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Abstract

Concerns with CO_2 emissions are creating incentives for the development and deployment of energy technologies that do not use fossil fuels. Indeed, such technologies would provide tangible benefits in terms of avoided fossil-fuel costs, which are likely to increase as

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restrictions on CO_2 emissions are imposed. However, there are a number of challenges that need to be overcome, and the current costs of developing new alternative energy technologies would be too high to be handled privately. We analyse how a government may proceed with a staged development of meeting electricity demand as fossil-fuel sources are being phased out. A large-scale, new alternative technology is one possibility, where one would start a major research and development programme as an intermediate step. Alternatively, the government could choose to deploy an existing renewable energy technology, and using the real options framework, we compare the two projects to provide policy implications on how one might proceed.

JEL Classification Codes: D81, Q42

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1 Introduction

Global warming, the risk of fossil-fuel price increases, heavy-metal emissions from fossil-fuel use, new technology such as passively safe plants, and energy security concerns have all renewed interest in both nuclear power plants and renewable energy (RE) technologies. Combustion of fossil fuels contributes to the concentration of CO_2 in the atmosphere, thereby enhancing the greenhouse effect [IPCC, 2007]. Since prices of fossil fuels do not fully reflect the societal costs of the emissions they produce, government involvement in the energy sector is necessary in order to correct such externalities. As fossil-fuel sources for electricity generation are being phased out, new technologies are needed.

Currently undeveloped technologies that can serve as replacement for fossil-fuelled electricity generation include nuclear fusion, nuclear cycles based on thorium, and new generations of fast/breeding nuclear reactors as well as RE technologies that can potentially harness the power of waves or salt crystals. A common advantage of these technologies is that no greenhouse gases are emitted as a result of the actual electricity generation process, and that once built, the direct operating costs are low. The main nuclear fusion project is the International Thermonuclear Experimental Reactor (ITER) [ITER, 2007], which is attempting to exploit the energy provided by fusion of light atoms, and partners include the EU, Japan, China, India, Korea, Russia, and the USA. This technology has a long way to go before commercialisation, e.g., the time scale for technical development involves many decades.

Nuclear power based on thorium is another example. The advantages of this type of fuel are that it is potentially safer, it can make weapons proliferation more difficult, and it produces less long-lived waste than today's traditional uranium reactors do. Furthermore, thorium is much more abundant in nature than uranium is. These issues together make thorium cycles a considerable long-term option. In terms of technical feasibility, several thorium fuel reactor concepts have been studied since the 1960s. However, there is a wide range of unsolved technical challenges connected to this type of fuel. Consequently, thorium-fuelled reactors exist only in the planning stage. A final example we mention is breeder reactors, in which more fissile material is produced than consumed. This may contribute to mitigating a potential future shortage of uranium, a problem that has been foreseen since at least the 1970s. On the other hand, such reactors are not economically competitive and require fuel reprocessing, which has serious proliferation and radiotoxic waste concerns. In the words of Manne [1974], we are still waiting for the breeder. Basically, more uranium has been available than foreseen, and current and new reactors are getting more energy out of the fuel.

Regarding safety, the risk of severe accidents, such as the ones at Three Mile Island and Chernobyl, is much lower in new reactors. They are designed so that it is physically not possible to induce an uncontrolled chain reaction in the core, i.e., they are "passively safe," and this is applicable to thorium- as well as uranium-fuelled plants. However, no technology is fool-proof, and public acceptance of nuclear energy is still going to be an issue.

We abstract from most of the political and technical issues to take the view of a government planner that needs to meet the demand for electricity and is looking promote the development of a new power technology that is clean, cost-effective, long-term sustainable, and safe. Due to economies of scale, there may also be a minimum capacity level necessary to develop a new electricity source. For these reasons, we consider a situation in which the planner needs to choose between allocating funds to deploying an existing RE technology, e.g., wind, or developing and possibly deploying a large-scale alternative (LSA) technology, e.g., based on nuclear power (see Gollier et al. [2005] and Rothwell [2006] for recent studies of investment in nuclear power plants). Of course, there are other alternatives such as carbon capture and sequestration; however, this is feasible only in limited locations and depends on continued use of non-renewable fossil sources. The development of an LSA technology that avoids problems associated with CO_2 emissions restrictions, volatile fossil-fuel prices, and security of supply stemming from geopolitical risk may benefit from a phased approach where a research and development (R&D) programme is set up before actual deployment and building of power plants. Such an intermediate R&D phase would have the effect of reducing the total operating cost associated with the LSA technology.

As there is considerable uncertainty affecting the technology deployment decisions, we take a real options approach based on dynamic programming as outlined in Chapters 4–6 of Dixit and Pindyck [1994]. In contrast to the traditional deterministic "now or never" discounted cash flow (DCF) analysis, the real options one allows for decision-making under uncertainty when there exists managerial flexibility to invest, abandon, or modify a project. In particular, the real options approach trades off in continuous time the marginal benefits and costs from delaying an investment or operational decision. Here, the government planner has the option to defer the release of funds and will do so until a certain electricity price threshold is reached, which is set to maximise the option value of the opportunity. A recent paper uses the real options framework to quantify the optimal level of US federal R&D funding for a RE technology under uncertain fossil fuel prices and technical risk [Davis and Owens, 2003]. In the European context, a case for government support for undeveloped energy technologies is made in Alfsen et al. [2009].

In this paper, we outline a strategy for developing a non-fossil, LSA technology through a phased approach. We identify the factors affecting the tradeoff in choosing between an existing RE technology and an undeveloped, but potentially more promising, LSA technology. We find the value of an R&D programme to develop the LSA technology, where any R&D effort will reduce its operating cost, along with long-term electricity price thresholds at which to begin R&D and to deploy the LSA technology. Since the value of the LSA technology depends on the present value (PV) of cost savings of its generation relative to the fossil-based long-term electricity price, the option value of the investment is increasing in the electricity price. By comparing the phased LSA R&D programme to a more direct one, we also extract the option value of the intermediate R&D stage. Using the approach of Décamps et al. [2006], we then consider the impact of the mutually exclusive opportunity to deploy an existing RE technology. We find that the interaction of the two mutually exclusive projects increases the value of the entire alternative energy portfolio while making the selection of any given technology less likely.

Within the field of energy economics, this technique has been applied to investment and sizing of renewable generation capacity and transmission lines, two types of investments that are sensitive to market uncertainty and scale (see Fleten et al. [2007] and Siddiqui and Gupta [2007], respectively). In the literature, Pindyck [1993] uses nuclear power plants as an example to focus on uncertain costs in completing the project (an uncertainty that is resolved as one proceeds with development) and input costs to launch a final project (an uncertainty that is resolved solely by passage of time), whereas we consider operating costs of generating electricity, which will be reduced once the R&D programme is initiated.

We do not consider the technical design process of the LSA in any detail except through the reduction in its operating cost, which is a relatively aggregate description of technical learning (see Majd and Pindyck [1989] for a real options model of learning through production). Since modern-day designs must probably be empirically verified through laboratory and small-scale testing of experimental reactors, development engineers may insist on an intermediate R&D stage. In general, real options have been used to justify and value such R&D projects. Early work such as Roberts and Weitzman [1981] (actually predating the term "real options") analyses an investment project where an R&D effort reduces the variability of the cash flows of the project. Newton and Pearson [1994] uses the Black-Scholes formula to value R&D, and Jensen and Warren [2001] considers research and development as two distinct phases in project development. Recent work such as Malchow-Møller and Thorsen [2005] and Goetz and Yatsenko [2008] has extended the real options analysis to many stages and with technology updating, respectively.

The remainder of this paper is organised as follows:

- Section 2 states the assumptions and formulates the problem using the real options approach for various technology cases

- Section 3 presents the results of the numerical examples
- Section 4 summarises the contribution of this work, discusses its limitations, and offers directions for future research

2 Model and Assumptions

In formulating the government's decision-making problem under uncertainty, we assume that the long-term electricity price is exogenous to the model and, thus, unaffected by any technology deployment decisions. This is justified by the fact that although the scale of the potential investment, i.e., 10 TWh,[1] may be a sizeable fraction of a small country's annual energy consumption, it is, nevertheless, small compared to the worldwide consumption of energy. Furthermore, we analyse a one-time investment opportunity, the effects of which are unlikely to influence the long-term electricity price as it will have already anticipated the consequences of such technology adoption.

We assume that the long-term, time-t electricity price at which society's electricity needs are met, P_t (in \$/MWh), depends chiefly on fossil fuels and evolves according to a geometric Brownian motion (GBM) process, i.e., $dP_t = \alpha P_t dt + \sigma P_t dz_t$, where α is the annualised growth rate of P_t, σ is the annualised percentage volatility of P_t, and dz_t is an increment to the Wiener process.[2] As an alternative to using fossil fuels, the government may meet a given portion of

[1] Assuming a 90% capacity factor, this corresponds to approximately 1250 MW_e of power capacity.

[2] The difference between the long-term electricity price and the spot price is related to the fact that electricity prices are affected by fluctuations in short-term supply and demand and in expectations regarding long-term supply and demand. One can think of the long-term electricity price as the electricity price where short-term deviations have been removed from the spot price, so that the only source of uncertainty in the long-term electricity price is long-term uncertainty, related to changing expectations regarding future supply and demand.

the annual electricity demand via either an existing low-emitting RE technology at constant operating cost C^E (in \$/MWh) or an LSA technology at operating cost C_t (in \$/MWh), which evolves stochastically according to a GBM once the government starts an R&D programme, i.e., $dC_t = -\lambda C_t dt + \sigma_C C_t dz_t^C$. Here, λ is the annualised rate of decrease in the LSA technology's operating cost, while σ_C denotes the level of technical risk associated with the R&D programme. We assume that the LSA technology's operating cost is uncorrelated with fluctuations in the long-term electricity price.[3] If the LSA technology is to be realised early, then there will be increased safety and security costs, costs associated with gaining public acceptance, regulatory costs, transportation and other logistics costs, and costs for highly skilled, i.e., PhD-level, labour. For these reasons, we assume that $C_0 > C^E$, but that $C_{t^*} < C^E$ for some $t^* > 0$ once the R&D programme has lowered the cost of LSA generation sufficiently.

