Investment in Alternative Energy Technologies under Physical and Policy Uncertainty

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Abstract

Policymakers have often backed alternative energy technologies, e.g., nuclear power, due to their relatively low operating costs and emissions. However, they have also been quick to respond to public perceptions about the safety of such plants by suspending construction or even decommissioning existing facilities. We address public concerns about physical plant risks along with stochastic market prices for energy by modelling investment in and decommissioning of alternative energy technologies.

1 Objective

We formulate the decision-making problem with respect to the installation and the decommissioning of an alternative energy technology, e.g., a nuclear power plant, not only under market risk, i.e., price uncertainty, but also under physical or policy risks. While the former are centrepieces of most real options models, the latter are increasingly relevant with the adoption of intermittent renewables and investment in next-generation nuclear plants. In this context, physical risk may refer to unpredictable technological shutdowns of wind turbines or nuclear plants, while policy risk captures changes in government regulation or public opinion. Examples of the latter include changes in Nordic support schemes for renewables ([1]) and reversal of German government support for nuclear power plants in response to the physical catastrophe that occurred at the Fukushima site in 2011. Due to the increasing prevalence of such risks in the energy sector, we explore their impact on power companies' investment incentives. In particular,

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we address how local and global risks affect investment timing and option values. Within this framework, we also assess how decisions change with a subsequent decommissioning option.

The structure of this paper is as follows. First, we describe the model setting and assumptions in this study. Next, as a benchmark, we derive the optimal investment and decommissioning timing decisions. Numerical examples then illustrate some of the managerial and policy insights. Finally, the conclusions summarise the main findings and offer directions for future research in this area.

2 Assumptions

We assume that a single price-taking firm has the perpetual option to invest in an alternative energy power plant. Upon investment of $\$I > 0$, a plant is able to produce K MWh$_e$ of electricity per annum immediately and forever. From such an active plant, the firm is able to sell electricity at exogenous price E_t (in \$/MWh$_e$) at time $t \geq 0$ while incurring constant operating costs of k (in \$/MWh$_e$). The electricity price follows a geometric Brownian motion (GBM), i.e.,

$$dE_t = \alpha E_t dt + \sigma E_t dz_t, \qquad E_0 \equiv E > 0, \tag{1}$$

where α is the instantaneous expected growth rate, $\sigma \geq 0$ is the instantaneous volatility, and dz_t is a standard Brownian motion. All cash flows are in real terms and are discounted at the real subjective rate, $\rho > \alpha$. No operational flexibilities are assumed, i.e., the plant must be operated at full capacity once installed, but a decommissioning option may be exercised at any point after investment at cost $\$D$ such that $I + D > 0$.

Independently of the stochastic price process, the world evolves between two regimes, $j = 1, 2$, where regime 1 (2) is associated with an operating (a closed) plant. We assume that independent Poisson processes govern these transitions. The instantaneous rate out of regime j is $\lambda_j \geq 0$ and reflects energy policy due to technological risks or public perception about the alternative energy technology. In regime 1, the plant operates at full capacity, but in regime 2, it is shut down and incurs strengthening costs of s (in \$/MWh$_e$). A plant may be closed due to either local technical faults or changes in energy policy shaped by a failure of the technology elsewhere, e.g., in the case of the 2011 Fukushima incident. For now, we assume that the parameters of the underlying electricity price are not affected by such regime changes, which stem from physical or policy causes rather than market-based ones. Thus, the instantaneous cash flow from an installed plant in regime j at time t is $\pi_j(E_t)$:

$$\begin{aligned} \pi_1(E_t) &= (E_t - k)K, \\ \pi_2(E_t) &= -sK. \end{aligned}$$

From the firm's perspective, there are three states with two regimes as indicated in the state-transition diagram (Fig. 1). Consequently, the firm's value function in state i, $i = 0, 1, 2$ and regime j for a given electricity price of E is $V_{ij}(E)$. We surmise threshold rules for exercising both investment and decommissioning options, ϵ_j^* and ϵ_j^{**}, respectively, that are dependent on the regime. Finally, we assume that the value function in state 2 is independent of the regime as the firm is no longer exposed to the risk of any switching.

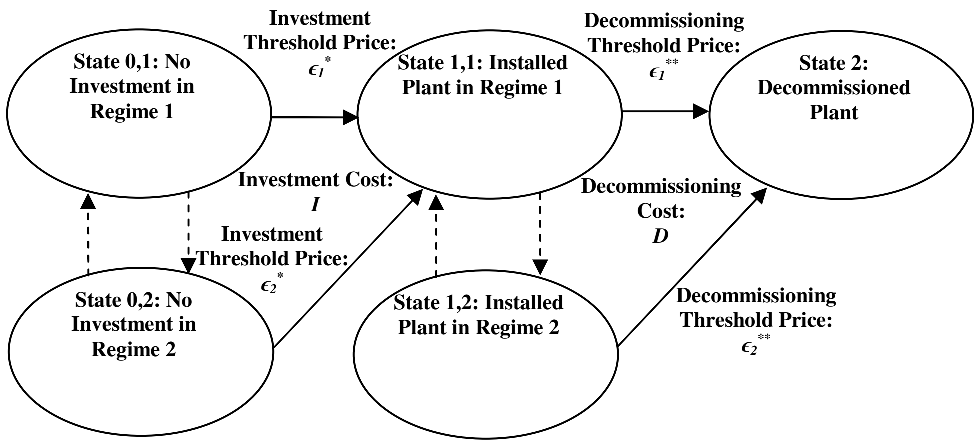

Figure 1: State-transition diagram for investment and decommissioning problem with physical and policy risks

3 Analytical Models

3.1 No Decommissioning Option

We proceed first by ignoring the decommissioning option, i.e., the possibility to transition to state 2. Thus, we seek the optimal investment thresholds from state 0 in each regime. This is in contrast to [5], who treats investment under uncertainty with regime switching only in state 0. An analysis of regime switching that persists after investment has taken place, i.e., the firm is in state 1, is carried out in [3]. In that paper, as in [4], the parameters of the underlying price process are different in each regime. By contrast, since we treat physical or policy risks, we assume that the electricity price process has the same parameters in either regime.

3.1.1 No Regime Switching

First, we ignore regime switching and obtain the standard real options result. Working backward, the firm's value function in state 1 is simply the present value (PV) of cash flows from operating the plant forever:

$$\begin{aligned} V_{11}(E) &= \mathbb{E}_E\left[\int_0^\infty \pi_1(E)e^{-\rho t}dt\right] \\ \Rightarrow V_{11}(E) &= K\left(\frac{E}{\rho-\alpha}-\frac{k}{\rho}\right) \end{aligned} \tag{2}$$

Via the standard approach of [2], we also obtain the value in state 0 by first setting up the Bellman equation and invoking Itô's lemma:

$$\begin{aligned} \rho V_{01}(E)dt &= \mathbb{E}\left[dV_{01}\right] \\ \Rightarrow & \quad \frac{1}{2}\sigma^2E^2V_{01}''(E)+\alpha EV_{01}'(E)-\rho V_{01}(E)=0 \\ \Rightarrow V_{01}(E) &= a_0E^{\beta_1} \end{aligned} \tag{3}$$

where the boundary condition $\lim_{E\to 0}V_{01}(E)=0$ is used, a_0 is a positive endogenous constant, and $\beta_1>1$ is the positive root of the characteristic quadratic equation $\mathcal{Q}(\beta)=\frac{1}{2}\sigma^2\beta(\beta-1)+\alpha\beta-\rho=0$. Using value-matching (VM) and smooth-pasting (SP) conditions, we obtain a_0 and $\epsilon_1^*\equiv\epsilon^*$, the investment threshold:

$$V_{01}(\epsilon^*) = V_{11}(\epsilon^*)-I \tag{4}$$

$$V_{01}'(\epsilon^*) = V_{11}'(\epsilon^*) \tag{5}$$

Hence, we have:

$$\epsilon^* = \left(\frac{\beta_1}{\beta_1-1}\right)\frac{(\rho-\alpha)(I+\frac{Kk}{\rho})}{K} \tag{6}$$

$$a_0 = \frac{K(\epsilon^*)^{1-\beta_1}}{\beta_1(\rho-\alpha)} \tag{7}$$

3.1.2 Local Regime Switching

Next, we assume that regime switching occurs due to localised physical faults. This implies that no regime switching takes place in state 0. Once the firm is in state 1, its plant's operations are affected by physical risk, and the regime switches between 1 and 2.

