing the optimal BIOCO rejuvenation period before plant replacement. The results provide insights for public utilities and policymakers wishing to revamp the coal industry in a cost-efficient manner. This report will provide a foundation for others interested in theoretical approaches to asset replacement decisions and developing policy aids for revitalizing U.S. industries, such as coal mining.

The report was initiated by Cooperative Agreement No. 58-0111-15-019 between USDA's Office of Energy Policy and New Uses, and Michael Wetzstein, Professor of Agricultural Economics, Purdue University. Wetzstein has published extensively on renewable energy and is recognized as a leading researcher in the area of asset replacement theory. He has an excellent reputation for guiding graduate students, and their published research has made valuable contributions to the literature, including much of the work presented in this report. In addition to Wetzstein, other authors include Sarah Stutzman, an economist in the U.S. Bureau of Economic Analysis, and Brandon Weiland, a graduate research assistant, Juan Sesmero, an assistant professor, and Paul Preckel a professor, all in the Department of Agricultural Economics, Purdue University. Finally,

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Introduction

Can BIOCO save coal power plants? BIOCO (BIOmass CO-firing with COal) is an approach that extends the life of coal-fired plants by rejuvenation (retrofitting to co-firing coal with biomass). The idea is to consider an investment in a coal plant with the possibility of a future BIOCO retrofit. If desired, government programs could be established to promote BIOCO. The underlying foundation for determining these programs is a theoretical understanding of the interplay of costs between the existing coal plant prior to retrofitting and post-retrofitting costs. Our objective is to develop such a theoretical understanding.

The potential advantage is that BIOCO extends coal plants' life while aiding in meeting the more stringent EPA regulations for reducing carbon dioxide (CO_2), sulfur hexafluoride (SF_6), and other pollutants under the Clean Power Plan. Extending the life of some coal plants delays the decision to replace a portion of the aging coal-firing capacity. This allows spreading irreversible replacement costs over longer time periods and results in keeping the option of replacement opened. Such an option has value in terms of allowing alternative renewable energy technologies more time to mature before replacement options must be finalized. It also allows additional time for coal-dependent communities to transition toward an alternative economic base. BIOCO is a distinct choice, which can complement the other current choices:

- Adopting clean coal,
- Installing pollution controls,
- Converting to natural gas,
- Not complying and paying penalties,
- Replacing a portion of existing coal plants with a renewable fuel (Sklar, 2011).

Our aim is to study the conditions under which rejuvenation of coal-power plants with BIOCO can become an economically efficient path for society to transition from a high-to a low-emission power system. For BIOCO to become feasible, current policies and government incentive programs may require modification or new programs to be adopted. The theoretical developed model for investigating the conditions required for BIOCO can serve as a foundation for policy analysis.

Coal-plant rejuvenation is at the heart of all three dimensions of sustainability. It contributes to economic/social sustainability of emerging bio-markets as (1) a low-cost strategy for deployment of bioenergy markets and compliance with emission-reduction regulations, and (2) a benefit to multiple sectors along the vertical supply chain including rural communities producing and selling bioproducts, coal-mining communities, and energy consumers through a diversified energy mix. Third, it also contributes to environmental sustainability by reducing emissions.

A major concern with policies aimed at lowering emissions from power generation is the cost of drastic technological changes. These changes take place in an environment surrounded by uncertainty on technical and economic aspects of the newly adopted technologies. The most prominent example of such policies is the Environmental Protection Agency's Clean Power Plan (CPP). Debate over its costs and benefits has prompted the Supreme Court to grant a stay (Chamber of Commerce, et al. v. EPA et al.), halting implementation of CPP.

The costs imposed on society during the transition from a high- to a low-emissions scheme is at the heart of these legal and policy debates. Such debates, as well as existing and proposed legislation, operate on the premise of abrupt technology change. The push back on such abrupt change has some merit. Abrupt technical change can generate cost spikes, which will ultimately be passed on to consumers through higher energy prices (Zhang et al., 2010). Successful transitions require instead a thorough and systematic evaluation of the cost of limiting polluting emissions via conducting careful cost-benefit analysis of each alternative, especially those that hold promise of a smooth transition (in its social, economic, and environmental dimensions) from a high- to a low-emission system.

For BIOCO, biomass in general and biopellets in particular are a renewable resource with lower greenhouse gas (GHG) emissions, which can be co-fired in coal plants (ACC, 2015; Basu et al., 2011; De and Assadi, 2009; FEMP, 2004; Kinney, 2012; Nicholls and Zerbe, 2012; Zhang et al., 2009). Biopellets are a biocoal in which biomass (such as Miscanthus or crop residue), corn, or wood is processed into fuel pellets. The use of biomass in BIOCO is not without its own costs. BIOCO may reduce fuel-price uncertainty, through a portfolio effect, but will not eliminate uncertainty. Further, the investment costs of BIOCO are largely irreversible. There are sunk costs, which are not recoverable if BIOCO is adopted and then suspended.

While Xian et al. (2015) examined the economics of co-firing coal with biopellets, no studies have examined dynamic asset replacement with stochastic costs in the context of power plants. One reason is perhaps the difficulty to achieve analytical tractability when analyzing the cost-benefit of this alternative. BIOCO provides a way to phase-in bioenergy sources into the power supply system, without extremely high upfront costs associated with plant decommission and constructing new alternative-energy plants. BIOCO can also help managers comply with increasingly strict environmental regulations. Its economic viability hinges upon the cost at which rejuvenated plants can deliver power relative to competing technologies that can also meet compliance regulation. Rejuvenation and other alternative technology investment costs are uncertain and largely irreversible. This poses a considerable challenge to economic analysis. Real options analysis offers an avenue to address this challenge. It examines the economics of rejuvenation under multiple and correlated stochastic processes.