If the government initiates such a programme, then it must pay a lump sum of I (in \$), which covers the initial start-up cost of the programme plus the PV of the annual R&D expenses. After the LSA R&D programme has been under way, the government may decide to deploy the newly developed technology to meet the electricity demand, X (in MWh). In this case, X MWh of electricity are provided by the LSA each year, and the R&D programme continues indefinitely, thereby reducing the cost of electricity production forever. Instead of undertaking the staged development of the LSA technology, the government may choose to proceed with an existing RE technology by paying a lump-sum cost $I^E < I$, which allows it to meet a more modest electricity demand, X^E (in MWh), at cost C^E per year forever plus the right to switch to the LSA R&D programme at any point by paying I. Due to the intermittency and constraints

See Schwartz [1998] for an example of how this can be estimated and operationalised.

[3]Incorporating instantaneous correlation between dz_t and dz_t^C poses no analytical difficulty in our model.

on suitable sites for RE technologies, we assume that $X^E < X$. Furthermore, we assume that all investment and deployment options are perpetual, which not only eases the analysis, but also reflects the flexibility a government planner may have over timing.

The limitations of our approach include the assumption of an exogenous long-term electricity price, a lower possible capacity for the existing RE technology installment, and the treatment of the existing RE technology and LSA as mutually exclusive alternative projects due to limited government funding. We provide justifications for these assumptions, but for future work, it would be instructive to explore relaxing them. In particular, optimising the level of funding for a portfolio of energy technology programmes would be closer to a typical government's decision-making problem. In Sections 2.1 and 2.2, we formulate the government's problem and find analytical solutions where possible.[4]

2.1 Case 1: No Existing Renewable Energy Technology

For now, we ignore the opportunity to use the existing RE technology and focus on the staged development of the LSA project. The state transition diagram for this simplified problem may be seen in Figure 1. There are, thus, three states of the world:

- State 0, in which no R&D programme exists.
- State 1, in which the R&D programme exists, thereby decreasing the LSA operating cost, C_t, but no incremental savings accrue since the LSA technology has not been deployed.
- State 2, in which the LSA technology has been deployed with ongoing R&D that lowers its operating cost and is accruing savings relative to fossil-fuel generation.

[4]The Appendix covers the case in which it is possible to switch from the existing RE to the LSA programme.

In order to solve the government's LSA R&D investment problem, we start at the end in state 2 and work backwards. Given that LSA technology has been deployed and will operate forever, the expected PV of cost savings is:

$$\begin{aligned}
V_2(P,C) &= X\left(\int_0^\infty \mathcal{E}[P_t|P]e^{-\rho t}dt - \int_0^\infty \mathcal{E}[C_t|C]e^{-\rho t}dt\right)\\
\Rightarrow V_2(P,C) &= X\left(\int_0^\infty Pe^{-(\rho-\alpha)t}dt - \int_0^\infty Ce^{-(\lambda+\rho)t}dt\right)\\
\Rightarrow V_2(P,C) &= X\left(\frac{P}{\rho-\alpha} - \frac{C}{\lambda+\rho}\right) \qquad (1)
\end{aligned}$$

Here, ρ is the discount rate used by the government.

In state 1, while the R&D programme is ongoing, the government holds a perpetual option to deploy the LSA technology. The value of this option to the government is $V_1(P,C)$, which we find by using Itô's Lemma to expand dV_1 and then use the Bellman Equation. First, we find the expected appreciation of the value of the option to deploy:

$$\begin{aligned}
dV_1 &= \frac{1}{2}\frac{\partial^2 V_1}{\partial P^2}(dP)^2 + \frac{1}{2}\frac{\partial^2 V_1}{\partial C^2}(dC)^2 + \frac{\partial V_1}{\partial P}dP + \frac{\partial V_1}{\partial C}dC\\
\Rightarrow \mathcal{E}[dV_1] &= \frac{1}{2}\frac{\partial^2 V_1}{\partial P^2}\sigma^2 P^2 dt + \frac{1}{2}\frac{\partial^2 V_1}{\partial C^2}\sigma_C^2 C^2 dt + \frac{\partial V_1}{\partial P}\alpha P dt - \frac{\partial V_1}{\partial C}\lambda C dt \qquad (2)
\end{aligned}$$

Next, we equate the expected appreciation of V_1 to the instantaneous rate of return on V_1 via the Bellman Equation:

$$\mathcal{E}[dV_1] = \rho V_1 dt$$

$$\Rightarrow \quad \tfrac{1}{2}\tfrac{\partial^2 V_1}{\partial P^2}\sigma^2 P^2 + \tfrac{1}{2}\tfrac{\partial^2 V_1}{\partial C^2}\sigma_C^2 C^2 + \tfrac{\partial V_1}{\partial P}\alpha P - \tfrac{\partial V_1}{\partial C}\lambda C - \rho V_1 = 0 \qquad (3)$$

Equation 3 is solved subject to the following value-matching and smooth-pasting conditions:

$$\begin{aligned}
V_1(P^*,C^*) &= V_2(P^*,C^*)\\
\Rightarrow V_1(P^*,C^*) &= X\left(\frac{P^*}{\rho-\alpha} - \frac{C^*}{\lambda+\rho}\right) \qquad (4)
\end{aligned}$$

$$\left.\frac{\partial V_1}{\partial P}\right|_{P=P^*,C=C^*} = \left.\frac{\partial V_2}{\partial P}\right|_{P=P^*,C=C^*}$$
$$\Rightarrow \left.\frac{\partial V_1}{\partial P}\right|_{P=P^*,C=C^*} = \frac{X}{\rho-\alpha} \quad (5)$$

$$\left.\frac{\partial V_1}{\partial C}\right|_{P=P^*,C=C^*} = \left.\frac{\partial V_2}{\partial C}\right|_{P=P^*,C=C^*}$$
$$\Rightarrow \left.\frac{\partial V_1}{\partial C}\right|_{P=P^*,C=C^*} = -\frac{X}{\lambda+\rho} \quad (6)$$

Equation 4 states that at deployment, the value of the option to use LSA generation equals the expected net present value (NPV) of an active investment. Meanwhile, Equations 5 and 6 are first-order necessary conditions that equate the marginal benefit of delaying deployment with its marginal cost. Since the solution to system of Equations 3 to 6 involves a free boundary, i.e., P^* depends on C, we convert the partial differential equation (PDE) to an ordinary differential equation (ODE) as discussed in Dixit and Pindyck [1994].

We start by defining $p \equiv \frac{P}{C}$ and assuming that $V_1(P,C)$ is homogenous of degree one in (P,C). Then, we note that $V_1(P,C) = Cv_1(P/C) = Cv_1(p)$. Using the definition of p and $v_1(p)$, we re-write Equations 3 through 6 as follows:

$$\tfrac{1}{2}v_1''(p)(\sigma^2+\sigma_C^2)p^2 + v_1'(p)(\alpha+\lambda)p - v_1(p)(\lambda+\rho) = 0 \quad (7)$$

$$v_1(p^*) = X\left(\frac{p^*}{\rho-\alpha} - \frac{1}{\lambda+\rho}\right) \quad (8)$$

$$v_1'(p^*) = \frac{X}{\rho-\alpha} \quad (9)$$

$$v_1(p^*) - p^*v_1'(p^*) = -\frac{X}{\lambda+\rho} \quad (10)$$

Since Equation 10 follows from Equations 8 and 9, we may ignore it. The solution to the ODE in Equation 7 is:

$$v_1(p) = a_1 p^{\gamma_1} \quad (11)$$

This is the normalised value of the option to deploy the LSA technology, where γ_1 is a positive exogenous constant that is the solution to the characteristic quadratic equation, i.e.,

$$\gamma_1 = \frac{-(\alpha + \lambda - \frac{1}{2}(\sigma^2 + \sigma_C^2)) + \sqrt{(\alpha + \lambda - \frac{1}{2}(\sigma^2 + \sigma_C^2))^2 + 2(\sigma^2 + \sigma_C^2)(\lambda + \rho)}}{\sigma^2 + \sigma_C^2} \quad (12)$$

Using Equations 8 and 9, we can solve simultaneously for the deployment price-cost threshold ratio, p^*, and the positive endogenous constant, a_1:

$$p^* = \left(\frac{\gamma_1}{\gamma_1 - 1}\right)\frac{\rho - \alpha}{\lambda + \rho} \quad (13)$$

$$a_1 = \frac{X(p^*)^{1-\gamma_1}}{\gamma_1(\rho - \alpha)} \quad (14)$$

From Equations 11 and 13, the value of the R&D programme and the deployment threshold price-cost ratio, respectively, may be determined.

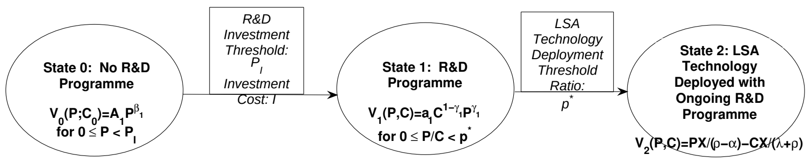

Figure 1: State transition diagram for an LSA R&D project with an intermediate learning step that reduces the operating cost.

Moving once step back, we would like to obtain the value of the perpetual option to invest in the R&D programme, $V_0(P; C_0)$, along with the investment threshold price, P_I. By following reasoning similar to that in Equations 2 and 3, we obtain the option value to start the R&D programme:

$$V_0(P; C_0) = A_1 P^{\beta_1} \tag{15}$$

In order to find the investment threshold price, P_I, and the endogenous constant, A_1, we use the following value-matching and smooth-pasting conditions:

$$\begin{aligned} V_0(P_I; C_0) &= V_1(P_I, C_0) - I \\ \Rightarrow A_1 P_I^{\beta_1} &= a_1 (C_0)^{1-\gamma_1} P_I^{\gamma_1} - I \end{aligned} \tag{16}$$

$$\begin{aligned} \left.\frac{dV_0}{dP}\right|_{P=P_I} &= \left.\frac{\partial V_1}{\partial P}\right|_{P=P_I, C=C_0} \\ \Rightarrow \beta_1 A_1 P_I^{\beta_1 - 1} &= \gamma_1 a_1 (C_0)^{1-\gamma_1} P_I^{\gamma_1 - 1} \end{aligned} \tag{17}$$

Here, β_1 is a positive exogenous constant:

$$\beta_1 = \frac{-(\alpha - \frac{1}{2}\sigma^2) + \sqrt{(\alpha - \frac{1}{2}\sigma^2)^2 + 2\sigma^2 \rho}}{\sigma^2} \tag{18}$$

Note that in Equations 16 and 17 we use the fact that $v_1(p) \equiv \frac{V_1(P,C)}{C}$, which implies that $V_1(P, C) = C v_1(p) = C a_1 \left(\frac{P}{C}\right)^{\gamma_1}$. Solving Equations 16 and 17 simultaneously, we obtain the following:

$$P_I = \left[\left(\frac{I \beta_1}{\beta_1 - \gamma_1} \right) \frac{(C_0)^{\gamma_1 - 1}}{a_1} \right]^{\frac{1}{\gamma_1}} \tag{19}$$

$$A_1 = \frac{\gamma_1 a_1 (C_0)^{1-\gamma_1} P_I^{\gamma_1 - \beta_1}}{\beta_1} \tag{20}$$

Although we solve the problem backwards, in terms of implementation, the government would first wait until the electricity price reaches P_I before paying I to enter state 1. Once the LSA R&D programme is active, the operating cost would decrease stochastically. The important point is that the government does not care about the absolute level of the cost of generation; instead, it deploys the LSA technology once the ratio of the electricity price to the cost of LSA generation reaches p^*. What makes this possible is the assumption of homogeneity in the value of the option to deploy LSA and the conglomeration of any deployment costs into the investment cost, I. Even if C_t were correlated with P_t, the result would hold as the NPV of the deployed LSA generation depends only on the ratio of the long-term electricity price to the cost of LSA generation.[5] We will illustrate the intuition with a numerical example in Section 3.1. Before that, we formulate the government's problem with a mutually exclusive investment opportunity in an existing RE technology.