Starting at the end, we first obtain the firm's value functions in state 1. Unlike in Section 3.1.1, we must condition on what happens in the next dt time units to determine value functions $V_{11}(E)$ and $V_{12}(E)$ in terms of each other:

$$\begin{aligned} V_{11}(E) &= \pi_1(E)dt + (1-\rho dt)\left[\lambda_1 dt \mathbb{E}_E\left[V_{12}(E+dE)\right] + (1-\lambda_1 dt)\mathbb{E}_E\left[V_{11}(E+dE)\right]\right] \\ \Rightarrow V_{11}(E) &= \pi_1(E)dt + \lambda_1 dt\left[V_{12}(E) + \alpha E V_{12}'(E)dt + \frac{1}{2}\sigma^2 E^2 V_{12}''(E)dt\right] \\ &\quad + (1-(\rho+\lambda_1)dt)\left[V_{11}(E) + \alpha E V_{11}'(E)dt + \frac{1}{2}\sigma^2 E^2 V_{11}''(E)dt\right] \\ \Rightarrow &\quad \frac{1}{2}\sigma^2 E^2 V_{11}''(E) + \alpha E V_{11}'(E) - \rho V_{11}(E) + \lambda_1\left(V_{12}(E) - V_{11}(E)\right) + K(E-k) = 0 \end{aligned} \tag{8}$$

$$\begin{aligned} V_{12}(E) &= \pi_2(E)dt + (1-\rho dt)\left[\lambda_2 dt \mathbb{E}_E\left[V_{11}(E+dE)\right] + (1-\lambda_2 dt)\mathbb{E}_E\left[V_{12}(E+dE)\right]\right] \\ \Rightarrow &\quad \frac{1}{2}\sigma^2 E^2 V_{12}''(E) + \alpha E V_{12}'(E) - \rho V_{12}(E) + \lambda_2\left(V_{11}(E) - V_{12}(E)\right) - Ks = 0 \end{aligned} \tag{9}$$

As indicated in [3], speculative bubbles must be ruled out as there are no further options, which leaves only the fundamental value of the power plant in each regime:

$$V_{1j}(E) = a_j E + b_j, j = 1, 2 \tag{10}$$

where a_j and b_j are constants to be determined. By taking derviatives of the function in Eq. 10 and substituting them into Eqs. 8 and 9, we obtain the following:

$$a_1 = -\frac{K(\rho+\lambda_2-\alpha)}{\lambda_1\lambda_2 - (\rho+\lambda_1-\alpha)(\rho+\lambda_2-\alpha)} \tag{11}$$

$$a_2 = -\frac{K\lambda_2}{\lambda_1\lambda_2 - (\rho+\lambda_1-\alpha)(\rho+\lambda_2-\alpha)} \tag{12}$$

$$b_1 = \frac{K\left[\lambda_1 s + (\rho+\lambda_2)k\right]}{\lambda_1\lambda_2 - (\rho+\lambda_1)(\rho+\lambda_2)} \tag{13}$$

$$b_2 = \frac{K\left[\lambda_2 k + (\rho+\lambda_1)s\right]}{\lambda_1\lambda_2 - (\rho+\lambda_1)(\rho+\lambda_2)} \tag{14}$$

Working backward, since the firm is not subject to regime switching in state 0, its value function is again $V_{01}(E) = a_0 E^{\beta_1}$, where a_0 and ϵ^* are found via VM and SP conditions between $V_{01}(E)$ and $V_{11}(E) - I$:

$$\epsilon^* = \left(\frac{\beta_1}{\beta_1 - 1}\right)\frac{(I - b_1)}{a_1} \tag{15}$$

$$a_0 = \frac{a_1(\epsilon^*)^{1-\beta_1}}{\beta_1} \tag{16}$$

3.1.3 Global Regime Switching

With exposure to global physical or policy risks, the firm now faces two regimes even in state 0 as the government may respond to physical catastrophes elsewhere in the world by halting construction of new plants and ordering the suspension of existing ones. However, its value functions in state 1 are still represented by those in Eqs. 10 through 14. In state 0, there are two possibilities:

- Never invest from regime 2
- Possibly invest from regime 2

In [5], the two possibilities are compared by examining the expected payoffs from two strategies assuming that the initial regime is 2:

- Invest immediately from regime 2
- Wait until the regime is 1 and then invest immediately

The expected payoff of the first strategy is simply $a_2 E + b_2 - I$, whereas that of the second strategy is $\int_0^\infty \lambda_2 e^{-\lambda_2 \tau_{21}} e^{-\rho \tau_{21}} \left(E a_1 e^{\alpha \tau_{21}} + b_1 - I\right) d\tau_{21}$. We obtain this expression by first writing the expected NPV of a project that starts at known time $\tau_{21} \geq 0$ and lasts forever: $e^{-\rho\tau_{21}} \left(E a_1 e^{\alpha \tau_{21}} + b_1 - I\right)$. Next, we treat τ_{21}, the time to the arrival of the regime switch as random and use its probability density function, $\lambda_2 e^{-\lambda_2 \tau_{21}}$, to carry out the expectation. Thus, waiting until the regime switches to 1 is a better strategy as long as $a_2 E + b_2 - I < \frac{\lambda_2 a_1 E}{\rho + \lambda_2 - \alpha} + \frac{\lambda_2}{\rho + \lambda_2} (b_1 - I)$, which simplifies to the condition $-\left(\frac{Ks + \rho I}{\rho + \lambda_2}\right) < 0$. Since this is always true, we conclude that it is never optimal to invest from regime 2. Fig. 2 summarises the optimal strategies where we note that in regime 2, there are two waiting regions.

Regime	$E<\epsilon^*_1$	$E\geq\epsilon^*_1$
1	Wait	Invest
2	Wait	Wait

Figure 2: Optimal strategies from state 0 in the global-risk model without decommissioning

Based on the preceding argument, there are two regions of interest in state 0 for each regime: $E < \epsilon_1^* \equiv \epsilon^*$ and $E \geq \epsilon^*$. In the latter, the value function in regime 1 is simply $V_{11}(E) - I$ as identified in Eq. 10, while $V_{02}(E)$ is governed by the following ODE:

$$\begin{aligned} & \frac{1}{2}\sigma^2 E^2 V_{02}''(E) + \alpha E V_{02}'(E) - \rho V_{02}(E) + \lambda_2 \left(V_{11}(E) - I - V_{02}(E)\right) = 0 \\ \Rightarrow \quad & V_{02}(E) = c_{22} E^{\delta_2} + c_{23} E + c_{24} \end{aligned} \tag{17}$$

where $\lim_{E\to\infty} V_{02}(E) = c_{23}E + c_{24}$ is the boundary condition, c_{22} is a positive endogenous constant, and δ_2 is the negative root of $\frac{1}{2}\sigma^2\delta(\delta-1) + \alpha\delta - (\rho + \lambda_2) = 0$. Using the particular solution of Eq. 17, we find that:

$$c_{23} = \frac{\lambda_2 a_1}{\rho + \lambda_2 - \alpha} \tag{18}$$

$$c_{24} = \frac{\lambda_2 (b_1 - I)}{\rho + \lambda_2} \tag{19}$$

By contrast, for $E < \epsilon^*$, it is optimal to wait in state 0 for both regimes. Thus, $V_{01}(E)$ and $V_{02}(E)$ satisfy the following pair of ODEs:

$$\frac{1}{2}\sigma^2 E^2 V_{01}''(E) + \alpha E V_{01}'(E) - \rho V_{01}(E) + \lambda_1 \left(V_{02}(E) - V_{01}(E)\right) = 0 \tag{20}$$

$$\frac{1}{2}\sigma^2 E^2 V_{02}''(E) + \alpha E V_{02}'(E) - \rho V_{02}(E) + \lambda_2 \left(V_{01}(E) - V_{02}(E)\right) = 0 \tag{21}$$

We solve the two equations by first multiplying Eqs. 20 and 21 by λ_2 and λ_1, respectively, and adding them to obtain the following single ODE:

$$\frac{1}{2}\sigma^2 E^2 H_1''(E) + \alpha E H_1'(E) - \rho H_1(E) = 0 \tag{22}$$

where $H_1(E) \equiv \lambda_2 V_{01}(E) + \lambda_1 V_{02}(E)$. Using the boundary condition $\lim_{E\to 0} H_1(E) = 0$, we obtain:

$$H_1(E) = d_1 E^{\beta_1} \tag{23}$$

where d_1 is an endogenous constant. Similarly, by subtracting the ODEs in Eqs. 20 and 21, we obtain the following ODE:

$$\frac{1}{2}\sigma^2 E^2 H_2''(E) + \alpha E H_2'(E) - (\rho + \lambda_1 + \lambda_2) H_2(E) = 0 \tag{24}$$

where $H_2(E) \equiv V_{02}(E) - V_{01}(E)$. Again, using the boundary condition $\lim_{E\to 0} H_2(E) = 0$, we obtain:

$$H_2(E) = e_1 E^{\theta_1} \tag{25}$$

where e_1 is an endogenous constant and $\theta_1 > 1$ is the positive root of $\frac{1}{2}\sigma^2\theta(\theta-1)+\alpha\theta-(\rho+\lambda_1+\lambda_2) = 0$. From the definitions of and solutions to $H_1(E)$ and $H_2(E)$, we can extract the value functions of interest:

$$V_{01}(E) = \frac{d_1}{\lambda_1+\lambda_2}E^{\beta_1} - \frac{\lambda_1 e_1}{\lambda_1+\lambda_2}E^{\theta_1} \tag{26}$$

$$V_{02}(E) = \frac{d_1}{\lambda_1+\lambda_2}E^{\beta_1} + \frac{\lambda_2 e_1}{\lambda_1+\lambda_2}E^{\theta_1} \tag{27}$$