The use of this technique will allow us to determine the optimal steady-state rejuvenation/replacement (R/R) sequence. If BIOCO is economically and environmentally feasible, it leads to the following hypothesis:

> **Hypothesis:** Under the right conditions and policies, it may be feasible to rejuvenate a power plant through retrofitting for co-firing, BIOCO. With such rejuvenation, the life of the power plant can be extended, which delays the plant replacement decision, including the choice of technology and fuel. Value is created when the option of replacement is kept open. Considering this option value mitigates the cost of BIOCO, making it more attractive.

Our aim is to first develop a dynamic theoretical model for an R/R asset under a real options analysis. Performing comparative statistics will reveal the impact of changes in key parameter values on the timing and length of the retrofit and renewal periods. Numerical analysis will then be applied to coal-power plant replacements where the problem centers on decisions to retrofit the plant by co-firing with biopellets, BIOCO. The numerical analysis results lead to evaluating policy impacts on co-fired electricity plant rejuvenation and replacement.

Background

Aging Power Supply and the Clean Power Plan

The United States is facing an aging fleet of generators, with 51 percent of its generating capacity older than 30 years (EIA, 2011), as well as more stringent EPA regulations to reduce CO_2 emissions under CPP. Under CPP, States are required to reduce CO_2 emissions according to prescribed emission targets by the year 2030, with interim goals in the years 2020-2029. Emission targets are assigned individually to States based upon a Best System of Emission Reductions. Each State is allowed to draft a unique plan on how to meet these goals. The effort required to meet these goals will vary by State.

As an example, in Indiana 85 percent of electricity generation comes from coal-fired plants, as compared to 45 percent nationwide (Venere, 2012). Under the Clean Power Plan, Indiana must reduce emissions by 38.7 percent compared to 2012 levels by the year 2030 (E&E Publishing, LLC, 2016). According to a recent report by the State Utility Forecasting Group (Phillips et al., 2015), this will result in the closing of 19 of 28 coal plants and a reduction of 2,280 megawatts of Indiana's power-generating capacity (E&E Publishing, LLC, 2016). For meeting future demand, Indiana must install an additional 2,960 megawatts of generating capacity by 2020 and 4,380 by 2025 (E&E Publishing, LLC, 2016). Additional power sources include conservation, purchases from other utilities, and/or construction of new facilities.

This shift away from coal-generating capacity has community impacts. Coal mining communities face a shifting identity as the coal-based economic driver of community welfare declines. The impacts of this decline can change the community economic identity (Bell and York, 2010). This community cost may be mitigated by developing transition programs from coal to an alternative economic driver. Extending the life of coal plants through rejuvenation may soften the transition costs.

For addressing a shift away from coal, 29 States have adopted renewable portfolio standards, which require utilities to sell a specified percent or amount of renewable electricity. While these standards can potentially increase the demand for biomass, other policies such as USDA's Biomass Crop Assistance Program and Advanced Biofuel Payment Program target biomass supply. Through competitive grants and payments, they provide incentives to expand the biomass infrastructure and other renewables. These standards and programs are integral to States' diversification of their energy mix, promoting economic development and reducing emissions. For policy analysis, it is important to understand how these standards and programs impact investments in new facility construction, including BIOCO.

Previous Economic Analysis

The economics behind new facility construction are embedded in the theory of asset replacement. This theory has continuously evolved since the Faustmann-Samuelson replacement criterion, centered on maximizing the present value of deterministic net returns from an infinite asset chain (Faustmann, 1968; Samuelson, 1937). Relatively recent literature has extended the replacement criterion to consider the stochastic nature of replacement in a real options framework. Specifically, the asset yields a constant revenue stream with increasing operation costs following a Brownian motion process (McLaughlin and Taggart, 1992; Mauer and Ott, 1995; Dobbs, 2004). Adkins and Paxson (2011) and Hritonenko and Yatsenko (2008) consider a nonconstant revenue stream and technological change. This research vein continues with Reindorp and Fu (2011) employing real options in consideration of asset renewals instead of total replacement. A natural extension of this research is combining replacement with renewal.

The replacement literature in agricultural applications that proliferated once-appropriate modifications to the theory were correctly established by Burt (1965), Chisholm (1966), and Perrin (1972). A recent addition is determining the optimal replacement time for multiple assets with a single technological improved asset (Ibendahl et al., 2014). Consideration of rejuvenation was then incorporated deterministically by McClelland et al. (1989) and stochastically by Smith et al. (1992). However, extensions of this rejuvenation research were hampered by lack of theoretical advancements in real options applied to asset replacement. With recent advancements in the field of real options, such as Dobbs (2004), the R/R problem can be couched in a real options framework.

The unique aspect of this research is to theoretically integrate recent advancements in real options replacement theory into the asset R/R problem. The first choice becomes when and if to rejuvenate the asset. This is followed by the choice of when to replace the rejuvenated asset, if rejuvenation was chosen, or when to replace the original asset, if rejuvenation was not pursued.

Methodology

As a foundation for this research, a theoretical model of the stochastic dynamic R/R problem is developed (Stutzman et al., 2016). The model incorporates Brownian motion into a stochastic R/R model. As a foundation, consider operating cost following a Brownian stochastic process where fuel costs are a major component. For BIOCO, per-unit fuel costs are composed of both coal and biopellet prices. This results in two stochastic price series with an associated correlation, which leads to a portfolio effect, yielding reduced fuel-price volatility. This portfolio effect is modeled based on the analysis of correlated stochastic price series (Price et al., 1999; Vedenov et al., 2006; Xian et al., 2015). Consideration of stochastic electric power prices also yields additional correlations with fuel prices. As a benchmark, a 650-megawatt (MW) coal plant is assumed.

The developed theory for R/R is investigated first through a comparative statics analysis where the direction that condition variables have on operating costs and R/R period length is determined. Specifically, the directional impact that outlay costs, operating-cost growth rates, salvage values, and discount rates have on the R/R period length is determined. Numerical analysis is then employed to resolve any comparative statics ambiguities and provide insights on the relative responsiveness of the optimal period lengths to parameter variation. The numerical analysis involves calculating the optimal length of time spent in the virgin and rejuvenation periods as well as the total cycle length and then employing these estimates to calculate the elasticities with respect to the parameters. The virgin period is the length of time a new coal plant is operated from initial startup to the time of rejuvenation. Rejuvenation period is the time span of a newly rejuvenated plant to when the plant is decommissioned. Summing the virgin and rejuvenated periods yields the total cycle length.