2.2 Case 2: Existing Renewable Energy Technology without Switching Option to the Large-Scale Alternative Technology

We now include the flexibility of using the existing RE technology but without the possibility of reverting to the staged development of the LSA project. Here, there are four states of the world (see Figure 2):

- State 0, in which neither the LSA R&D programme exists nor the existing RE technology is deployed.
- State E, in which the existing RE technology has been deployed to meet the available electricity demand.

[5] Nevertheless, it should be noted that the real options approach becomes analytically intractable with more than two risk factors.

- State 1, in which the LSA R&D programme exists, thereby decreasing the LSA operating cost, C_t, but no incremental savings accrue since the LSA technology has not been deployed.

- State 2, in which the LSA technology has been deployed with ongoing R&D that lowers its operating cost and is accruing savings relative to fossil-fuel generation.

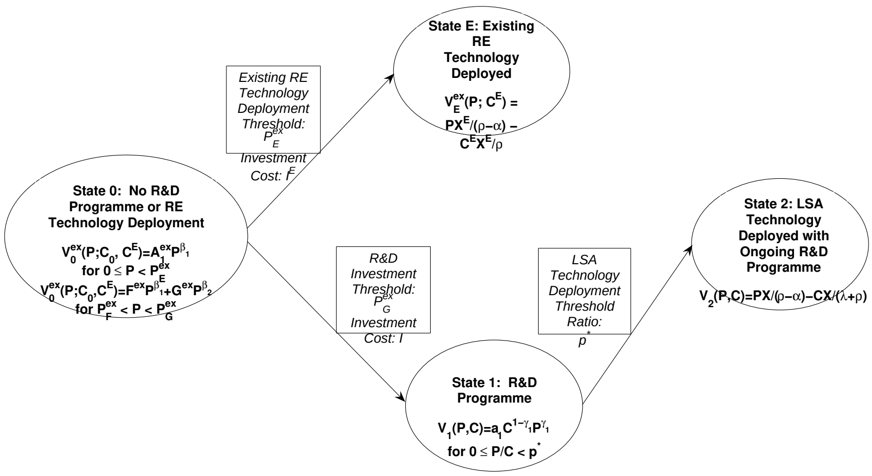

Figure 2: State transition diagram with a mutually exclusive existing RE technology option. The government may choose either to deploy an existing RE technology or to start a major LSA R&D project. If the latter avenue is selected, then the government may subsequently deploy the LSA technology.

Since the switching option is not available, we assume that in state 0, the government can choose either the existing RE technology or initiate the LSA R&D programme; however, once state E is entered, it is no longer possible to switch to the LSA option. Following Décamps et al. [2006], we note that the value of the option to meet electricity demand via alternative energy sources, $V_0^{ex}(P; C_0, C^E)$, may be dichotomous for small enough σ, with immediate investment occurring in the existing RE (LSA) technology for $P_E^{ex} \leq P \leq P_F^{ex}$ ($P \geq P_G^{ex}$); specifically, we may have:

$$V_0^{ex}(P; C_0, C^E) = \begin{cases} A_1^{ex} P^{\beta_1} & \text{if } 0 \leq P < P_E^{ex} \\ F^{ex} P^{\beta_1} + G^{ex} P^{\beta_2} & \text{if } P_F^{ex} < P < P_G^{ex} \end{cases} \tag{21}$$

Here, β_1 is defined as in Equation 18, respectively, while $\beta_2 = \frac{-(\alpha - \frac{1}{2}\sigma^2) - \sqrt{(\alpha - \frac{1}{2}\sigma^2)^2 + 2\sigma^2 \rho}}{\sigma^2}$ (the negative root of the characteristic quadratic function). In order to find A_1^{ex} and P_E^{ex} analytically for the first branch of $V_0^{ex}(P; C_0, C^E)$, we use the following value-matching and smooth-pasting conditions between $V_0^{ex}(P; C_0, C^E)$ and $V_E^{ex}(P; C^E)$:

$$\begin{aligned} V_0^{ex}(P_E^{ex}; C_0, C^E) &= V_E^{ex}(P_E^{ex}; C^E) - I^E \\ \Rightarrow A_1^{ex}(P_E^{ex})^{\beta_1} &= X^E \left(\frac{P_E^{ex}}{\rho - \alpha} - \frac{C^E}{\rho} \right) - I^E \end{aligned} \tag{22}$$

$$\begin{aligned} \left. \frac{dV_0^{ex}}{dP} \right|_{P = P_E^{ex}} &= \left. \frac{dV_E^{ex}}{dP} \right|_{P = P_E^{ex}} \\ \Rightarrow \beta_1 A_1^{ex}(P_E^{ex})^{\beta_1 - 1} &= \frac{X^E}{\rho - \alpha} \end{aligned} \tag{23}$$

Note that $V_E^{ex}(P; C^E)$ is simply equal to the PV of cost savings from using the existing RE technology. Solving Equations 22 and 23 simultaneously, we obtain the investment threshold price and endogenous constant for the existing RE technology:

$$P_E^{ex} = \left(\frac{\beta_1(\rho - \alpha)}{X^E(\beta_1 - 1)} \right) \left[\frac{C^E X^E}{\rho} + I^E \right] \tag{24}$$

$$A_1^{ex} = \frac{(P_E^{ex})^{1 - \beta_1} X^E}{\beta_1(\rho - \alpha)} \tag{25}$$

However, the endogenous constants, F^{ex} and G^{ex}, and the thresholds, P_F^{ex} and P_G^{ex}, for the second branch of $V_0^{ex}(P; C_0, C^E)$ have no analytical solution and must be determined numerically for specific parameter values via appropriate value-matching and smooth-pasting conditions to find the four unknowns. We also know that $P_F^{ex} < \tilde{P}^{ex} < P_G^{ex}$, where $\tilde{P}^{ex}$ is the price at which $V_E^{ex}(P;C^E) - I^E$ and $V_1(P, C = C_0) - I$ intersect. Since the latter function is nonlinear, $\tilde{P}^{ex}$ itself must be found numerically. Of course, for large values of σ, it may be preferable to skip considering the state E option, in which case the problem reduces to one of Section 2.1: the key is to check whether $A_1 > A_1^{ex}$. If so, then the government can proceed as in Section 2.1 [Dixit, 1993].

From state 0, if the threshold P_E^{ex} is reached, then the existing RE technology is deployed to meet electricity demand X^E at a marginal cost of C^E each year forever. This implies that the PV of cost savings in state E is:

$$V_E^{ex}(P;C^E) \quad = \quad X^E\left(\frac{P}{\rho-\alpha} - \frac{C^E}{\rho}\right) \tag{26}$$

By contrast, no action will be taken if the electricity price is between P_F^{ex} and P_G^{ex}, while immediate initiation of the LSA R&D programme (state 1) will occur if the latter threshold price is exceeded. Therefore, the value functions in states 1 and 2 are the same as those defined in Equations 2 and 1, respectively. The two endogenous constants, F^{ex} and G^{ex}, and threshold prices, P_F^{ex} and P_G^{ex}, are determined by the following four value-matching and smooth-pasting conditions between $V_0^{ex}(P;C_0,C^E)$ and $V_E^{ex}(P;C^E)$ as well as between $V_0^{ex}(P;C_0,C^E)$ and $V_1(P,C_0)$:

$$\begin{aligned} V_0^{ex}(P_F^{ex};C_0,C^E) &= V_E^{ex}(P_F^{ex};C^E) - I^E \\ \Rightarrow F^{ex}(P_F^{ex})^{\beta_1} + G^{ex}(P_F^{ex})^{\beta_2} &= X^E\left(\frac{P_F^{ex}}{\rho-\alpha} - \frac{C^E}{\rho}\right) - I^E \end{aligned} \tag{27}$$

$$\begin{aligned} \tfrac{dV_0^{ex}}{dP}\Big|_{P=P_F^{ex}} &= \tfrac{dV_E^{ex}}{dP}\Big|_{P=P_F^{ex}} \\ \Rightarrow \quad \beta_1 F^{ex}(P_F^{ex})^{\beta_1-1} + \beta_2 G^{ex}(P_F^{ex})^{\beta_2-1} &= \tfrac{X^E}{\rho-\alpha} \end{aligned} \tag{28}$$

$$\begin{aligned} V_0^{ex}(P_G^{ex}; C_0, C^E) &= V_1(P_G^{ex}, C_0) - I \\ \Rightarrow F^{ex}(P_G^{ex})^{\beta_1} + G^{ex}(P_G^{ex})^{\beta_2} &= a_1(C_0)^{1-\gamma_1}(P_G^{ex})^{\gamma_1} - I \end{aligned} \tag{29}$$

$$\begin{aligned} \left.\frac{dV_0^{ex}}{dP}\right|_{P=P_G^{ex}} &= \left.\frac{\partial V_1}{\partial P}\right|_{P=P_G^{ex}, C=C_0} \\ \Rightarrow \beta_1 F^{ex}(P_G^{ex})^{\beta_1-1} + \beta_2 G^{ex}(P_G^{ex})^{\beta_2-1} &= \gamma_1 a_1(C_0)^{1-\gamma_1}(P_G^{ex})^{\gamma_1-1} \end{aligned} \tag{30}$$

In the Appendix, we consider the case with a switching option, i.e., in which it is possible to proceed from state 1 to E. Next, however, we illustrate the intuition and policy insights of the models we have developed via numerical examples.