The endogenous constants, d_1, e_1, and c_{22}, along with the investment threshold, ϵ^*, may be found analytically via the following four VM and SP conditions:

$$V_{01}(\epsilon^*) = V_{11}(\epsilon^*) - I \tag{28}$$

$$V'_{01}(\epsilon^*) = V'_{11}(\epsilon^*) \tag{29}$$

$$V_{02}(\epsilon^{*-}) = V_{02}(\epsilon^{*+}) \tag{30}$$

$$V'_{02}(\epsilon^{*-}) = V'_{02}(\epsilon^{*+}) \tag{31}$$

Solving, we obtain the following:

$$\epsilon^* = \frac{c_{24}\delta_2\lambda_1(\theta_1-\beta_1) - (b_1-I)\left[\theta_1\lambda_1(\delta_2-\beta_1)+\beta_1\lambda_2(\delta_2-\theta_1)\right]}{a_1\left[\lambda_1(\delta_2-\beta_1)(\theta_1-1)+\lambda_2(\delta_2-\theta_1)(\beta_1-1)\right] - c_{23}\lambda_1(\theta_1-\beta_1)(\delta_2-1)} \tag{32}$$

$$d_1 = \frac{(\lambda_1+\lambda_2)}{(\theta_1-\beta_1)\left(\epsilon^*\right)^{\beta_1}}\left[a_1\epsilon^*(\theta_1-1)+\theta_1(b_1-I)\right] \tag{33}$$

$$e_1 = \frac{(\lambda_1+\lambda_2)}{\lambda_1(\theta_1-\beta_1)(\epsilon^*)^{\theta_1}}\left[a_1\epsilon^*(\beta_1-1)+\beta_1(b_1-I)\right] \tag{34}$$

$$\begin{aligned} c_{22} = {} & \frac{1}{\delta_2(\theta_1-\beta_1)(\epsilon^*)^{\delta_2}}\left[a_1\epsilon^*\left(\beta_1(\theta_1-1)+\frac{\theta_1\lambda_2(\beta_1-1)}{\lambda_1}-\frac{c_{23}(\theta_1-\beta_1)}{a_1}\right)\right. \\ & \left. +\beta_1\theta_1\left(1+\frac{\lambda_2}{\lambda_1}\right)(b_1-I)\right] \end{aligned} \tag{35}$$

Finally, it can be shown that in the limiting case where no physical or policy risk exists, the optimal investment threshold is equal to the one in Eq. 6 since $\lim_{\lambda_1\to 0} a_1 = \frac{K}{\rho-\alpha}$, $\lim_{\lambda_1\to 0} b_1 = -\frac{K}{\rho}$, and $\lim_{\lambda_1\to 0}\theta_1 = \delta_1$.

3.2 Decommissioning Option

We now consider the firm's discretion to decommission the plant subsequent to its adoption. Such an option may also affect the original decision to invest, especially with global regime switching.

3.2.1 No Regime Switching

Working backward from state 2 without regime switching, we first conclude that the value of the plant that has been decommissioned is simply zero, i.e.,

$$V_2(E) = 0 \tag{36}$$

In state 1, the value function is the expected PV of an active plant plus the option value to decommission that becomes more valuable with a price decrease, i.e.,

$$V_{11}(E) = K\left(\frac{E}{\rho-\alpha} - \frac{c}{\rho}\right) + f_2 E^{\beta_2} \tag{37}$$

Finally, the value function in state 0 is similar to that in Eq. 3, albeit with a different endogenous constant.

In order to determine the constant f_2 and the optimal decommissioning threshold $\epsilon_1^{**} \equiv \epsilon^{**}$, we first use VM and SP conditions between states 1 and 2:

$$V_{11}(\epsilon^{**}) \quad = \quad V_2(\epsilon^{**}) - D \tag{38}$$

$$V_{11}'(\epsilon^{**}) \quad = \quad V_2'(\epsilon^{**}) \tag{39}$$

Solving these two equations analytically, we obtain the following:

$$\epsilon^{**} \quad = \quad \left(\frac{\beta_2}{\beta_2-1}\right)\frac{(\rho-\alpha)\left(\frac{Kk}{\rho} - D\right)}{K} \tag{40}$$

$$f_2 \quad = \quad -\frac{K(\epsilon^{**})^{1-\beta_2}}{\beta_2\,(\rho-\alpha)} \tag{41}$$

From state 0, there are VM and SP conditions with state 1 as in Eqs. 4 and 5. Together, these lead to the following non-linear equation that may be solved numerically to yield the optimal investment threshold, ϵ^*:

$$\frac{K\epsilon^*}{\rho-\alpha}\left(\frac{1-\beta_1}{\beta_1}\right) + f_2(\epsilon^*)^{\beta_2}\left(\frac{\beta_2-\beta_1}{\beta_1}\right) + \frac{Kk}{\rho} + I = 0 \tag{42}$$

Since the second term is negative, it may be shown that the optimal investment threshold is reduced relative to that in Section 3.1.1. Intuitively, the subsequent option to decommission facilitates investment in the first place. Finally, a_0 may be obtained as follows:

$$a_0 \quad = \quad \frac{K(\epsilon^*)^{1-\beta_1}}{\beta_1(\rho-\alpha)} + \frac{\beta_2 f_2(\epsilon^*)^{\beta_2-\beta_1}}{\beta_1} \tag{43}$$

3.2.2 Local Regime Switching

With local regime switching, we first consider the decommissioning decision from state 1. Intuitively, it would make more sense not to decommission from regime 1 and to wait for a switch to regime 2. We can, thus, check whether it is ever optimal to decommission directly from state 1 when in regime 1 by comparing the payoff of immediate decommissioning ($-D$) versus that from waiting until a regime switch and subsequent decommissioning. In order to calculate the latter payoff, we first fix the time to the regime switch, τ_{12}, and obtain the payoff as:

$$
\begin{aligned}
& \mathbb{E}_E\left[\int_0^{\tau_{12}} K(E_t-k)e^{-\rho t}dt - e^{-\rho\tau_{12}}D\right] \\
= & \int_0^{\tau} K(\mathbb{E}_E\left[E_t\right]-k)e^{-\rho t}dt - e^{-\rho\tau_{12}}D \\
= & \int_0^{\tau_{12}} K(Ee^{\alpha t}-k)e^{-\rho t}dt - e^{-\rho\tau_{12}}D \\
= & \frac{KE}{\rho-\alpha}\left(1-e^{-(\rho-\alpha)\tau_{12}}\right) - \frac{kK}{\rho}\left(1-e^{-\rho\tau_{12}}\right) - e^{-\rho\tau_{12}}D
\end{aligned} \tag{44}
$$

After letting τ_{12} be an exponential random variable with parameter λ_1, we take expectations to obtain the following:

$$
\begin{aligned}
& \int_0^{\infty} \lambda_1 e^{-\lambda_1\tau_{12}}\frac{KE}{\rho-\alpha}\left(1-e^{-(\rho-\alpha)\tau_{12}}\right)d\tau_{12} - \int_0^{\infty} \lambda_1 e^{-\lambda_1\tau_{12}}\frac{kK}{\rho}\left(1-e^{-\rho\tau_{12}}\right)d\tau_{12} \\
- & \int_0^{\infty} \lambda_1 e^{-\lambda_1\tau_{12}} e^{-\rho\tau_{12}} D d\tau_{12} = \frac{KE}{\rho+\lambda_1-\alpha} - \frac{kK}{\rho+\lambda_1} - \frac{\lambda_1 D}{\rho+\lambda_1}
\end{aligned} \tag{45}
$$

Hence, immediate decommissioning from regime 1 is dominated by the strategy of waiting for a regime switch as long as:

$$
\begin{aligned}
& \frac{KE}{\rho+\lambda_1-\alpha} - \frac{kK}{\rho+\lambda_1} - \frac{\lambda_1 D}{\rho+\lambda_1} \geq -D \\
\Rightarrow \quad & E \geq \frac{(\rho+\lambda_1-\alpha)}{(\rho+\lambda_1)}\left[k - \frac{\rho D}{K}\right]
\end{aligned} \tag{46}
$$

From now on, we assume that this condition holds, which implies that the optimal strategy is to decommission only from regime 2 (see Fig. 3), i.e., only ϵ_2^{**} exists.