Models and Comparative Statics

Model 1: Pure Rejuvenation/ Replacement Deterministic Case

Let the initial financial outlay costs for a virgin coal-fired power plant be K_1 with rejuvenation costs denoted as K_2. Associated with these costs are variable operation costs c_{it}, $i = 1, 2$, with 1 representing costs over the virgin period and 2 representing rejuvenation periods. Assume these operation costs increase at a constant growth rate of θ_1 for virgin and θ_2 for rejuvenation periods, $c_{1t} = c_{10}e^{\theta_1 t}$ and $c_{2t} = c_{20}e^{\theta_2(t-T_1)}$, where c_{i0} denotes virgin and rejuvenation periods' initial operating costs with T_1 and T_2 representing the end of virgin and rejuvenation period, respectively. Denote V as the present value of the R/R cycle and let S represent the residual salvage value, which could be positive or negative. It is assumed the initial outlay and operating cost series do not change from one replacement to another. The present value of the R/R cycle can be expressed as

$$(1)\quad V = K_1 + \int_0^{T_1} c_{1t}\, e^{-rt}dt + K_2\, e^{-rT_1} + \int_{T_1}^{T_2} c_{2t}\, e^{-rt}\, dt + (V - S)e^{-rT_2},$$

where r is the discount rate. The first term on the right-hand side is the initial financial outlay, the second is the present value of virgin operating costs. The virgin power plant is then rejuvenated at a cost of K_2 followed by the present value of rejuvenated operating costs. The final term is the present value of the salvage value and the present value of the next and subsequent power plants.

As outlined in Stutzman et al. (2016), the optimal length of the virgin period, T_1^*, and the end of rejuvenated period, T_2^*, can then be determined from first order conditions of (1).

For T_1 it is

$$T_1^* = \frac{ln\left[\frac{rK_2+c_{20}}{c_{10}}\right]}{\theta_1}.$$

The condition leading to determining the optimal end of the rejuvenated period, T_2^*, is of a non-linear form, which requires numerical analysis for determining T_2^*.

Comparative Statics

Despite the implicit nature of the function characterizing T_2^*, some comparative statics analysis is possible by applying the implicit function theorem. These comparative statics are presented in Appendix A. These statics results indicate the marked difference the parameters have on the optimal length of cycles when comparing the conventional and R/R decisions. The interplay of the relative costs between the virgin and replacement periods leads to differing comparative statics results. For conventional replacement, relatively high virgin outlay costs, K_1, and virgin initial operating costs, c_{10}, along with a low residual salvage value, S, will result in a longer plant life. In contrast, with replacement, high virgin outlay costs, K_1, and low residual salvage value, S, will also yield longer life. However, higher initial operating costs, c_{10}, lead to a shorter virgin period length with an ambiguous effect on total cycle length. The interplay of virgin and rejuvenation costs is responsible for the difference in these results. On the other hand, higher initial rejuvenation operating costs, c_{20}, lead to a shorter total plant life but increase the time spent in the virgin period and reduce the time spent in the rejuvenation cycle. Applying these results to co-firing with wood pellets, it is the relative difference in coal versus co-firing costs that determines when to adopt co-firing.

Model 2. Pure Rejuvenation/Replacement (R/R) Stochastic Case

As addressed by Dobbs (2004), assume operating costs c_{it}, $i = 1, 2$ follow the geometric Brownian motion processes

$$dc_{it}/c_{it} = \theta_i dt + \sigma_i dz_i ,$$

where θ is the trend rate of increased operating costs, σ is the measure of volatility, and dz is the increment of a Wiener process. Let C_i at $i = 1$ denote the operating costs threshold for recycling the plant and at $i = 2$ the threshold costs at replacement. Given the stochastic nature of the operation costs, the timing of recycling and replacement is then a function of these costs, $T_1(C_1)$ and $T_2(C_2)$. The expected present value of the R/R cycle for an existing plant at time τ is then

$$V_1(c_{1\tau}) = E_\tau[\int_\tau^{T_1(C_1)} c_{1t}\, e^{-r(t-\tau)} dt + W_1(C_1) e^{-r[T_1(C_1)-\tau]}],$$

$$W_1(C_1) = K_2 + V_2(C_1),$$

$$V_2(C_1) = E_\tau[\int_{T_1(C_1)}^{T_2(C_2)} c_{2t}\, e^{-rt}\, dt + W_2(C_2) e^{T_2(C_2)}],$$

$$W_2(C_2) = K_1 - S + V_1(c_{10}).$$

The conditions are then

(2) $rV_i dt = C_i dt + E(dV_i),\ i = 1, 2.$

Over the time period dt, the total expected return on the investment opportunity is equal to the expected rate of capital appreciation.

Comparative Statics

Table 1 summarizes the comparative statics conditions associated with (2) along with Dobbs (2004) conventional replacement statics. Figure 1 then provides the comparative statics results for parameter influences on the optimal virgin period length, $\hat{T}_1$ and the total cycle, $\hat{T}_2$. These comparative statics were derived by Stutzman et al. (2016).

Consistent with deterministic comparative statics, for R/R, a change in virgin outlay costs, K_1, will positively influence the virgin period length but with a corresponding negative affect on the total cycle length. This implies a reduction in the rejuvenation period length resulting from the interaction of the threshold operating costs, C_1 and C_2. If an increase in C_1, as a result of K_1 increasing, leads to a decrease in C_2, then $\hat{T}_2$ decreases. This interaction between C_1 and C_2 is further explored in the numerical analysis. Consistent with the deterministic results, the reverse occurs for a change in the salvage value, *S*. An increase in the salvage value leads to a shorter virgin time period but overall longer total plant life. There is an inverse relationship between initial virgin operating costs, c_{10}, and the virgin period length under both the deterministic and stochastic models. As opposed to what occurs under the deterministic model, in a stochastic setting under some conditions, the total cycle length is now positively related to the salvage value, *S*. The explanation remains the same; an increase in c_{10} will decrease the wedge between rejuvenation and virgin costs and trigger a shorter virgin period. Finally, in contrast to the positive relation between virgin operation cost volatility, σ_1, and replacement length under the conventional asset replacement problem, under the R/R problem these relationships are ambiguous. In general, the comparative statics effect on the length of the virgin and rejuvenation periods along with the total cycle length are difficult to obtain given volatility in operating costs leading to stochastic optimal R/R lengths.