3 Numerical Examples

3.1 Numerical Example 1: No Existing Renewable Energy Technology

For the numerical example, we use the following parameters: $\alpha = 0.04$, $\sigma = 0.20$, $\rho = 0.10$, $I = \$1$ billion, $\lambda = 0.04$, $C_0 = \$100$/MWh, and $X = 1 \times 10^7$ MWh (10 TWh). Furthermore, we allow σ to vary between 0.15 and 0.40 and λ to become 0.08 as parameter estimates. Initially, in Section 3.1.1, we set $\sigma_C = 0$ to abstract from technical uncertainty in the LSA technology's intermediate R&D stage. Then, in Section 3.1.2, we set $\sigma_C = 0.10$ to examine how the results are affected by technical uncertainty.

3.1.1 No Technical Uncertainty in LSA R&D

For $\sigma = 0.20$ and $\lambda = 0.04$, we obtain $\beta_1 = 1.7913$, $\gamma_1 = 1.5414$, $A_1 = 2.29$, $P_I = 82.13$, and $p^* = 1.22$. According to Figures 3 and 4, the government's strategy is to wait until the long-term electricity price reaches \$82.13/MWh before initiating the LSA R&D programme and then to wait again until the long-term electricity price is 1.22 times the nominal LSA operating cost before deployment. With $\sigma = 0.20$, once state 1 is entered, the R&D programme will continue since the ratio of the long-term electricity price to the LSA operating cost is $\frac{82.13}{100} = 0.8213 < p^*$. In other words, there will not be an instantaneous transition from state 0 to state 2. From Figure 3, the value of the option to invest in LSA R&D is worth approximately $V_0(P_I; C_0) = V_1(P_I, C_0) - I = \$6.17 \times 10^9$, i.e., around \$6.17 billion, at deployment, which is equal to the initial value in Figure 4 minus the investment cost: $C_0 v_1(p = P_I/C_0) - I$. Finally, the value of the investment opportunity at state 0 for $P_0 = 60$ is $V_0(P_0; C_0) = \$3.52 \times 10^9$, i.e., around \$3.52 billion. If we use the "now or never" DCF approach to value to benefit of the LSA generation technology, then we would obtain an expected NPV of only \$1.86 billion, i.e., $V_2(P_0, C_0) - I = X\left(\frac{P_0}{\rho-\alpha} - \frac{C_0}{\lambda+\rho}\right) - I$, which is almost 50% lower than the value from the real options approach.

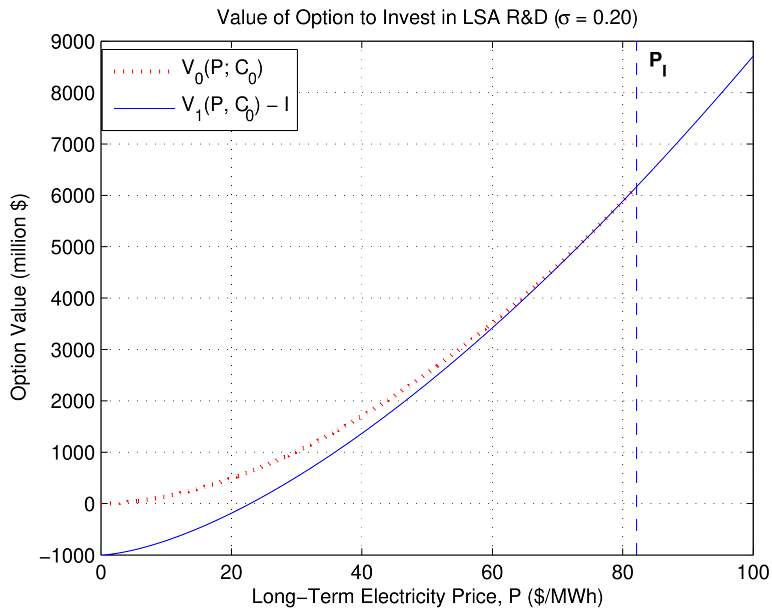

Figure 3: Value of option to invest in LSA R&D without an existing RE technology ($\sigma = 0.20$).

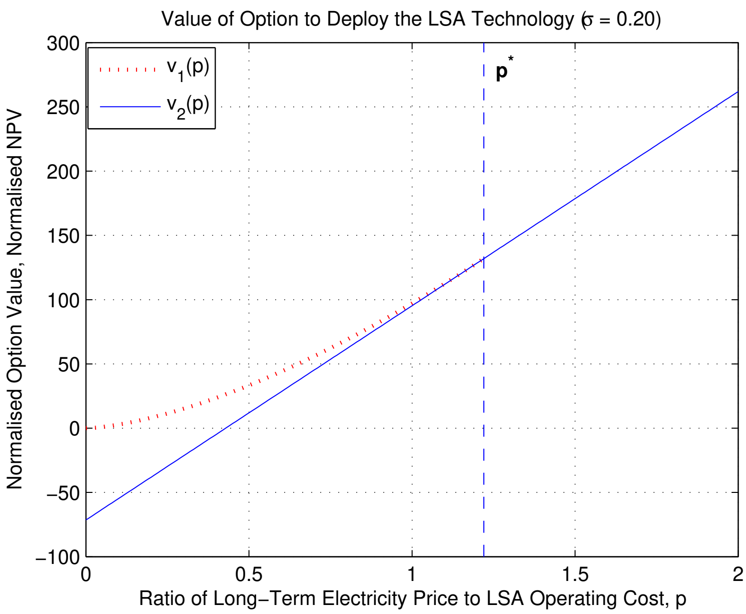

Figure 4: Value of option to deploy the LSA technology without an existing RE technology from an R&D state ($\sigma = 0.20$).

By contrast, if state 1 were avoided, i.e., if the government had only the option to deploy the LSA technology at initial generating cost C_0 without waiting to improve its performance via the intermediate R&D stage, then the value of the entire programme in state 0 would be:

$$V_0^D(P; C_0) = A_1^D P^{\beta_1} \tag{31}$$

Solving simultaneously for the deployment threshold, P_I^D, and endogenous constant, A_1^D, via the value-matching and smooth-pasting conditions between $V_0^D(P; C_0)$ and $V_2(P, C)$, i.e., $V_0^D(P_I^D; C_0) = V_2(P_I^D, C_0) - I$ and $\frac{dV_0^D}{dP}\Big|_{P=P_I^D} = \frac{\partial V_2}{\partial P}\Big|_{P=P_I^D, C=C_0}$, we obtain the following:

$$P_I^D = \left(\frac{\beta_1(\rho - \alpha)}{X(\beta_1 - 1)}\right)\left[\frac{C_0 X}{\rho + \lambda} + I\right] \tag{32}$$

$$A_1^D = \frac{(P_I^D)^{1-\beta_1} X}{\beta_1(\rho - \alpha)} \tag{33}$$

Upon solving for the base-case parameter values, i.e., with $\sigma = 0.20$ and $\lambda = 0.04$, we find $A_I^D = 2.25$ and $P_I^D = 110.60$ as opposed to $A_1 = 2.29$ and $P_I = 82.13$ when state 1 was available (see Figure 5). In effect, there is considerable option value to improving the performance of the LSA technology before deploying it. Quantitatively, it is worth:

$$\mathcal{F}(P_0) \quad = \quad \begin{cases} V_0(P_0; C_0) - V_0^D(P_0; C_0) & \text{if } P_0 < P_I \text{ and } P_0 < P_I^D \\ V_1(P_0, C_0) - I - V_0^D(P_0; C_0) & \text{if } P_0 \geq P_I \text{ and } P_0 < P_I^D \\ V_0(P_0; C_0) - V_2^D(P_0, C_0) + I & \text{if } P_0 < P_I \text{ and } P_0 \geq P_I^D \\ V_1(P_0, C_0) - V_2^D(P_0, C_0) & \text{if } P_0 \geq P_I \text{ and } P_0 \geq P_I^D \end{cases} \tag{34}$$

For $\sigma = 0.20$ and $\lambda = 0.04$, this option value to perform the intermediate R&D is worth \$73 million, which is 2.1% of the entire programme in state 0. Notably, with increasing uncertainty, the value of intermediate R&D decreases as the greater probability of higher electricity prices makes the existing LSA technology more attractive even without the enhancement provided by R&D from state 1 (see Figure 6). Indeed, it is only in a scenario with low electricity price volatility does intermediate LSA R&D add value by making the technology more cost effective. Furthermore, as λ increases *ceteris paribus*, i.e., as the LSA R&D programme becomes more effective, the option value of the intermediate R&D state becomes more valuable. For example, for $\lambda = 0.08$, it is worth 8.33% of the entire programme.

Varying estimates of the volatility of the long-term electricity price, σ, reveals that the R&D investment price threshold increases with uncertainty as the value of waiting also increases (see Figure 7). As indicated earlier, since greater volatility diminishes the value of the intermediate R&D from state 1, the investment threshold price, P_I, and direct deployment threshold price, P_I^D, converge. Similarly, the LSA deployment price-cost ratio increases as the volatility increases (see Figure 8). However, it is interesting to note that for $\sigma = 0.40$, although the ratio

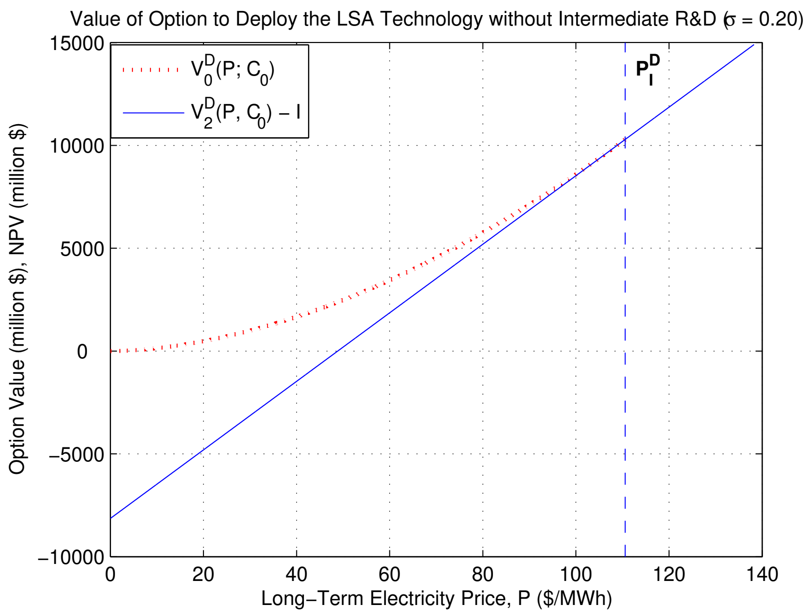

Figure 5: Value of option to deploy the LSA technology without intermediate R&D ($\sigma = 0.20$).