There are two parts to the value functions for each regime: one for $E > \epsilon_2^{**} \equiv \epsilon^{**}$ and another one for $E \leq \epsilon^{**}$. In the former case, we have similar ODEs as in Eqs. 8 and 9. However, the solutions are not restricted to the particular ones as the option value of decommissioning must also be considered. Therefore, the homogenous solutions, $\overline{V}_{11}(E)$ and $\overline{V}_{12}(E)$, are found by first multiplying the homogenous parts of the analogous ODEs by λ_2 and λ_1, respectively, and adding them to obtain the following single ODE:

$$
\frac{1}{2}\sigma^2E^2F_1''(E) + \alpha EF_1'(E) - \rho F_1(E) = 0 \tag{47}
$$

Regime	$E \leq \epsilon_2^{**}$	$E > \epsilon_2^{**}$
1	Wait	Wait
2	Decommission	Wait

Figure 3: Optimal strategies from state 1 in the local-risk model with decommissioning

where $F_1(E) \equiv \lambda_2 \overline{V}_{11}(E) + \lambda_1 \overline{V}_{12}(E)$. Using the boundary condition $\lim_{E\to\infty} F_1(E) = 0$, we obtain:

$$F_1(E) = h_2 E^{\beta_2} \tag{48}$$

where h_2 is an endogenous constant. Similarly, by subtracting the homogenous parts of Eqs. 8 and 9, we obtain the following ODE:

$$\frac{1}{2}\sigma^2 E^2 F_2''(E) + \alpha E F_2'(E) - (\rho + \lambda_1 + \lambda_2) F_2(E) = 0 \tag{49}$$

where $F_2(E) \equiv \overline{V}_{11}(E) - \overline{V}_{12}(E)$. Again, using the boundary condition $\lim_{E\to\infty} F_2(E) = 0$, we obtain:

$$F_2(E) = \ell_2 E^{\theta_2} \tag{50}$$

where k_2 is an endogenous constant and θ_2 is the negative root of $\frac{1}{2}\sigma^2\theta(\theta-1) + \alpha\theta - (\rho + \lambda_1 + \lambda_2) = 0$. From the definitions of and solutions to $F_1(E)$ and $F_2(E)$, we can extract the value functions of interest:

$$\overline{V}_{11}(E) = \frac{h_2}{\lambda_1 + \lambda_2} E^{\beta_2} + \frac{\lambda_1 \ell_2}{\lambda_1 + \lambda_2} E^{\theta_2} \tag{51}$$

$$\overline{V}_{12}(E) = \frac{h_2}{\lambda_1 + \lambda_2} E^{\beta_2} - \frac{\lambda_2 \ell_2}{\lambda_1 + \lambda_2} E^{\theta_2} \tag{52}$$

Hence, the value functions for $E > \epsilon^{**}$ are as follows:

$$V_{1j}(E) = \overline{V}_{1j}(E) + a_j E + b_j, j = 1, 2 \tag{53}$$

For $E \leq \epsilon^{**}$, we first note that $V_2(E) = 0$. As for $V_{11}(E)$, it follows the following ODE:

$$V_{11}(E) \quad = \quad \pi_1(E)dt + (1 - \rho dt)\left[\lambda_1 dt\left[-D\right] + (1 - \lambda_1 dt)\, \mathbb{E}_E\left[V_{11}(E + dE)\right]\right]$$

$$\begin{aligned}
\Rightarrow V_{11}(E) &= \pi_1(E)dt - \lambda_1 D dt \\
&\quad + (1-(\rho+\lambda_1)\,dt)\left[V_{11}(E) + \alpha E V_{11}'(E)dt + \frac{1}{2}\sigma^2 E^2 V_{11}''(E)dt\right] \\
\Rightarrow &\quad \frac{1}{2}\sigma^2 E^2 V_{11}''(E) + \alpha E V_{11}'(E) - \rho V_{11}(E) - \lambda_1\left(D + V_{11}(E)\right) + K(E-k) = 0 \\
\Rightarrow &\quad V_{11}(E) = g_{11}E^{\gamma_1} + g_{13}E + g_{14} \qquad (54)
\end{aligned}$$

where we use the boundary condition $\lim_{E\to 0} V_{11}(E) = g_{14}$, g_{11} is a positive endogenous constant, and γ_1 is the positive root of $\frac{1}{2}\sigma^2\gamma(\gamma-1) + \alpha\gamma - (\rho+\lambda_1) = 0$. Using the particular solution of Eq. 54, we find that:

$$g_{13} = \frac{K}{\rho + \lambda_1 - \alpha} \qquad (55)$$

$$g_{14} = -\frac{(Kk + \lambda_1 D)}{\rho + \lambda_1} \qquad (56)$$

Thus, $V_{11}(E)$ is equal to the expected PV of a plant that will die in a mean time of $\frac{1}{\lambda_1}$ years plus the option value of a reprieve if the electricity price increases.

The endogenous constants, h_2, ℓ_2, and g_{11}, along with the decommissioning threshold, ϵ^{**}, may be found analytically via the following four VM and SP conditions:

$$V_{11}(\epsilon^{**+}) = V_{11}(\epsilon^{**-}) \qquad (57)$$

$$V_{11}'(\epsilon^{**+}) = V_{11}'(\epsilon^{**-}) \qquad (58)$$

$$V_{12}(\epsilon^{**}) = V_2(\epsilon^{**}) - D \qquad (59)$$

$$V_{12}'(\epsilon^{**}) = V_2'(\epsilon^{**}) \qquad (60)$$

Solving, we obtain the following:

$$\epsilon^{**} = \frac{b_1 - g_{14} + \left(\frac{D+b_2}{\theta_2-\beta_2}\right)\left[\frac{\theta_2\lambda_2(\beta_2-\gamma_1)+\beta_2\lambda_1(\theta_2-\gamma_1)}{\gamma_1\lambda_2}\right]}{(a_1 - g_{13})\left(\frac{1-\gamma_1}{\gamma_1}\right) - a_2 X} \qquad (61)$$

where $X = \frac{\lambda_2(\beta_2-\gamma_1)(\theta_2-1)+\lambda_1(\theta_2-\gamma_1)(\beta_2-1)}{\gamma_1\lambda_2(\theta_2-\beta_2)}$

$$\ell_2 = -\frac{(\lambda_1+\lambda_2)}{\lambda_2(\theta_2-\beta_2)\left(\epsilon^{**}\right)^{\theta_2}}\left[a_2\epsilon^{**}(\beta_2-1) + \beta_2(b_2+D)\right] \qquad (62)$$

$$h_2 = -\frac{(\lambda_1+\lambda_2)}{(\theta_2-\beta_2)}\left[a_2(\epsilon^{**})^{1-\beta_2}(\theta_2-1) + \theta_2(\epsilon^{**})^{-\beta_2}(b_2+D)\right] \qquad (63)$$

$$g_{11} = \frac{1}{\gamma_1 (\epsilon^{**})^{\gamma_1}} \left[\epsilon^{**} \left(a_1 - a_2 - g_{13} - \frac{\theta_2(\beta_2 - 1)(\lambda_1 + \lambda_2) a_2}{\lambda_2(\theta_2 - \beta_2)} \right) - \frac{\theta_2(\lambda_1 + \lambda_2)\beta_2(D + b_2)}{\lambda_2(\theta_2 - \beta_2)} \right] \quad (64)$$

Finally, the value of the option to invest from state 0 is again $V_{01}(E) = a_0 E^{\beta_1}$, where VM and SP conditions between $V_{01}(E)$ and $V_{11}(E) - I$ are used to find a_0 and ϵ^* assuming that $\epsilon^* > \epsilon^{**}$. This time, only numerical solutions are possible:

$$\frac{h_2}{\lambda_1 + \lambda_2} \left(\frac{\beta_2 - \beta_1}{\beta_1} \right) (\epsilon^*)^{\beta_2} + \frac{\lambda_1 \ell_2}{\lambda_1 + \lambda_2} \left(\frac{\theta_2 - \beta_1}{\beta_1} \right) (\epsilon^*)^{\theta_2} + a_1 \epsilon^* \left(\frac{1 - \beta_1}{\beta_1} \right) - b_1 + I = 0 \quad (65)$$

$$a_0 = \frac{\beta_2 h_2}{\beta_1(\lambda_1 + \lambda_2)} (\epsilon^*)^{\beta_2 - \beta_1} + \frac{\theta_2 \lambda_1 \ell_2}{\beta_1(\lambda_1 + \lambda_2)} (\epsilon^*)^{\theta_2 - \beta_1} + \frac{a_1 (\epsilon^*)^{1 - \beta_1}}{\beta_1} \quad (66)$$