Numerical Analysis

A numerical analysis is employed to resolve the comparative statics ambiguities and provide insights on the relative responsiveness of the optimal period lengths to parameter variation. The numerical analysis involves calculating the optimal length of time spent in the virgin and rejuvenation periods as well as the total cycle length and then employing these estimates to calculate the elasticities with respect to the parameters at their mean values.

Parameter values and methodology

Table 2 lists the parameter values employed with the caveat that they are for illustration purposes only. The objective is to derive further understanding of the R/R theory and not to determine to actual optimal virgin, rejuvenation, and total cycle lengths for some specific coal power plant. As a result, the chosen values, while as realistic as possible, are not construed as necessarily representative of a current coal power plant.

The virgin outlay costs are set at $2 per 1,000 kW, which is representative of the cost for a 650 MW coal plant (EIA, 2013; Nderitu, 2014; Schlissel et al., 2008; Sekar et al., 2007). Initial rejuvenation outlay costs are set at $1.9 per 1,000 kilowatt (kW). While this is larger than currently calculated in the literature (IRENA, 2012; IRENA, 2013), this estimate is not completely out of the range of possible values. The actual costs of conversion to co-firing with woody biomass can vary greatly depending on the existing coal firing technology, the type of material burned, and the technology employed (IRENA, 2012, IRENA, 2013). The associated annual initial operating costs are approximately $0.065 per 1,000 kW in the virgin period and $0.075 per 1,000 kW in the rejuvenation period, or approximately 30 times less than that of the initial outlay costs. These costs are respective of the total costs obtained by Stutzman et al. (2016) calculations when accounting for fixed and variable operating and fuel costs. It is expected that operating costs will increase slightly in the rejuvenation period due to replacing a small percent (10 percent is assumed reasonable) of the coal used with wood pellets.

Wood pellets are costlier relative to coal in terms of dollars per million British Thermal Units ($/mmBTU) acquisition costs. The exact nature of the relative costs in each period will also depend on the age of the plant and the associated difference in variable and fixed costs. This would include maintenance and repairs from the addition of the co-firing technology. The growth rates and associated volatility are assumed to be approximately the same in the virgin and rejuvenation periods. This is reasonable given the small portion of coal replaced with wood pellets in the rejuvenation period and the importance of fuel costs in determining total annual cost volatility. The price of coal relative to wood pellets has varied widely over the past decade, making an exact estimate difficult. The chosen parameters are within the range calculated by Stutzman et al. (2016) using coal price data from the Energy Information Administration (EIA, 2016) and wood pellet futures prices for Southwest United States provided by Xian (2015). A lower value for the rejuvenation period was considered based on a possible fuel-portfolio effect. The salvage value is set at less than 4 percent of the outlay costs, given a large sunk cost in coal plant investments. Finally, a discount rate of 6 percent is assumed.

Based on these parameter values, the optimal cycle lengths for the deterministic model are solved by first determining virgin cycle optimal length and then employing this to determine the optimal rejuvenation and total cycle lengths. Optimal times for the virgin and rejuvenation periods are jointly solved under the stochastic model. The resulting optimal length estimates are provided in Table 2. The elasticities are then calculated using these lengths and the given parameter values. The elasticity estimates, or the relative responsiveness of the optimal lengths to changes in the parameter changes, are provided in Tables 3 and 4.

Numerical Analysis Results

As indicated in Table 2, the estimated optimal length within the virgin cycle is less under the deterministic case compared to the stochastic case, while the optimal lengths in the rejuvenation period and total cycle decrease under the stochastic case compared to the deterministic case. A reason for these differences may be the greater linkage between the optimal lengths and the parameter values under the stochastic case as compared to the deterministic case. In the stochastic case, both the virgin and total cycle lengths are solved simultaneously while in the deterministic case, the optimal virgin length is solved independently of the optimal total cycle length. In addition, the optimal stochastic length, $\hat{T}$, has the additional determinants σ_1, σ_2, θ_2, K_1, and S (Stutzman et al., 2016). Considering these additional parameters in the stochastic optimal virgin length, along with the net cost of instigating a new cycle $(K_1 - S)$, results in prolonging the optimal virgin period length. These additional parameters have relatively strong and different impacts compared to the other parameter values on the optimal lengths under the stochastic and deterministic cases. The different impacts of these parameters help explain the different optimal cycle lengths under the deterministic and stochastic model.

Elasticities

The calculated elasticities shown in Tables 3 and 4 provide additional insights into the impact that changes in key parameter values have on the length of time spent in each cycle stage. For the deterministic case, the elasticities for virgin outlay costs, K_1, are either zero or very inelastic, which is in contrast to the elastic response under the stochastic case. This larger elasticity with respect to initial outlay costs contributes to the longer optimal virgin length under the stochastic case versus the deterministic case. The reverse occurs for the rejuvenation outlay costs, K_2, where the responsiveness of the optimal stochastic length to changes in K_2 is quite small. Relative to the other parameters, K_2 exerts limited if any influence on the stochastic optimal lengths. In contrast, under the deterministic case, an increase in K_2 extends the deterministic optimal virgin period and retards the rejuvenation period and the total cycle length. As indicated by Stutzman et al. (2016), if the length of the virgin period is responsive to changes in initial rejuvenation outlay costs, then the elasticity of T_2^* with respect to a change in K_2 will be less than zero. In this instance, the large increase in the virgin period postpones the incurrence of rejuvenation to such a degree that the total cycle length is reduced. Finally, the salvage value, S, has limited impact on the optimal lengths under either the stochastic or the deterministic case.