$\frac{P_I}{C_0}$ is quite close to p^*, instantaneous deployment of the LSA technology still does not occur. Hence, for reasonable values of σ, it is always optimal to perform intermediate R&D.

3.1.2 Technical Uncertainty in LSA R&D

Here, we allow for uncertainty in the R&D of the LSA technology, i.e., the decrease in its operating cost is not deterministic after state 1 is entered. We use a representative value of $\sigma_C = 0.10$ to capture this technical risk. Referring to our base-case parameter values of $\sigma = 0.20$ and $\lambda = 0.04$, we find that the inclusion of technical uncertainty increases the option value of the entire LSA programme to \$3.58 billion at $P_0 = 60$ from \$3.52 billion and decreases the long-term electricity price threshold, P_I, at which to initiate R&D (see Figure 9). Indeed, we find that $P_I = 75.21$ as opposed to \$82.13/MWh as in the case with $\sigma_C = 0$. The reason for this is that the value of the option to deploy the R&D-enhanced LSA technology from state

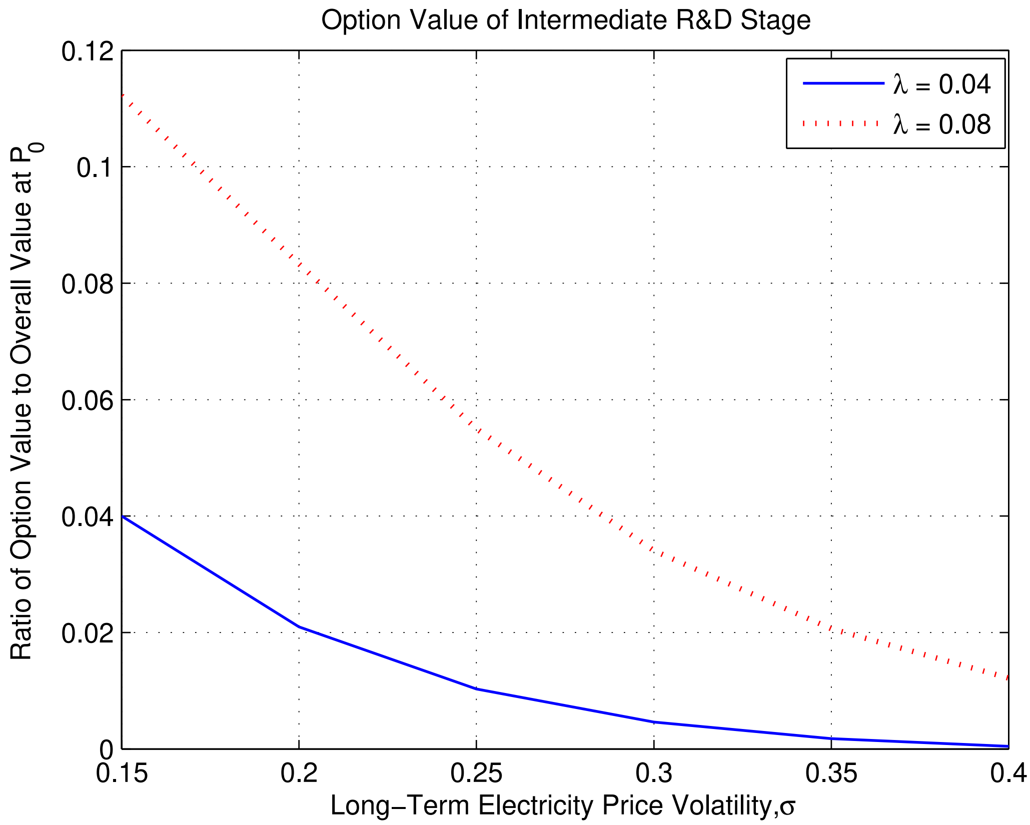

Figure 6: Option value of intermediate R&D stage without an existing RE technology. Faster learning to reduce the LSA technology's operating cost makes the R&D step more valuable. The R&D option value decreases with uncertainty since the probability of high long-term electricity prices makes even the non-R&D enhanced LSA technology increase in option value.

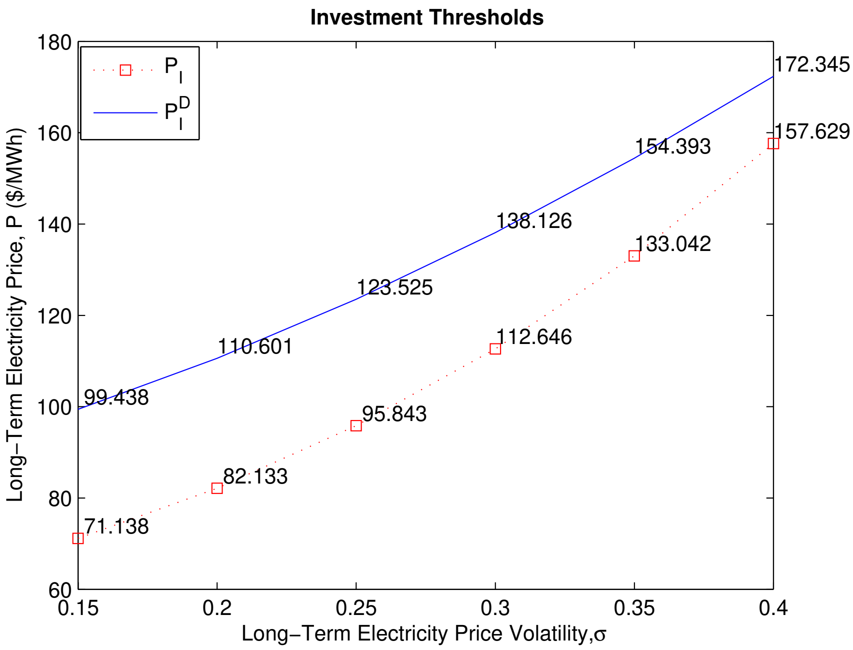

Figure 7: Investment thresholds as functions of long-term electricity price uncertainty. The blue curve indicates when to build a 10 TWh per annum LSA technology plant when there is no intermediate R&D step. This occurs at high electricity prices, and the trigger level increases with uncertainty. If such an R&D step is available, then the trigger is lower due to the improved possibility of managing deployment timing and is shown in red.

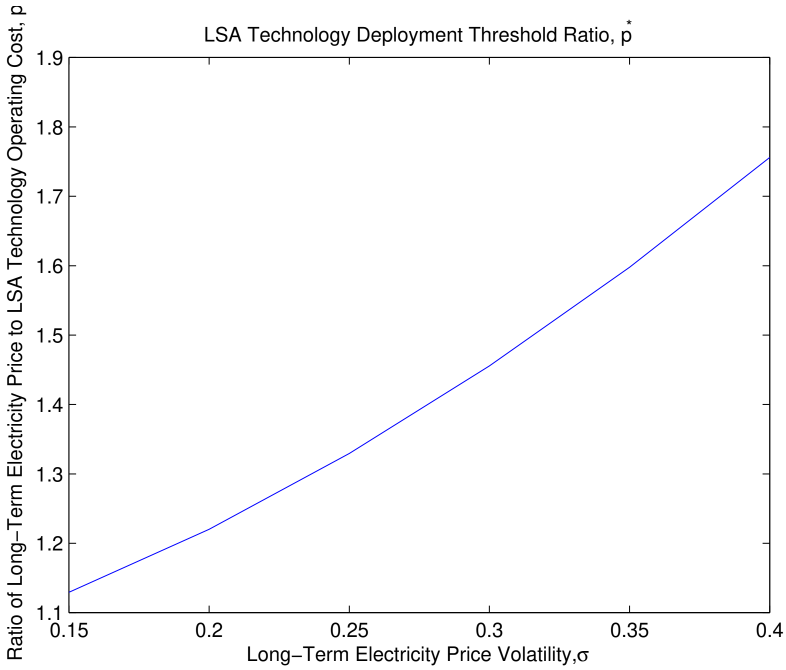

Figure 8: Deployment threshold ratio indicates when to leave the LSA R&D programme and deploy a 10 TWh per annum LSA technology plant. This decision depends on the ratio $p \equiv P/C$, where P follows a GBM process and C is reduced gradually in the R&D state. The graph shows the familiar result that the value of waiting increases with uncertainty.

1 increases with technical uncertainty as discretion over timing implies that it is possible to take advantage of rapid decreases in the operating cost without being adversely affected by unexpected increases. In effect, the government has a greater option value in state 0 without having to worry about technical risk until state 1. Thus, it is easier for it to initiate the LSA R&D programme. On ther other hand, in Figure 10, it is optimal to wait *longer* than in the case without technical uncertainty, i.e., until $p^* = 1.27$, before deploying the R&D-enhanced LSA technology as greater uncertainty also increases the value of waiting and, therefore, the opportunity cost of killing the waiting option in state 1.

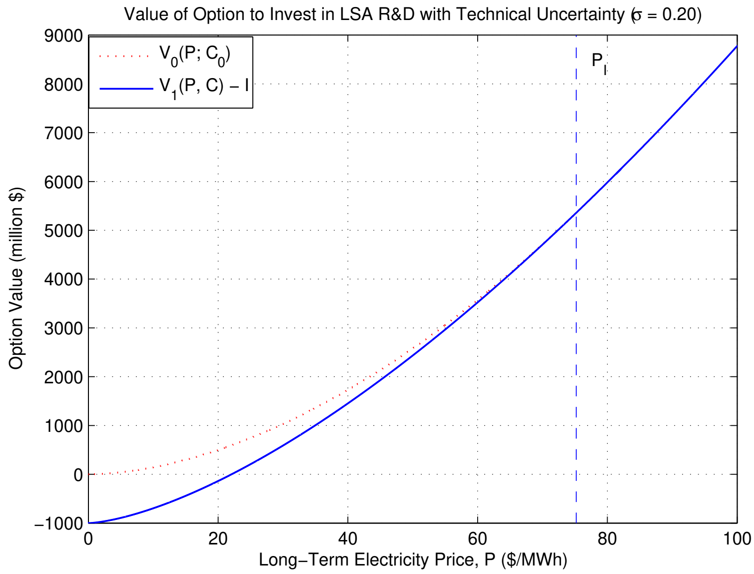

Figure 9: Value of option to invest in LSA R&D without an existing RE technology under technical uncertainty ($\sigma = 0.20$, $\sigma_C = 0.10$).