3.2.3 Global Regime Switching

With global regime switching and a decommissioning option, we again speculate whether it is ever optimal to invest from state 0 when in regime 2. We reason as in Section 3.1.3 by comparing the immediate payoff from investing when in regime 2 ($a_2 E + b_2 - I + \frac{h_2 E^{\beta_2}}{\lambda_1 + \lambda_2} - \frac{\lambda_2 \ell_2 E^{\theta_2}}{\lambda_1 + \lambda_2}$) and that from waiting until the first passage to regime 1, i.e.,

$$\begin{aligned}
& \int_0^\infty \lambda_2 e^{-\lambda_2 \tau_{21}} e^{-\rho \tau_{21}} \left(a_1 E e^{\alpha \tau_{21}} + b_1 - I + \frac{h_2 E^{\beta_2} e^{\alpha \beta_2 \tau_{21}}}{\lambda_1 + \lambda_2} + \frac{\lambda_1 \ell_2 E^{\theta_2} e^{\alpha \theta_2 \tau_{21}}}{\lambda_1 + \lambda_2} \right) d\tau_{21} \\
= \ & \frac{\lambda_2 a_1 E}{\rho + \lambda_2 - \alpha} + \frac{\lambda_2}{\rho + \lambda_2} (b_1 - I) + \frac{\lambda_2 h_2 E^{\beta_2}}{(\lambda_1 + \lambda_2)} \int_0^\infty e^{-(\rho + \lambda_2 - \alpha \beta_2)\tau_{21}} d\tau_{21} \\
+ \ & \frac{\lambda_1 \lambda_2 \ell_2 E^{\theta_2}}{(\lambda_1 + \lambda_2)} \int_0^\infty e^{-(\rho + \lambda_2 - \alpha \theta_2)\tau_{21}} d\tau_{21} = \frac{\lambda_2 a_1 E}{\rho + \lambda_2 - \alpha} + \frac{\lambda_2}{\rho + \lambda_2} (b_1 - I) + \frac{\lambda_2 h_2 E^{\beta_2}}{(\lambda_1 + \lambda_2)(\rho + \lambda_2 - \alpha \beta_2)} \\
+ \ & \frac{\lambda_1 \lambda_2 \ell_2 E^{\theta_2}}{(\lambda_1 + \lambda_2)(\rho + \lambda_2 - \alpha \theta_2)} \quad (67)
\end{aligned}$$

Although it is not unconditionally the case that the payoff of the second strategy is greater than that of the first, we assume that it holds and perform subsequent numerical examples with this in mind. Also, we assume that $\epsilon^* > \epsilon^{**}$ in order to rule out any degenerate cases. Thus, the decommissioning strategy used here is the same as the one depicted in Fig. 3.

As in Section 3.1.3, there are two regions to analyse in state 0. First, for $E \geq \epsilon^*$, $V_{01}(E)$ is simply $V_{11}(E) - I$ as identified in Eq. 53, while $V_{02}(E)$ is governed by the ODE from Eq. 17. However, the solution is no longer simply the one in Eq. 17 due to the presence of the decommissioning option in state 1. Thus, its solution must reflect that embedded option:

$$V_{02}(E) = c_{22} E^{\delta_2} + c_{23} E + c_{24} + \frac{h_2 E^{\beta_2}}{\lambda_1 + \lambda_2} + \frac{\lambda_1 \lambda_2 \ell_2 Z E^{\theta_2}}{\lambda_1 + \lambda_2} \quad (68)$$

where c_{23} and c_{24} are defined as in Eqs. 18 and 19, respectively, c_{22} is an endogenous constant to be determined, h_2 and ℓ_2 are defined as in Eqs. 63 and 62, respectively (along with the same ϵ^{**} as in the case with local risk because the decision-making problem is identical once state 1 is entered), and Z is a forcing term that ensures that Eq. 68 satisfies the ODE. It is obtained by taking the relevant derivatives of $V_{02}(E)$ and substituting them back into Eq. 17 to yield the following:

$$Z = \frac{1}{(\rho + \lambda_2) - \alpha\theta_2 - \frac{1}{2}\sigma^2\theta_2(\theta_2 - 1)} \tag{69}$$

Since the solutions to $V_{01}(E)$ and $V_{02}(E)$ for $E < \epsilon^*$ are similar to those in Eqs. 26 and 27, respectively, the endogenous constants c_{22}, d_1, and e_1 along with ϵ^* may be obtained via VM and SP conditions such as those in Eqs. 28 through 31. Due to the presence of the decommissioning option from state 1, the resulting system of equations is highly non-linear and must be solved numerically. Facilitating the solution is the reduction of the four non-linear equations to a single one for ϵ^*:

$$\begin{aligned}
& \frac{(b_1 - I)}{(\theta_1 - \beta_1)}\left[\theta_1 + \frac{\lambda_2\beta_1}{\lambda_1} - \frac{\beta_1\theta_1}{\delta_2} - \frac{\lambda_2\beta_1\theta_1}{\delta_2\lambda_1}\right] - c_{24} - c_{23}\left(\frac{\delta_2 - 1}{\delta_2}\right)\epsilon^* \\
+ \quad & a_1\epsilon^*\left[\frac{(\theta_1 - 1)}{(\theta_1 - \beta_1)} - \frac{\beta_1(\theta_1 - 1)}{\delta_2(\theta_1 - \beta_1)} + \frac{\lambda_2(\delta_2 - \theta_1)(\beta_1 - 1)}{\delta_2\lambda_1(\theta_1 - \beta_1)}\right] \\
+ \quad & \frac{h_2\left(\epsilon^*\right)^{\beta_2}}{(\lambda_1 + \lambda_2)}\left[\frac{(\theta_1 - \beta_2)}{(\theta_1 - \beta_1)} - \left(\frac{\delta_2 - \beta_2}{\delta_2}\right) - \frac{\beta_1(\theta_1 - \beta_2)}{\delta_2(\theta_1 - \beta_1)} + \frac{\lambda_2(\beta_1 - \beta_2)(\delta_2 - \theta_1)}{\delta_2\lambda_1(\theta_1 - \beta_1)}\right] \\
+ \quad & \frac{\ell_2\left(\epsilon^*\right)^{\theta_2}}{(\lambda_1 + \lambda_2)}\left[\frac{\lambda_1(\theta_1 - \theta_2)}{(\theta_1 - \beta_1)} - \lambda_1\lambda_2 Z\left(\frac{\delta_2 - \theta_2}{\delta_2}\right) - \frac{\beta_1\lambda_1(\theta_1 - \theta_2)}{\delta_2(\theta_1 - \beta_1)} + \frac{\lambda_1\lambda_2(\delta_2 - \theta_1)(\beta_1 - \theta_2)}{\delta_2\lambda_1(\theta_1 - \beta_1)}\right] \\
= \quad & 0
\end{aligned} \tag{70}$$

4 Numerical Examples

We use the following parameters for the numerical examples: $\alpha = 0$, $\sigma \in (0.20, 0.40)$, $\rho = 0.10$, $\lambda_1 = 0.15$, $\lambda_2 \in (0.15, 1.35)$, $K = 1$, $I = 10$, $D = 10$, $k = 1.10$, $s = 2$, and $E_0 \equiv E = 1$.

4.1 No Decommissioning Option

Figs. 4 through 6 indicate the value functions for the three cases without the decommissioning option. We note that local risk reduces the expected NPV of the plant in state 1 due to the threat of suspension. This requires a higher electricity investment threshold price for the firm in order to cover its capital and opportunity costs. For the local-risk case, there are two value functions in state 1, i.e., one for each regime. Introduction of global risk further erodes the firm's option value in state 0 with investment only ever possible from regime 1. As part of the value of waiting is folded into a regime from which no investment occurs, the investment threshold with global risk is lower than that with local risk (albeit still higher than without risk). Intuitively, a firm facing only local risk has the full value of waiting, which is why it can afford to delay its investment decision relative to a firm facing global risk. In Fig. 6, the value function in state 0 with regime 2 has two parts.

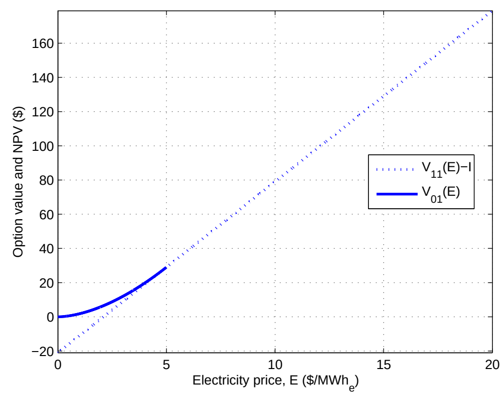

Figure 4: Value functions without risk or decommissioning option ($\sigma = 0.40, \lambda_2 = 0.15$)

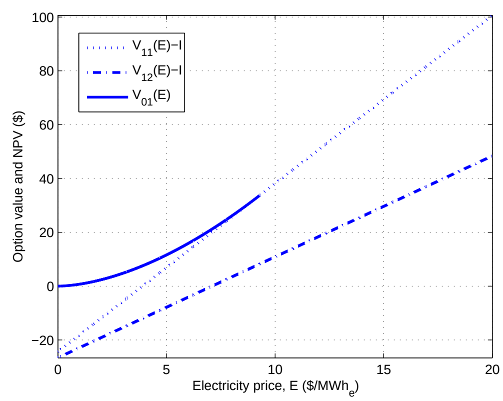

Figure 5: Value functions with local risk without decommissioning option ($\sigma = 0.40, \lambda_2 = 0.15$)