The responsiveness of the optimal virgin length given a change in the initial virgin operating costs, c_{10}, is more elastic given stochastic operating costs compared to deterministic operating costs. These elasticities also exhibit a negative relation compared with a positive optimal rejuvenation period and total cycle response for the deterministic operating costs. The negative relationship between costs in the virgin period and the rejuvenation length and total cycle length in the stochastic case can be explained by comparing the relative elasticities of the threshold operating costs at the end of the total cycle, C_2^*, with that of the threshold operating costs at the end of the virgin period, C_1^*.

In the deterministic case, an increase in rejuvenation initial operating costs, c_{20}, is associated with an increase in the optimal virgin period and a decrease in the optimal rejuvenation period and total cycle length. In contrast to c_{10}, this negative relationship between a change in operating cost levels in the rejuvenation period and the length of the virgin cycle holds for stochastic operating costs, but with more inelastic responses.

The optimal cycle lengths are the most responsive to changes in the parameters for operating cost growth rates, θ_1 and θ_2. Their impacts are markedly larger under the stochastic case versus the deterministic case. In the deterministic case, the elasticities with respect to θ_1 and θ_2 are of opposite sign and reversed when comparing across periods and between θ_1 and θ_2. Their large magnitudes under the chosen parameter values, especially when allowing for stochastic operating costs, illustrates that the optimal lengths are very sensitive to the growth-rate parameter values. The positive elasticity of the optimal lengths to a change in θ_2 under stochastic costs is counterintuitive. Intuitively, one would expect an increase in the rejuvenation operation-cost growth rate would lead to a rejuvenation shorter period length. However, the interplay between the virgin- and rejuvenation-cost growth rates can explain these results. An increase in θ_2 will move the growth-rate differential toward zero. Given this occurs, the difference between the virgin- and rejuvenation-cost trends becomes small, diminishing the advantage to ending a virgin or rejuvenation period. This leads to longer optimal virgin and rejuvenation periods.

This finding illustrates a key result, which is the relative importance of the interaction between virgin and rejuvenation costs. These costs are heavily influenced by the relative initial parameters chosen. The interplay of virgin with rejuvenation parameters leads to this and other interesting results when the option to rejuvenate and/or replace an asset is examined. One such interesting result is the reversal of the elasticities for the discount rate, r, under the stochastic case compared to the deterministic case. Again, it is the interaction of r with θ_1 and θ_2, as well as the addition of parameters, and jointly solving for costs under the stochastic case compared to the deterministic case, that possibly causes this reversal.

The elasticities with respect to the volatility parameters, σ_1 and σ_2, are consistent with the conventional replacement comparative statics in Table 1. The virgin (rejuvenation) volatility elasticity is inelastic (elastic). This difference between the elasticities in the virgin and rejuvenation periods indicates that the volatility of rejuvenation operation costs may have a larger impact on determining optimal lengths than the volatility of virgin operating costs.

The above finding illustrates how numerical results can complement comparative statics analysis. Both reveal it is the wedge between virgin and rejuvenation costs that determine the optimal period lengths. By considering this cost wedge, counterintuitive results, including that increases in the growth rate of cycle operating costs can prolong the cycle length, become intuitive.

Implications

Results indicate that the interplay of factors impacting virgin and rejuvenation periods in asset adoption can have major effects on the optimal lengths. Given the relative importance of these interactions, government mechanisms designed to promote the adoption of BIOCO and to aid in market internalization of associated external costs should consider this interplay. Failure to do so will result in insufficient mechanisms and possibly in unintended consequences. This is particularly true when considering policies to expand power-generation capacity and meeting Clean Power Plan goals by retrofitting a portion of existing coal-fired power plants with BIOCO. Applying these results in the application of government incentives under stochastic costs, such as the adoption of BIOCO, indicates that in these circumstances, government mechanisms have markedly different and unexpected affects when the stochastic nature of adoption is considered versus when it is ignored. Under stochastic costs, mechanisms designed to reduce retrofitting costs, K_2, will have limited effects on encouraging earlier adoption or extending the retrofitted period length. In contrast, reducing the retrofit initial operating costs, c_{20}, will extend the length of time the plant is operated once retrofitted, but not lead to earlier adoption. Finally, mechanisms designed at reducing the retrofit cost growth, θ_2, may in fact retard the retrofitting period length.

Conclusions

The theory for determining the optimal times under an asset rejuvenation/replacement sequence is developed in a dynamic context. Both deterministic and stochastic models of R/R optimal timings for asset rejuvenation and then replacement are determined. Comparative statics results illustrate the marked difference the parameters have on the optimal length of cycles when comparing pure replacement with R/R policies. Leading to these differences in the comparative statics results are the interplay of the relative costs between the initial non-rejuvenation and rejuvenation periods. Based on the methodology employed, these results reveal it is the relative difference in costs in each stage that are key in determining the optimal time to rejuvenate the asset.

Numerical analysis provides additional implications with an application to the problem of deciding when to retrofit a coal-fired power plant to BIOCO. This option will extend a plant’s life and can delay the irreversible costs of replacement. Under uncertainty concerning changes in relative future costs of alternative technologies, retrofitting has a real option value in allowing the delay of the future investment until more information regarding the relative outlay costs, initial operating costs, and expected growth rate of costs of alternative energy sources become known. These dynamics naturally suggest evaluating the timing for retrofitting a coal-fired power plant with wood pellet BIOCO technology along with replacement in a real options framework.