Examining the value of the intermediate R&D for the LSA technology under technical uncertainty, we find that it is greater than in the case with $\sigma_C = 0$ (see Figure 11). Intuitively, this result arises for two reasons: first, the investment threshold for initiating the R&D programme

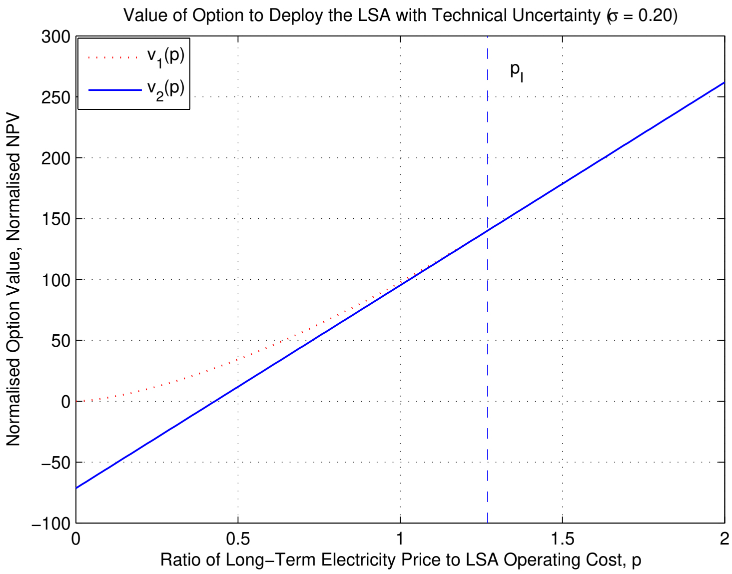

Figure 10: Value of option to deploy the LSA technology without an existing RE technology from an R&D state under technical uncertainty ($\sigma = 0.20$, $\sigma_C = 0.10$).

is lower, thereby implying that state 1 is entered sooner than in the example considered in Section 3.1.1; second, more time is spent in the intermediate R&D stage to ensure that deployment is done optimally to mitigate the effects of technical uncertainty. At the same time, technical uncertainty does not change the option value of direct deployment, $V_0^D(P; C_0)$, because the expected NPV from direct deployment, $V_2^D(P, C) - I$, is not affected by technical uncertainty, i.e., the average rate of decrease in the LSA technology's operating cost is still the same. Hence, the option value of the intermediate R&D stage as captured by $\mathcal{F}(P_0)$ in Equation 34 increases.

The other qualitative results of Section 3.1.1 also hold, viz., the investment thresholds all increase as parameter estimates of the long-term electricity price's volatility are increased. Again, P_I is lower here as the option value of the LSA R&D programme in state 0 is higher

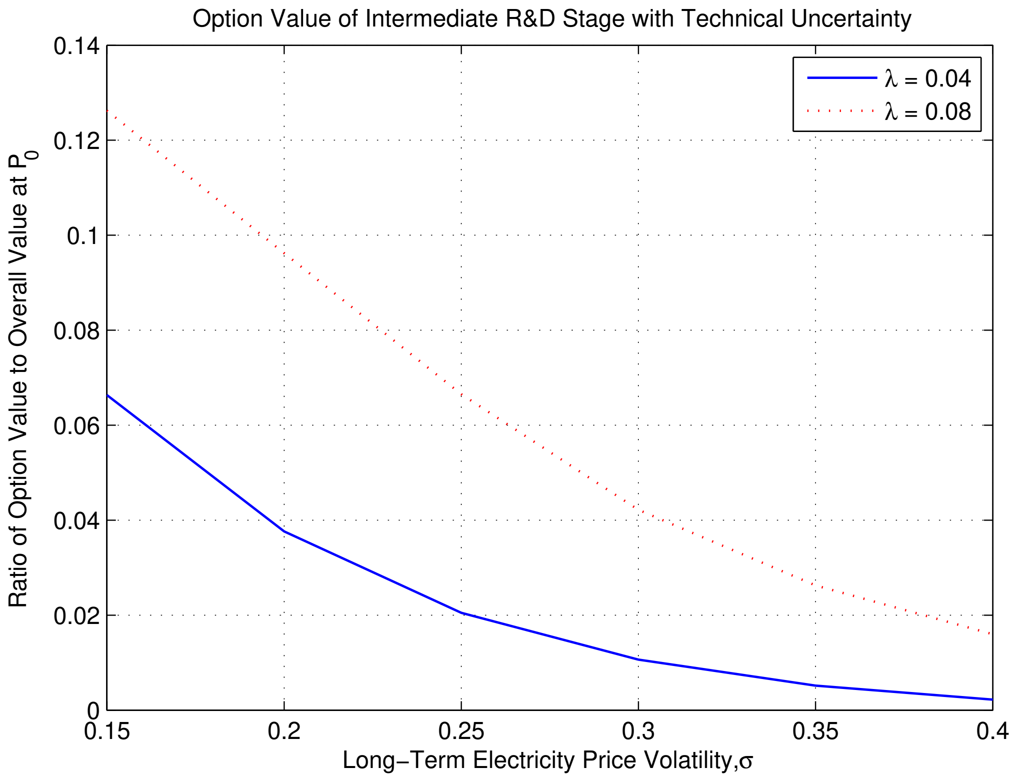

Figure 11: Option value of intermediate R&D stage without an existing RE technology under technical uncertainty. Relative to the case with $\sigma_C = 0$, the case here with $\sigma_C = 0.10$ implies that greater value is placed on the intermediate R&D stage. The other attributes of the option value are similar to those in the case without technical uncertainty.

due to a higher expected value in moving to state 1 without facing any technical risk until the R&D programme starts. Conversely, p^* is higher because technical uncertainty implies that more time must be spent in the intermediate R&D state to offset the effects of any adverse movements in the LSA technology's operating cost.

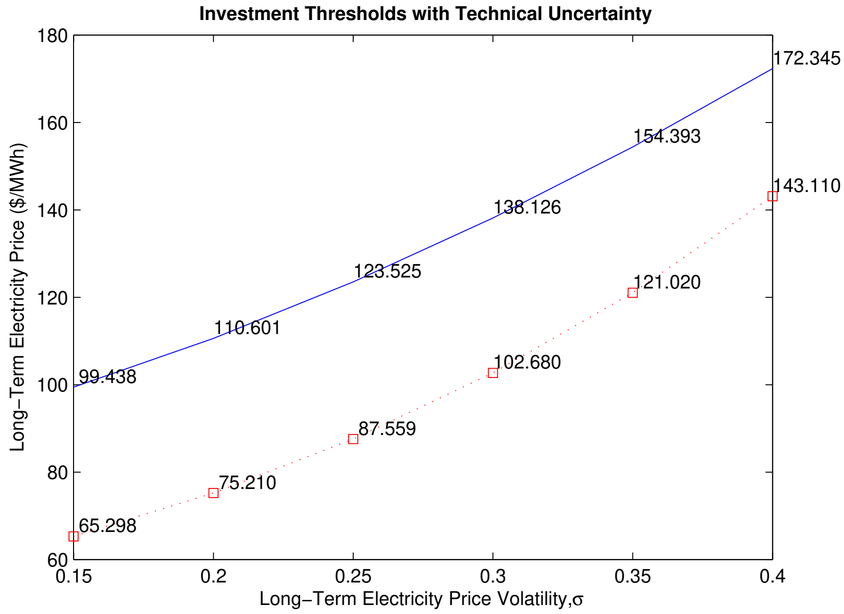

Figure 12: Investment thresholds as functions of long-term electricity price uncertainty under technical uncertainty. The general trends are the same as in the case without technical uncertainty except that the investment threshold for the LSA R&D programme is lower.

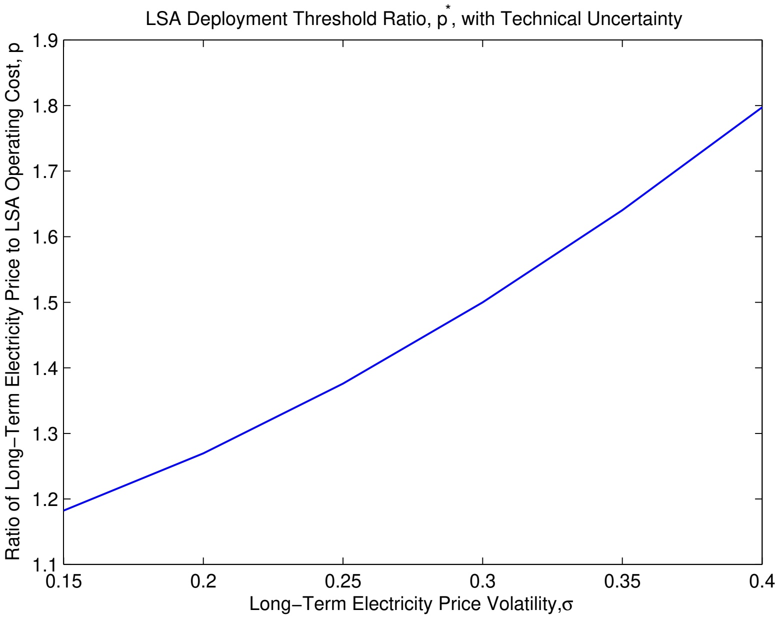

Figure 13: The deployment threshold ratio under technical uncertainty where the value of waiting has increased. As before, the value of waiting also increases with uncertainty.

3.2 Numerical Example 2: Existing Renewable Energy Technology without Switching Option to the LSA Technology

Assuming the same parameter values as in Section 3.1 for the LSA technology and using $I^E =$ \$200 million, $X^E = 5$ TWh,[6] and $C^E =$ \$25/MWh, we illustrate the intuition for R&D when there exists an available RE technology. We keep $\sigma_C = 0$ here because numerical examples with technical uncertainty do not reveal any insights additional to those discussed in Section 3.1.2. However, we will comment on how the numerical results are affected if $\sigma_C = 0.10$ is used. For $\sigma = 0.20$, we find that $A_1^{ex} > A_1$, which implies that the waiting region is dichotomous around the indifference point, $\tilde{P}^{ex} = 64.10$, i.e., the government's optimal policy is to deploy the existing RE when the long-term electricity price is in the range $[P_E^{ex}, P_F^{ex}] = [39.39, 52.05]$ and to start the LSA R&D programme if the long-term electricity price is greater than $P_G^{ex} = 87.80$ (see Figure 14).[7] For all other prices, it is optimal to wait. Note that the threshold for initiating the LSA R&D programme is greater than what it was without the availability of the existing RE technology, $P_I = 82.13$, as the presence of an alternative project reduces the attraction of the LSA technology.