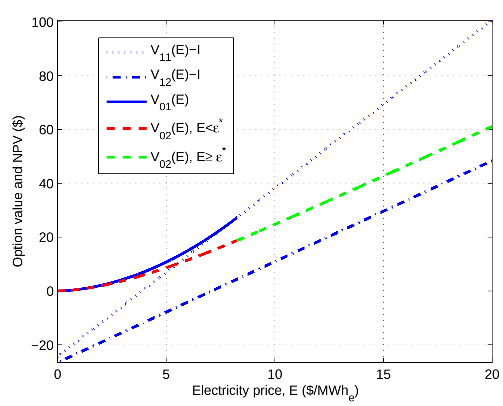

Figure 6: Value functions with global risk without decommissioning option ($\sigma = 0.40, \lambda_2 = 0.15$)

In order to explore the impact of underlying parameters such as the volatility and the resumption rate on investment thresholds and option values, we next perform sensitivity analyses in Figs. 7 through 10. First, in Fig. 7, we note that greater uncertainty increases the electricity price threshold for investment in all cases. Intuitively, as long as the marginal benefit (MB) of delaying the investment decision (due to the possibility of starting the project at a higher price and discounting the investment cost more heavily) is greater than its marginal cost (MC, stemming from the opportunity cost of forgone revenues), it is optimal to wait for a higher price. When local risk is introduced, the MC of delaying is reduced as the expected PV of cash flows in state 1 is lower. Meanwhile, the MB of delaying is not affected as much. Consequently, it is optimal to delay the investment decision relative to the case without risk. In the case of global risk, the MC of delaying is similarly reduced, but the MB of delaying is also eroded as the regime may have switched to 2 as the firm waits for a marginally higher price. For this reason, the investment threshold price for electricity is lower with global risk than with local risk, which is a seemingly counterintuitive result.

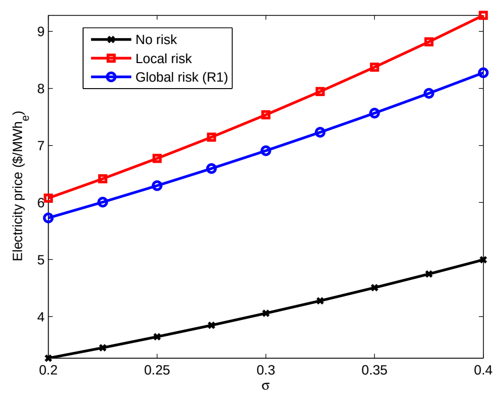

Figure 7: Effect of volatility on optimal investment thresholds without decommissioning option ($\lambda_2 = 0.15$)

For such a continuous-time Markov process, the stationary probability of being in regime 1 is $\frac{\lambda_2}{\lambda_1+\lambda_2}$. Thus, as λ_2 becomes large relative to λ_1, the long-run probability of being in regime 1 goes to 1. By varying λ_2, we find in Fig. 8 that the investment threshold without risk is unaffected, while those with local and global risks decrease and converge asymptotically to the former. Intuitively, increasing the rate of resumption (or equivalently, decreasing the risk of not operating) increases both the MB and the MC of delaying, which decreases the investment threshold price overall.

As for the option value of the investment opportunity in state 0, Figs. 9 and 10 indicate how it behaves with volatility and the resumption rate. First, higher uncertainty increases the option value as

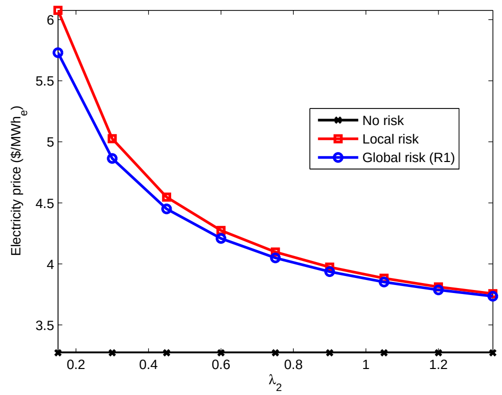

Figure 8: Effect of resumption rate on optimal investment thresholds without decommissioning option ($\sigma = 0.20$)

it is more worthwhile to wait. Nevertheless, the plant without risk is more valuable than the ones with risk, and, as expected, global risk affects the option value more than the local risk does. Decreasing the probability of being suspended increases the option values of plants with local and global risk until they asymptotically approach the value of a plant without risk.

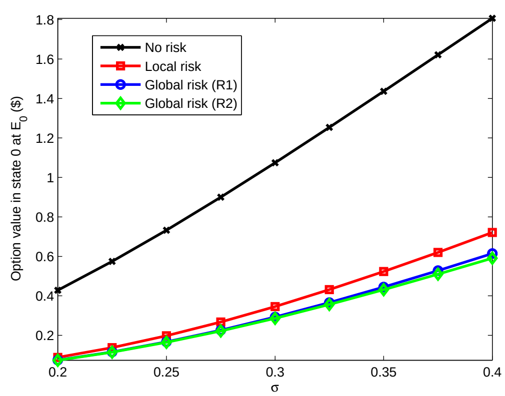

Figure 9: Effect of volatility on option values at initial price without decommissioning option ($\lambda_2 = 0.15$)

4.2 Decommissioning Option

A subsequent decommissioning option facilitates the firm's initial investment decision and increases the value of the investment opportunity. For the case without risk, the difference is hardly noticeable in Fig.

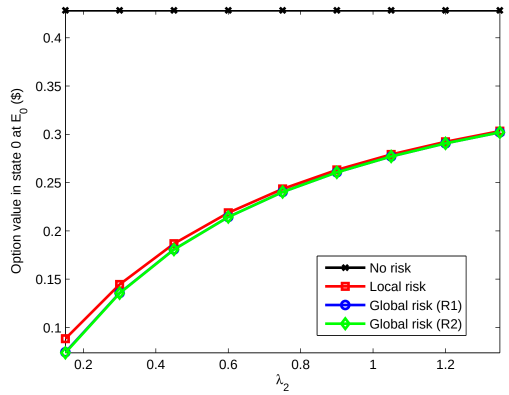

Figure 10: Effect of resumption rate on option values at initial price thresholds without decommissioning option ($\sigma = 0.20$)

11. However, the decommissioning threshold is 0.042 (Fig. 14), and the decommissioning option adds about 0.06% to the option value at E_0 (Fig. 18).

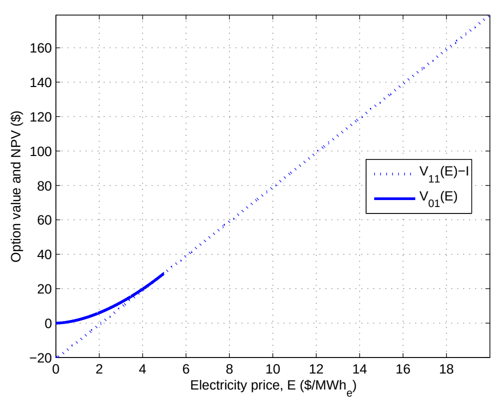

Figure 11: Value functions without risk and with decommissioning option ($\sigma = 0.40, \lambda_2 = 0.15$)

The results are more instructive with local risk. In Fig. 12, the presence of the decommissioning option gives curvature to both value functions in state 1. Since decommissioning occurs only from regime 2, $V_{12}(E) - I$ equals and is tangent to $-D$ at $E = \epsilon^{**}$. From Fig. 14, the latter threshold is 0.81 for $\sigma = 0.40$. As uncertainty increases, this decommissioning threshold decreases, which means that the firm becomes more hesitant to exit as is the standard result in real options. Although no exit is optimal from regime 1, $V_{11}(E) - I$ is affected by this decommissioning option because its value for $E < \epsilon^{**}$ internalises the possibility that exit will be immediate pending a regime switch. As expected, the decommissioning option lowers the investment threshold with local risk (Figs. 14 and 15) while increasing the value of the investment opportunity (Figs. 16 and 17). In particular, the decommissioning option adds 1.057% when $\sigma = 0.40$ and $\lambda_2 = 0.15$ in value (Fig. 18), which is order of magnitude greater than that without physical or policy risk. Indeed, it is the presence of such non-market risks that makes the decommissioning option valuable. Furthermore, this relative value increases (decreases) with the volatility (resumption rate). Intuitively, more uncertainty means more dispersed electricity prices. Consequently, the likelihood of more scenarios with low profits adds value to the decommissioning option, but this also means a greater opportunity cost to exercising the option in the form of higher forgone profits (lowering the decommissioning threshold). With a higher resumption rate, a plant spends less time on average in regime 2, which lowers the value of decommissioning as a put option against scenarios with low profits and makes it less likely for this option to be exercised. We also assess the impact of uncertainty and the resumption rate on the loss in the investment opportunity's value relative to the setting without risk, i.e., the ratio of the respective $V_{01}(E)$ functions evaluated at E_0 (Figs. 19 and 21). We find that the discrepancy in value due to local risk diminishes as both uncertainty and the resumption rate increase. Intuitively, more uncertainty means less likelihood of investment regardless of the physical/policy risk, while a higher rate of resumption lowers the impact of the physical/policy risk. The effect of the decommissioning option is to reduce the discrepancy further. Hence, market and physical/policy risks have subtly different impacts on both the decisions and values of the firm.