BIOCO is extensively employed throughout the European Union. Adoption of wood pellet technology in the EU over the past decade is heavily driven by mandates to reduce GHG emissions under the EU Renewable Energy Directive. Under the Clean Power Plan, the United States is facing a similar challenge. Each State must formulate a plan to reduce CO_2 emissions while maintaining the capacity to serve the demands for electric power. The main method of meeting these goals, replacing coal-power plants with natural gas plants, involves significant costs, time delays, and uncertainty regarding future natural gas prices. BIOCO can serve a complement to natural gas by possibly developing a portfolio of natural gas and BIOCO power plants. Utilizing the developed model and numerical analysis indicates how the theoretical results could assist public utilities to effectively transition to this new regulatory environment and encourage investment in BIOCO to assist in meeting Clean Power Plan emission standards. An example is that the theory explicitly indicates it is the relative cost of virgin versus rejuvenation periods that is important. By utilizing these results, many costly mistakes could be avoided, both in terms of dollars spent as well as achieving the optimal mix of traditional fossil fuel and renewable energy generation capacity.

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Appendix A

As addressed in Stutzman et al. (2016), the first-order conditions for (1) yields comparative static results summarized in Table A1 and Figure A1. For comparison, the conventional replacement comparative statics analysis, considering no rejuvenation, is also presented. The conventional results are from Dobbs (2004). As discussed below, the unique differences when considering rejuvenation are the interplay of virgin with rejuvenation cost parameters in the optimal threshold for rejuvenation, T_1^*. The optimal length of the virgin cycle, T_1^*, is dependent on the ratio of virgin to rejuvenation costs. These rejuvenation to virgin cost ratios yield different comparative statics for conventional versus R/R thresholds.

Considering first virgin outlay costs, K_1, comparative statics indicated K_1 is positively related to a power plant's total life (total cycle), regardless if it is rejuvenated. The reverse is true for the residual salvage value, S, with S negatively related to total plant life. Although K_1 and S do not influence the virgin period length, when considering R/R, they do affect the rejuvenation period. From the table and figure, an increase in the virgin outlay costs, K_1, will not change the virgin production period, but it will increase the rejuvenation period as a result of the total cycle increasing. The proportion of virgin to rejuvenation period length shifts, so an increase in virgin outlay costs will shorten the virgin relative to the rejuvenation period. This is in contrast to the rejuvenation outlay cost, K_2, where the virgin period is now generally positively influenced by this cost. The direction of the rejuvenation period is not revealed by the comparative statics, but as with K_1, the total cycle increases. However, as indicated in the comparative statistics results derived by Stutzman et al. (2016), it is possible if the virgin period is very responsive to rejuvenation cost, then the total cycle will decline with an increase in rejuvenation outlay cost. In this case, the large increase in the virgin period postpones the incurrence of rejuvenation costs to such a degree that the total cycle length is reduced. All of the savings in postponing the rejuvenation costs are absorbed by the increase in the virgin period.

With conventional replacement, there exists a positive relationship between virgin initial operating costs, c_{10}, and total plant life time. An increase in operating costs will extend the plant's operation length. The opposite can occur when rejuvenation is considered. In this case, the virgin period length, T_1, is shortened with an increase in its initial operating costs. This counterintuitive result, that more frequent replacement is triggered by increased initial operating costs, is caused by the interplay between virgin and rejuvenation costs. The length of the virgin cycle, T_1, is determined by the ratios of rejuvenation outlay cost to virgin initial operation costs, K_1/c_{10}, and rejuvenation initial operating costs to virgin initial operation costs, c_{20}/c_{10}. An increase in c_{10} will decrease the wedge between rejuvenation and virgin costs, which triggers a shorter virgin period. In conventional replacement, such a wedge does not exist, leading instead to a positive relationship between operating costs and plant life. Very similar results occur for the virgin operating-cost growth rate, θ_1. The only difference is that the sign is ambiguous for conventional replacement.

If the elasticity of T_1 with respect to c_{20} is inelastic, then an increase in rejuvenation initial operating costs will decrease the total cycle length of the R/R period. In this case, the virgin period is not very responsive to changes in c_{20}, so its length does not expand much for a change in c_{20}. As a result, the decrease in the rejuvenation period from an increase in c_{20} is sufficient to offset the rise in T_1, so total cycle length decreases.

The rejuvenation growth rate, θ_2, and the residual salvage value, S, only effect the rejuvenation period. An increase in the residual salvage value or rejuvenation growth rate, under the indicated conditions, will decrease the rejuvenation period, leading to an earlier decommission. Numerical analysis in the text illustrates these conditions. Finally, the more elastic T_1 is to r, the greater the likelihood that a rise in the discount rate, r, will increase the total cycle length. In this case, an increase in the discount rate, r, increases both the virgin period and the total cycle length. However, as also is the case for K_2, c_{10}, and θ_1, comparative statics did not reveal the effect on the rejuvenation period. Numerical analysis can be employed to reveal the parameter influences. The sensitivity of T_2 to these parameters along with the other parameters is examined concurrently with the stochastic case developed in the text.

Table 1. Stochastic Comparative Statics[a]

Parameter	ω	Conventional Replacement[b] $C_1^* = C_2^*$ $\frac{dC_1^*}{d\omega}$	Rejuvenation/Replacement Virgin Period $\frac{dC_1^*}{d\omega}$	Rejuvenation/Replacement Total Cycle $\frac{dC_2^*}{d\omega}$
Virgin outlay costs	K_1	+	+	−
Virgin initial operating costs	c_{10}	+	−	+
Residual salvage value	S	−	−	+
Virgin operating cost volatility	σ_1	+	Ambiguous	Ambiguous

[a] Results from Stutzman et al. (2016). For the rejuvenation outlay costs, K_2, initial operating costs, c_{20}, growth rate, θ_2, and operating cost volatility, σ_2, the statics are ambiguous. The statics are also ambiguous for virgin growth rate, θ_1, and the discount rate, r considering to both conventional and rejuvenation/replacement. Variables C_i at $i = 1$ denote the operating costs threshold for recycling the plant and at $i = 2$ the threshold costs at replacement.

[b] No rejuvenation; comparative statics results from Dobbs (2004).