Even though the R&D investment threshold has increased, immediate deployment does not take place once the R&D programme is commenced because the threshold ratio is still less than p^*, i.e., $\frac{P_G^{ex}}{C_0} = 0.88 < p^*$. The value of the entire investment opportunity at the initial long-term

[6] We assume that $X^E < X$ because the capacity of the existing RE technology is limited either by the number of desirable sites (e.g., for solar panels or windmills) or the waste-disposal issues (e.g., for conventional nuclear power plants).

[7] By comparison, for $\sigma_C = 0.10$, we have $\tilde{P}^{ex} = 60.93$, $[P_E^{ex}, P_F^{ex}] = [39.39, 50.24]$, and $P_G^{ex} = 80.46$. Intuitively, greater technical uncertainty facilitates investment in R&D for the LSA technology and reduces the immediate deployment region for the existing RE technology due to the greater potential upside of the LSA project.

electricity price, $P_0 = 60$, is worth $V_0^{ex}(P_0; C_0, C^E) = F^{ex} P_0^{\beta_1} + G^{ex} P_0^{\beta_2} = \$3.61$ billion, which is \$90 million higher than the value in Section 3.1.1 (an increase of 2.56%).[8] If the waiting region is ignored and the existing RE technology is deployed immediately as recommended by Dixit [1993], then the government would lose \$62 million from acting too quickly, which is 1.75% of the expected NPV. In effect, by using the approach of Décamps et al. [2006], we show how the government planner is able to optimise investment in the two mutually exclusive projects for all long-term electricity prices.

At higher levels of estimated volatility, the viability of the existing RE technology as an alternative to the LSA R&D programme gradually diminishes (see Figure 15). Here, as σ increases, the region for immediate deployment of the RE technology shrinks as there exists greater probability of high electricity prices in the future. Furthermore, the indifference point between the two projects, $\tilde{P}^{ex}$, decreases as the LSA R&D programme starts to look more promising. Indeed, for high enough levels of volatility, the option to deploy the existing RE technology may be disregarded, which then reduces the problem to a simple real options one with the same investment threshold as in Section 3.1.1.

Again, instead of managing the LSA project in a staged manner, the government may choose to pursue a more direct strategy in which state 1 is skipped. In terms of Figure 2, the government may transition from state 0 either to state E or directly to state 2, i.e., deploying the existing LSA technology at its initial operating cost with ongoing R&D to come later. In this case, the value of the entire programme in state 0 is similar to that in Equation 21:

$$V_0^{D,ex}(P; C_0, C^E) = \begin{cases} A_1^{ex} P^{\beta_1} & \text{if } 0 \leq P < P_E^{ex} \\ F^{D,ex} P^{\beta_1} + G^{D,ex} P^{\beta_2} & \text{if } P_F^{D,ex} < P < P_G^{D,ex} \end{cases} \tag{35}$$

[8] With technical uncertainty, this option value increases to \$3.64 billion.

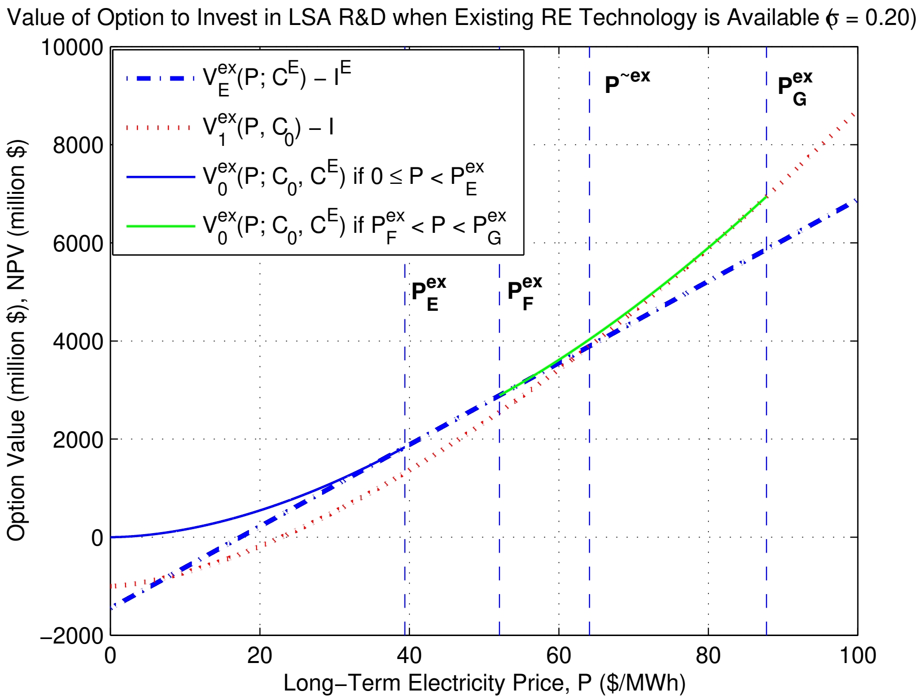

Figure 14: Value of option to invest in LSA R&D when an existing RE technology is available ($\sigma = 0.20$). The broken blue line is the expected NPV of the (small) existing RE technology, while the dotted red curve is the option value to deploy the LSA technology from an intermediate R&D state. The solid blue and green curves are the option values for state 0 when neither project has yet been selected.

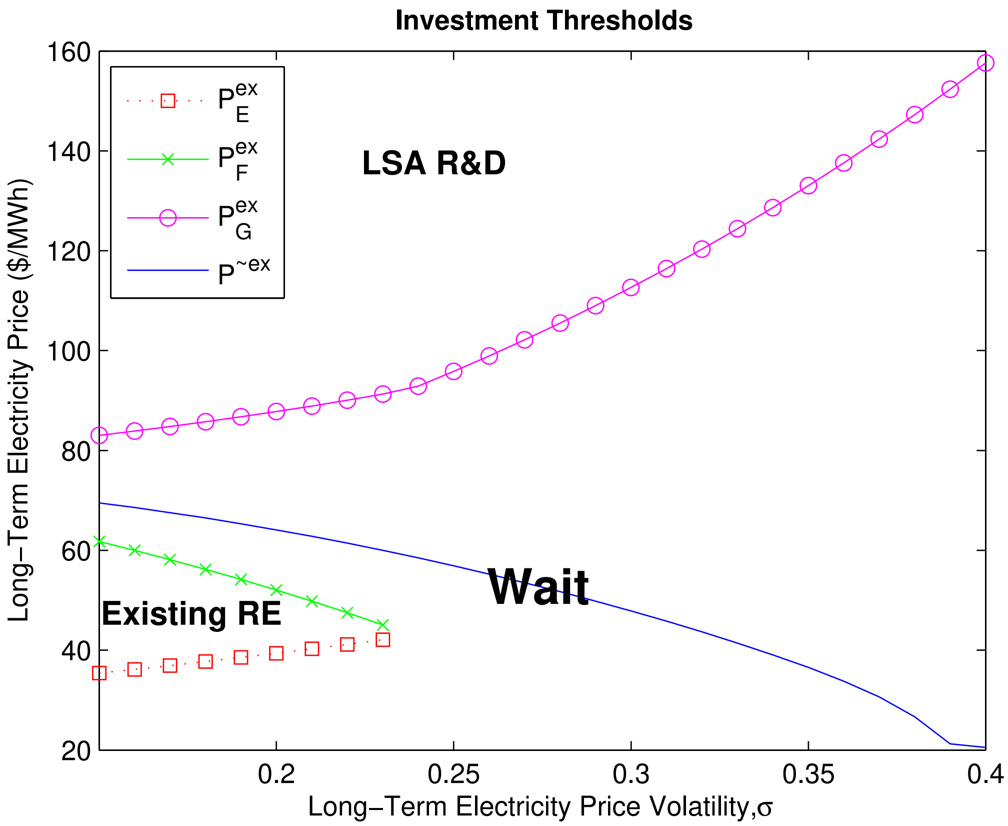

Figure 15: Investment thresholds when an existing RE technology is available. For low levels of uncertainty, the existing RE technology should be selected at moderate electricity price levels, whereas the LSA R&D project should be launched at higher electricity price levels. When uncertainty increases, the waiting region increases until the existing RE technology disappears as a candidate solution.

Now, the coefficients, $F^{D,ex}$ and $G^{D,ex}$, together with the threshold prices for the indifference zone, $P_F^{D,ex}$ and $P_G^{D,ex}$, must be found numerically via value-matching and smooth-pasting conditions analogous to those in Equations 27 through 30. The only difference is that the second set of value-matching and smooth-pasting conditions are defined with respect to a contact point on the expected NPV curve in state 2, $V_2(P, C) - I$. In Figure 16, we plot the option value and expected NPV curves for the direct investment strategy. We note that due to the lack of intermediate R&D opportunities with the LSA technology, the second waiting region widens. Indeed, since the LSA project's timing cannot be managed as precisely now, deployment of it is less likely to be precipitated, a fact that is also captured by the effect of varying the volatility parameter on the investment thresholds (see Figure 17). However, it is still the case that it dominates the existing RE technology option for $\sigma > 0.24$.