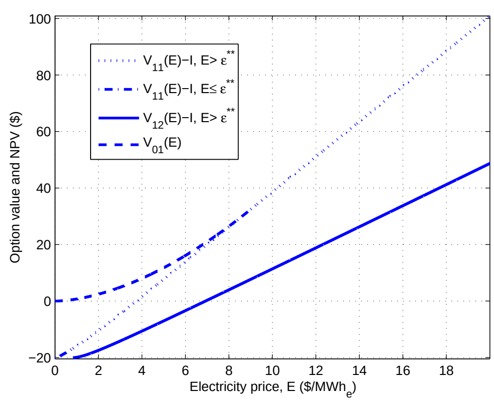

Figure 12: Value functions with local risk and decommissioning option ($\sigma = 0.40, \lambda_2 = 0.15$)

With global risk, the effect of the decommissioning option is qualitatively similar: it facilitates investment (Fig. 13) and increases the value of the investment opportunity (Fig. 18). As expected, the impact of risk is more severe because even the investment opportunity from state 0 may be lost with the arrival of a regime switch. Consequently, the loss in value relative to the no-risk case is about 65%

here as opposed to 60% with local risk for $\sigma = 0.40$ and $\lambda_2 = 0.15$.

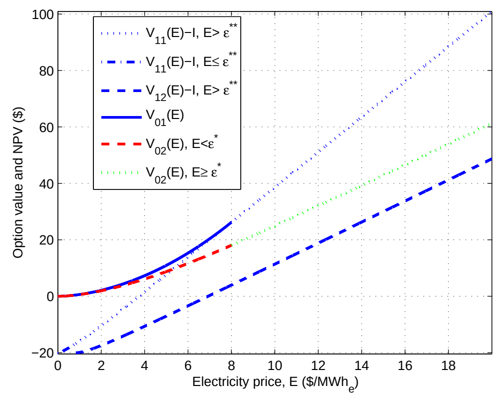

Figure 13: Value functions with global risk and decommissioning option ($\sigma = 0.40, \lambda_2 = 0.15$)

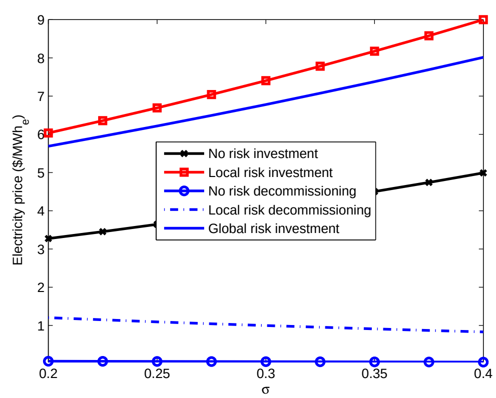

Figure 14: Effect of volatility on optimal thresholds with decommissioning option ($\lambda_2 = 0.15$)

4.3 Further Sensitivity Analysis

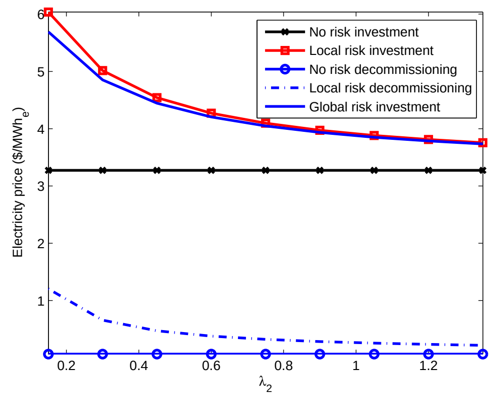

Figure 15: Effect of resumption rate on optimal investment thresholds with decommissioning option ($\sigma = 0.20$)

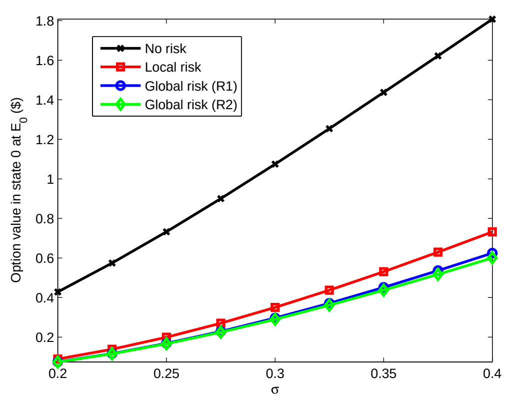

Figure 16: Effect of volatility on option values at initial price with decommissioning option ($\lambda_2 = 0.15$)

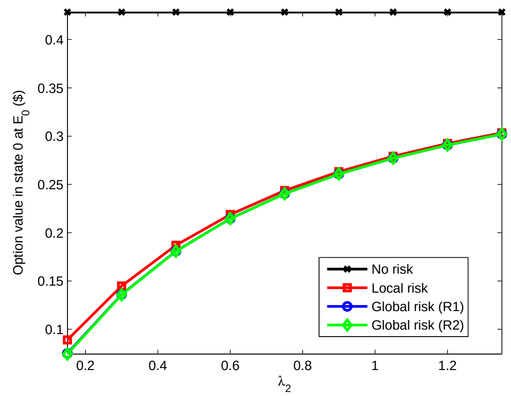

Figure 17: Effect of resumption rate on option values at initial price with decommissioning option ($\sigma = 0.20$)

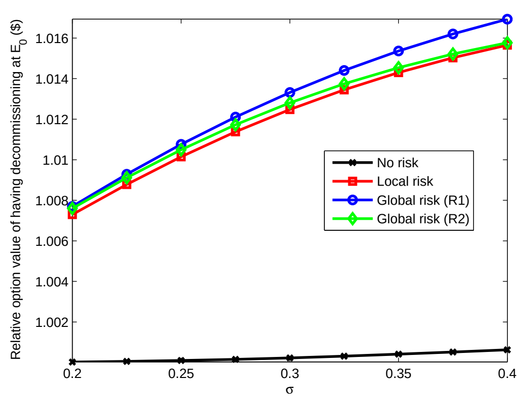

Figure 18: Effect of volatility on decommissioning value at initial price ($\lambda_2 = 0.15$)

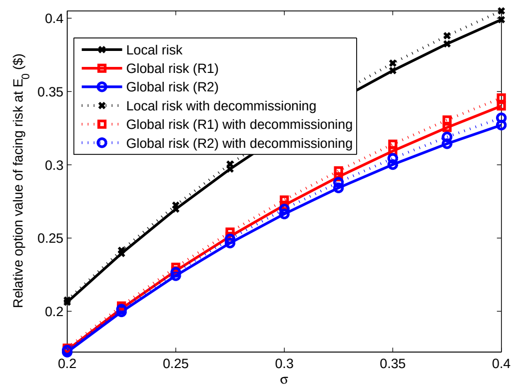

Figure 19: Effect of volatility on relative option values from risk exposure at initial price ($\lambda_2 = 0.15$)

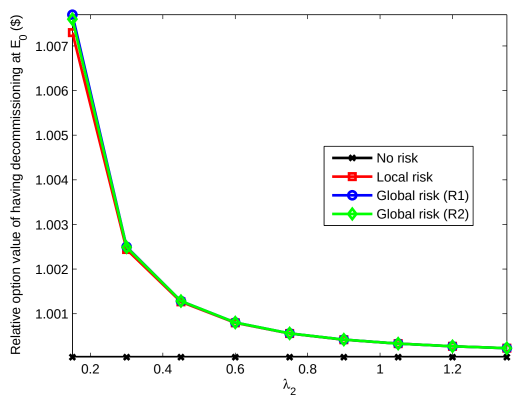

Figure 20: Effect of resumption rate on decommissioning value at initial price ($\sigma = 0.20$)

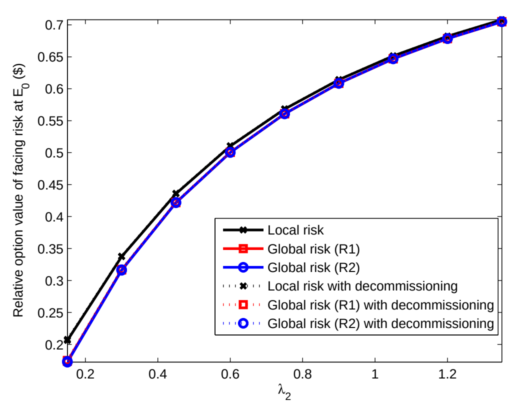

Figure 21: Effect of resumption rate on relative option values from risk exposure at initial price ($\sigma = 0.20$)