Table 2. Parameter Values and Optimal Rejuvenation/Replacement Periods

Parameter[a]	ω	Value	Parameters
Virgin outlay costs ($/1,000KW)	K_1	2.000	
Rejuvenation outlay costs ($/1,000KW)	K_2	1.900	
Virgin initial operating costs ($/1,000KW)	c_{10}	0.065	
Rejuvenation initial operating costs ($/1,000KW)	c_{20}	0.075	
Virgin operating-cost growth rate	θ_1	0.068	
Rejuvenation operating-cost growth rate	θ_2	0.067	
Residual salvage value	S	0.077	
Discount rate	r	0.060	
Virgin operating-cost volatility	σ_1	1.000	
Rejuvenation operating-cost volatility	σ_2	0.900	
Optimal length (years)			
Deterministic			
Virgin	T_1^*	15.700	
Rejuvenation	$T_2^* - T_1^*$	33.300	
Cycle (total)	T_2^*	50.000	
Stochastic			
Virgin	$\hat{T}_1$	22.491	
Rejuvenation	$\hat{T}_2 - \hat{T}_1$	19.649	
Cycle (total)	$\hat{T}_2$	42.140	

Table 3. Deterministic Numerical Elasticities

Parameter	ω	Rejuvenation/Replacement[a]		
		Virgin Period $\varepsilon_{T_1,\omega}$	Total Cycle $\varepsilon_{T_2\omega,}$	Rejuvenation Period $\varepsilon_{T_{2,\omega}} - \varepsilon_{T_{1,\omega}}$
Virgin outlay costs	K_1	0	0.102	0.149
Rejuvenation outlay costs	K_2	0.555	−0.232	−0.597
Virgin initial operating costs	c_{10}	−0.974	0.555	1.020
Rejuvenation initial operating costs	c_{20}	0.372	−1.191	−1.961
Virgin Operating-cost growth rate	θ_1	−1.171	1.088	2.120
Rejuvenation Operating-cost growth rate	θ_2	0	−4.035	−5.831
Residual salvage value	S	0	−0.004	−0.006
Discount rate	r	0.421	2.995	4.170

[a] The ε variables are elasticities with T_1 and T_2 denoting length of the virgin period and total cycle, respectively.

Table 4. Stochastic Numerical Elasticities

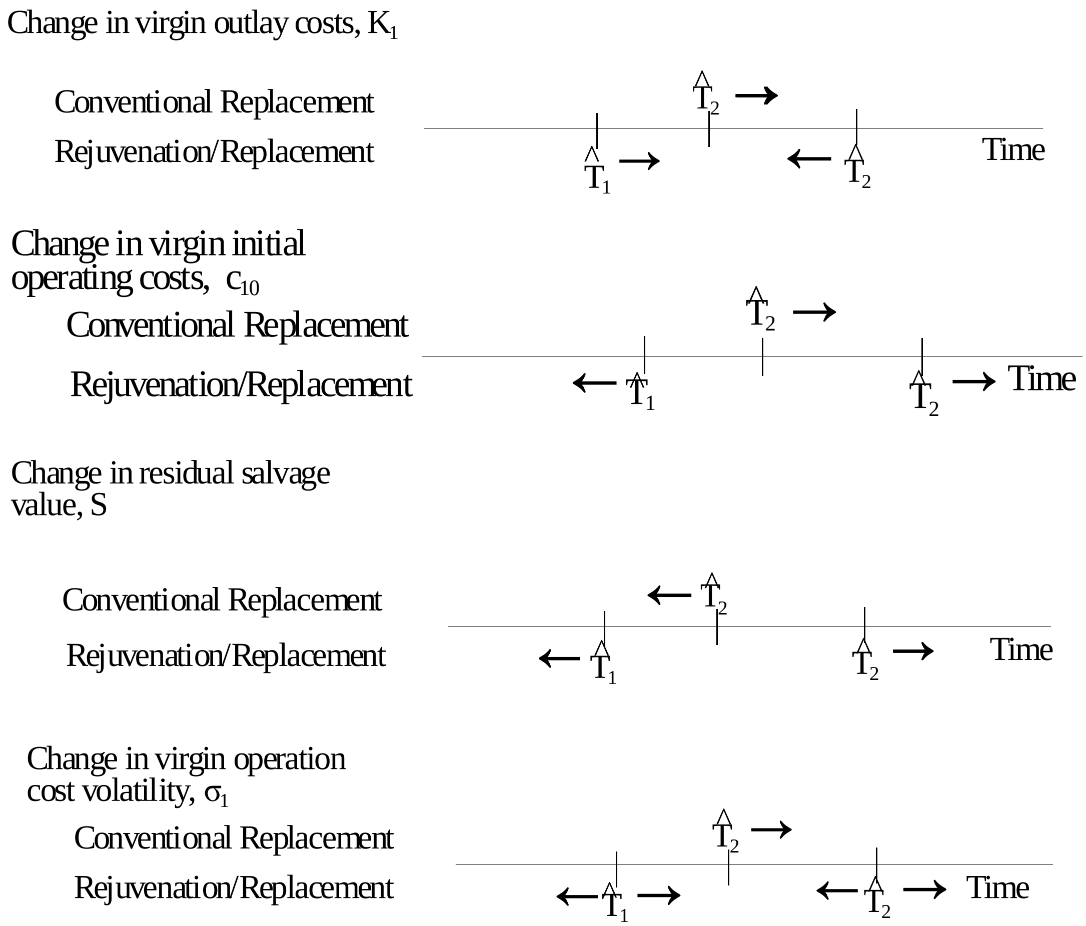
Parameter	ω	Rejuvenation/Replacement[a]		
		Virgin Period $\varepsilon_{T_1,\omega}$	Total Cycle $\varepsilon_{T_2\omega,}$	Rejuvenation Period $\varepsilon_{T_2-Y_1,\omega}$
Virgin outlay costs	K_1	1.719	1.835	1.966
Rejuvenation outlay costs	K_2	−0.008	−0.008	−0.007
Virgin initial operating costs	c_{10}	−1.997	−1.746	−1.464
Rejuvenation initial operating costs	c_{20}	0	−0.359	−0.780
Virgin Operating-cost growth rate	θ_1	−49.903	−54.617	−60.051
Rejuvenation Operating-cost growth rate	θ_2	54.931	59.229	64.326
Residual salvage value	S	−0.086	−0.093	0.100
Discount rate	r	−14.779	−15.896	−17.178
Virgin Operating-cost volatility	σ_1	0.262	0.452	0.669
Rejuvenation Operating-cost volatility	σ_2	1.260	1.167	1.062

[a] The ε variables are elasticities with T_1 and T_2 denoting length of the virgin period and total cycle, respectively.