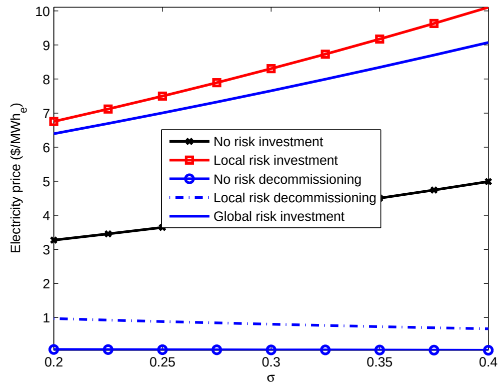

Figure 22: Effect of volatility on optimal investment thresholds with decommissioning option ($\lambda_1 = \lambda_2 = 0.30$)

As a first sensitivity, we increase both λ_1 and λ_2 to 0.30. We would like to explore if the results depend solely on the ratio of these two rates by keeping the long-run proportion of time spent in each regime equal to $\frac{1}{2}$ as before. This seems to reduce the value of a state-1 plant in regime 1 but to increase its value in regime 2. However, overall, the value of the option to invest decreases, which increases the investment thresholds as observed by comparing Figs. 22 and 14. Moreover, the decommissioning value decreases (compare Figs. 23 and 18), which decreases the decommissioning threshold even though the ratio $\frac{\lambda_1}{\lambda_2}$ is unchanged. Although we do not have a verified explanation for this intriguing finding, we suspect that it is because the revenues of the plant get shifted to later in time while the strengthening costs are incurred earlier in time as a result of shorter cycle times. Similarly, the effect of physical/policy risk (whether local or global) is made more severe (compare Figs. 24 and 19). Hence, exploring these results analytically will be an important next step in our work.

Our second sensitivity keeps the expected discounted cycle cost of strengthening while in regime 2, i.e., $\frac{Ks}{\rho+\lambda_2}$, unchanged while increasing both s and λ_2 to 3.2 and 0.30, respectively. We find that this increases the proportion of time that the plant is on, which increases the option value, increases the decommissioning value, reduces the investment threshold, mitigates the impact of physical/policy risk, and increases the decommissioning threshold (compare Figs. 25 through 27 with Figs. 14, 18, and 19, respectively). The findings here are relatively more clear cut because of the lower opportunity cost of forgone revenues from a plant that is less frequently suspended; however, we will aim to verify them analytically before moving on to a more interesting analysis in which we keep expected cycle profits unchanged while varying underlying parameters.

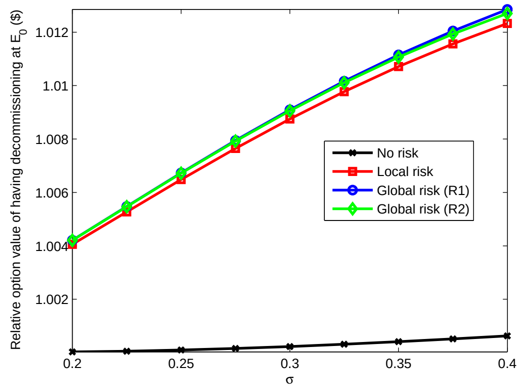

Figure 23: Effect of volatility on decommissioning value at initial price ($\lambda_1 = \lambda_2 = 0.30$)

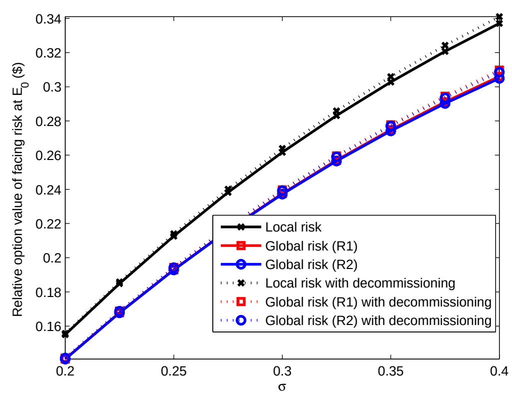

Figure 24: Effect of volatility on relative option values from risk exposure at initial price ($\lambda_1 = \lambda_2 = 0.30$)

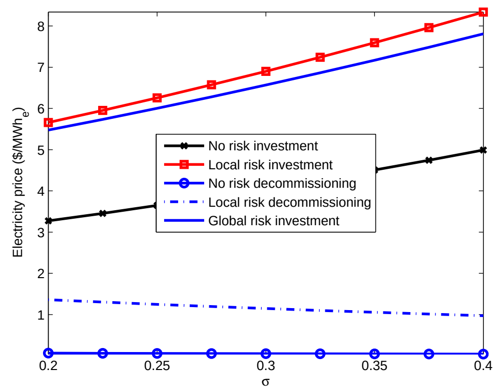

Figure 25: Effect of volatility on optimal investment thresholds with decommissioning option ($s = 3.2, \lambda_2 = 0.30$)

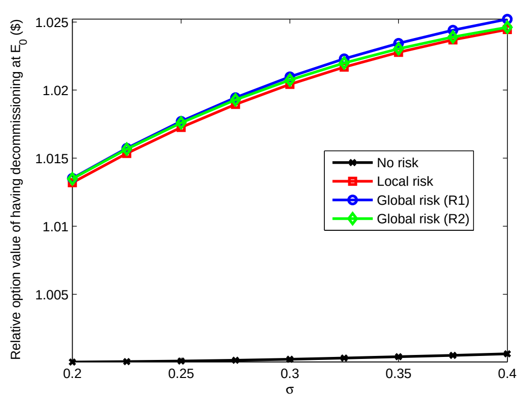

Figure 26: Effect of volatility on decommissioning value at initial price ($s = 3.2, \lambda_2 = 0.30$)

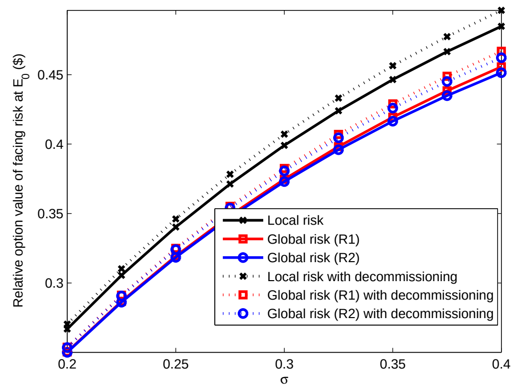

Figure 27: Effect of volatility on relative option values from risk exposure at initial price ($s = 3.2, \lambda_2 = 0.30$)

5 Conclusions

In this work, we address the problem of optimal investment and subsequent decommissioning timing of a power plant that is subject to physical or policy risks. Such an analysis is topical and relevant due to the prevalence of intermittent alternative energy resources in response to environmental concerns. Furthermore, decline in public approval for many nuclear power projects after the Fukushima Daiichi disaster of 2011 means that even plants that have been yet to be built may face such policy risk of suspension of the license to build. Therefore, we seek to incorporate these features in a real options approach that can handle embedded timing decisions in order to provide managerial and policy insights.

Taking the perspective of firm investing in plant subject to such physical/policy risks, which we model as independent regime switches, we find that their impact is more severe when the risk is global and tapers off as uncertainty increases. Rather counterintuitively, we obtain the result that investment under local risk is delayed by more than that under global risk. The value of the decommissioning option is neglible unless there is local or global risk, and it increases with uncertainty. Via sensitivity analyses, we determine that increasing the rates of regime switching while keeping the long-run proportion of time in each regime unchanged affects option values and thresholds because it changes how cash flows are discounted. On the other hand, in increasing the strengthening cost and resumption rate in order to keep the expected discounted cycle cost of strengthening the same, we find that the option value to invest increases along with the decommissioning threshold price and value. These insights about how investment incentives are affected by physical/policy risks can guide policymakers in shaping regulation that mitigates their impact.

For future work, we would like to verify some of the numerical findings analytically. Also, besides a decommissioning option, we would like to explore the value of an upgrade option, i.e., after initial investment, the firm may retrofit its plant in order to reduce the severity of future suspensions. Other possibilities for subsequent research include incorporating strategic interactions with other firms, allowing for operational flexibility, and investigating investment lags.

References

[1] Boomsma, T.K., N. Meade, and S.-E. Fleten (2012), "Renewable Energy Investments under Different Support Schemes: A Real Options Approach," European Journal of Operational Research 220: 225–237.

[2] Dixit, A.K. and R.S. Pindyck (1994), *Investment under Uncertainty*, Princeton University Press, Princeton, NJ, USA.

[3] Driffill, J., T. Kenc, and M. Sola (2009), "Real Options with Priced Regime-Switching Risk," working paper, Birkbeck College, London, U. K.

[4] Goto, M., K. Nishide, and R. Takashima (2012), "Irreversible Investment under Competition with Markov Switching Regime," in Annual Real Options Conference, London, U. K.

[5] Makimoto, N. (2006), "Optimal Investment Policy for Real Option Problems with Regime Switching," in The Sixth International Symposium on Operations Research and Its Applications, Xinjiang, P. R. China.