Table A1. Deterministic Comparative Statics[a]

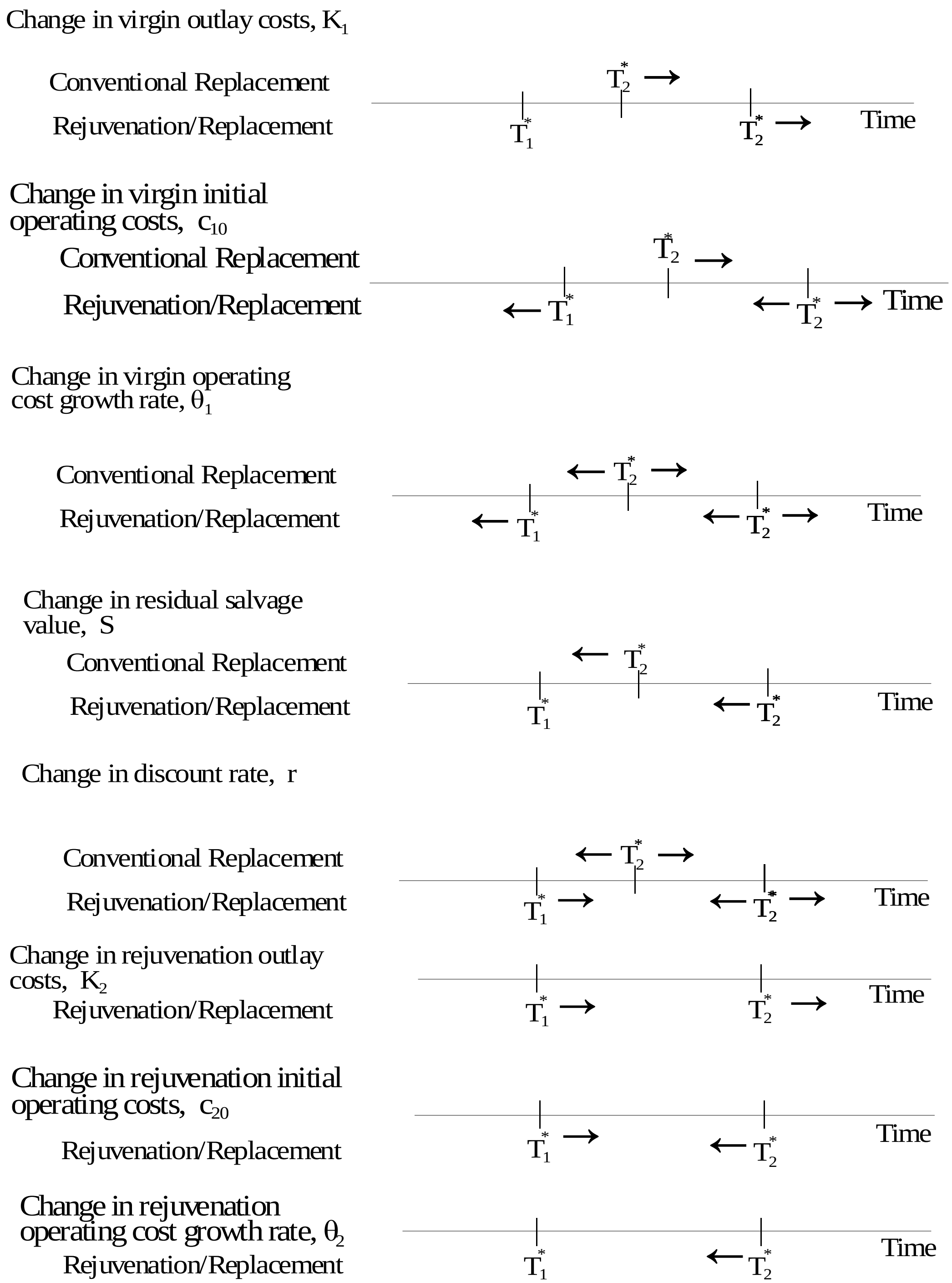
Parameter	ω	Conventional Replacement[b] $T_1^* = T_2^*$ $\frac{dT_1^*}{d\omega}$	Rejuvenation/Replacement Virgin Period $\frac{dT_1^*}{d\omega}$	Total Cycle $\frac{dT_2^*}{d\omega}$	Rejuvenation Period $\frac{[d(T]_2^* - T_1^*)}{d\omega}$
Virgin outlay costs	K_1	+	0	+	+
Rejuvenation outlay costs	K_2	N/A	+	+	?
Virgin initial operating costs	c_{10}	+	–	Ambiguous	?
Rejuvenation initial operating costs	c_{20}	N/A	+	–	–
Virgin Operating-cost growth rate	θ_1	Ambiguous	–	Ambiguous	?
Rejuvenation Operating-cost growth rate	θ_2	N/A	0	–	–
Residual salvage value	S	–	0	–	–
Discount rate	r	Ambiguous	+	Ambiguous	?

[a] Results from Stutzman et al. (2016). Variables T_1 and T_2 denote the length of the virgin period and total cycle, respectively.
[b] No rejuvenation; comparative statics results from Dobbs (2004).



$\hat{T}_1$ and $\hat{T}_2$ denote optimal time to rejuvenate and replace, respectively.

Figure 1. Stochastic Comparative Statics (Results from Stutzman et al., 2016)



T_1^* and T_2^* denote optimal time to rejuvenate and replace, respectively.

Figure A1. Deterministic Comparative Statics (Results from Stutzman et al., 2016)