As we did in Section 3.1.1, we now also illustrate the option value of the intermediate R&D state for various levels of σ and λ by using an analogue of Equation 34. First, fixing $\lambda = 0.04$ and $\sigma = 0.20$, we find that the option value of this state is less than 1% of the overall project's value. However, it is zero in the range $0.15 \leq \sigma \leq 0.16$, increasing in the range $0.16 < \sigma < 0.25$, and decreasing for $\sigma \geq 0.25$ (see Figure 18). The first component can be explained by the fact that both strategies recommend immediate deployment of the existing RE for low levels of volatility as there is not much value to waiting for the LSA technology to become attractive. We use the same intuition from Section 3.1.1 to explain why the option value decreases for high levels of σ: the prospect of sustained price increases makes disregarding the existing RE technology and focusing on the LSA technology attractive. However, the value of the intermediate R&D state decreases with σ in this region as greater electricity price uncertainty makes even the existing LSA generation capability competitive. By contrast, in the intermediate range of σ, there is

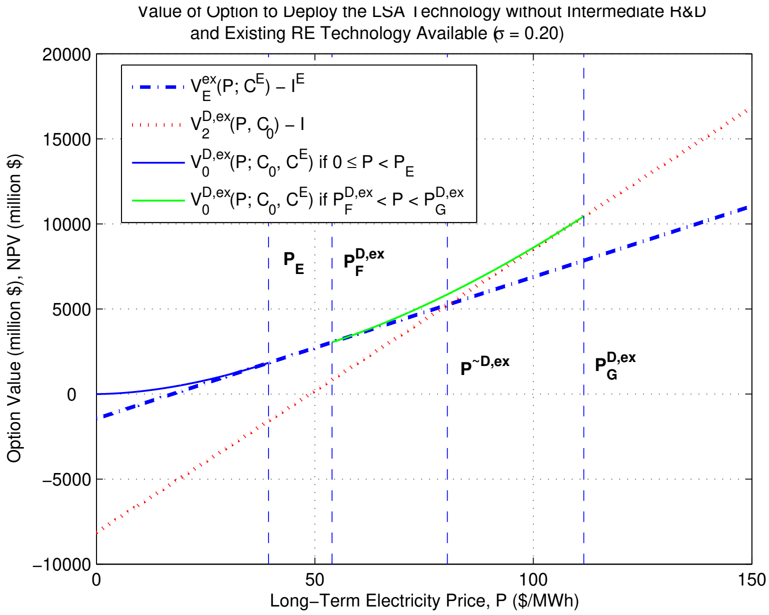

Figure 16: Value of option to deploy the LSA technology without intermediate R&D when an existing RE technology is available ($\sigma = 0.20$). The broken blue line is the expected NPV of the (small) existing RE technology, while the dotted red line is the expected NPV of the deployable LSA technology. The solid blue and green curves are the option values for state 0 when neither project has yet been selected.

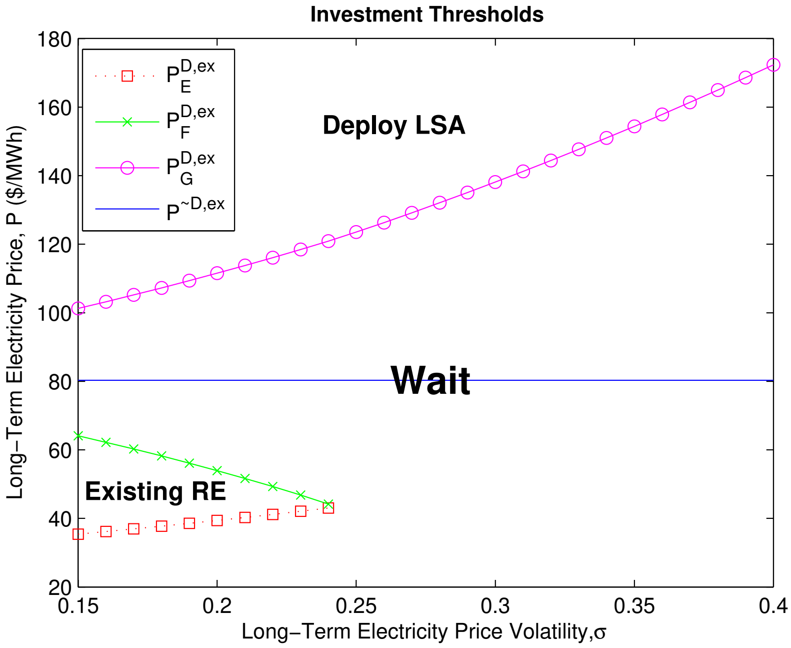

Figure 17: Investment thresholds with direct deployment of the LSA technoogy when an existing RE technology is available. The existing RE project is chosen only for small electricity price uncertainty levels and low levels of long-term electricity prices. The waiting region increases with uncertainty, and the LSA technology is deployed at high long-term electricity prices.

not enough information to make a decision between existing RE deployment or pursuing LSA generation at the initial price, P_0. Consequently, the resulting indifference zone also widens with more uncertainty starting from a low level of σ (until the existing RE technology is no longer considered). The option value increases in this range because the intermediate R&D programme provides a way to time the deployment of the new technology. Finally, note that the option value of the intermediate R&D is much higher (over 8% of the total project value for $\sigma = 0.20$) when λ is increased to 0.08. Due to the greater effectiveness of the LSA R&D programme, there is more value to the intermediate state. And, precisely due to its attraction, the LSA R&D programme is started more quickly, which then causes the option value to decrease with σ again as there is little competition with the existing RE technology.[9]

4 Conclusions

Given the concern over global warming, the development of alternative energy technologies with lower rates of carbon emissions is gaining prominence. Within the domain of existing RE technologies, biofuels, fuel cells, hydroelectric power, solar-based technologies, wave generation, and windmills have all demonstrated various levels of effectiveness and gained some measure of public support in contributing to the world's energy supply. As cap-and-trade systems for carbon emissions gain popularity, these aforementioned technologies will become only more competitive with traditional combustion technologies using fossil fuels. On the other hand, the allure of nuclear power technology has ebbed and flowed due to public concerns about the safety of reactors, processing of waste material, and the potential weaponisation of programmes. In addition, even if most of the world's energy supply were to come from nuclear power plants,

[9]These results also hold for the case in which C_t is stochastic.

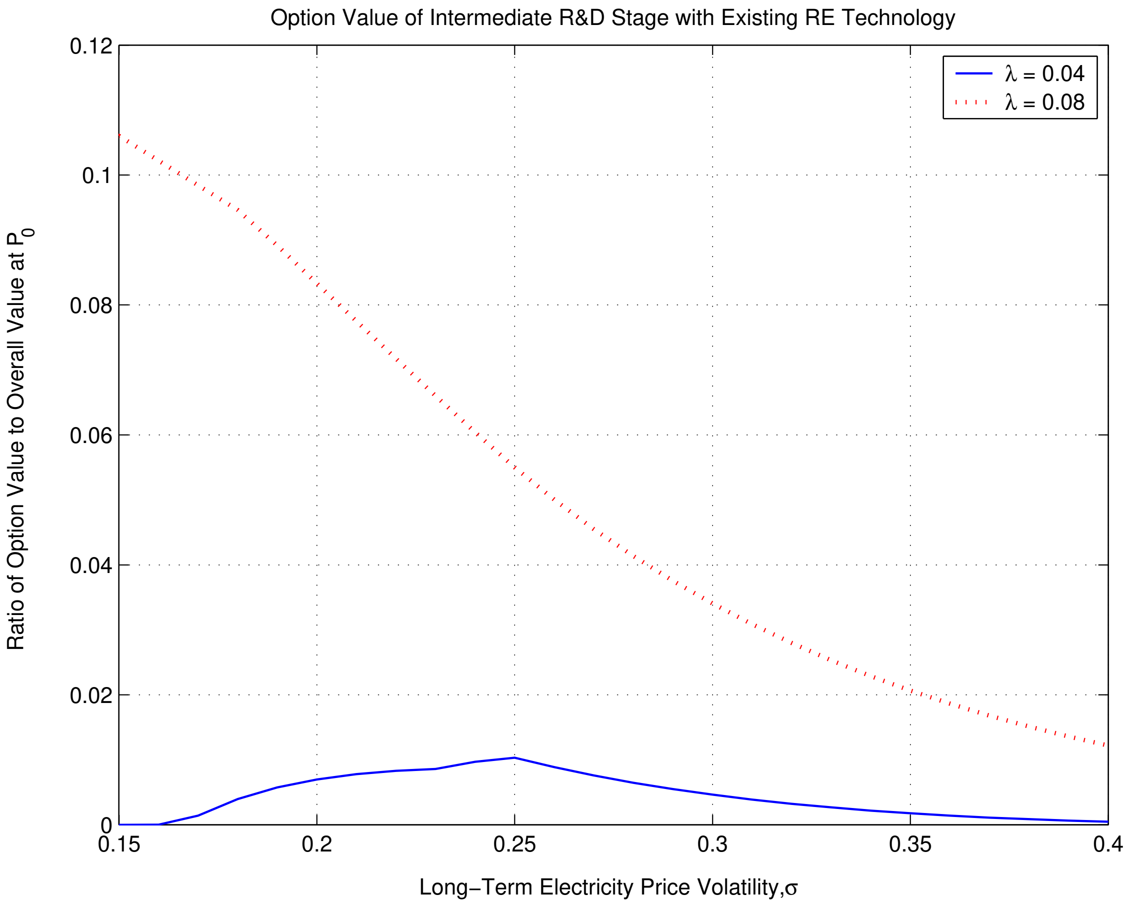

Figure 18: Option value of intermediate R&D stage with an existing RE technology. Faster learning to reduce the LSA technology's operating cost makes the intermediate R&D stage more valuable. For high learning rates, the intermediate R&D option value decreases with uncertainty since the probability of higher long-term electricity prices means that even the existing LSA technology dominates the smaller RE project. By contrast, for low learning rates and an intermediate level of uncertainty, the intermediate R&D option value increases with uncertainty since R&D provides a way to optimise the timing of the deployment of the LSA technology.

the known supply of uranium used in traditional reactors would not be enough to sustain the planet's demand for energy beyond a few decades. Therefore, a prudent policy for governments is to continue investing in existing RE technologies and energy efficiency measures along with funding R&D for promising new technologies possibly based on nuclear power.

In this paper, we examine how a staged R&D programme for an LSA technology could proceed under uncertainty. By taking the real options approach, we find that the option to develop such a technology would have considerable value. In particular, the value of the intermediate R&D state is worth more if the effectiveness of the R&D programme increases, while it decreases with the volatility of the long-term electricity price. The latter, seemingly counter-intuitive, result holds because it is only in a scenario with low price volatility that the intermediate R&D stage of the programme makes the LSA technology competitive. Otherwise, a high level of volatility makes even the rudimentary LSA technology attractive since there is a high probability of sustained electricity price increases. With the addition of an existing RE technology, we have the problem of mutually exclusive investment in alternative staged projects under uncertainty. We find in this case that the addition of an existing RE technology increases the value of the overall programme from the perspective of the government. However, it delays the potential initiation of the LSA R&D programme as the existing RE technology is more beneficial for a moderate range of electricity prices. Furthermore, the value of the intermediate R&D stage increases for an intermediate range of price volatility as such activity provides additional information about the relative benefit of the LSA versus the existing RE technology. For high volatility levels, the existing RE technology is not considered at all, which causes the value of the intermediate R&D stage to decrease as before. Hence, governments planning to initiate similar R&D programmes would be prudent not to neglect the effects of their interactions with existing RE technologies and should ideally try to optimise their R&D portfolios jointly.

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APPENDIX: Existing Renewable Energy Technology with Switching Option to the LSA Technology

Here, the setup is the same as in Section 2.2 except that once state E is entered, it is possible for a subsequent transition to state 1 by paying the full LSA R&D programme start-up and annual expense cost of I (see Figure 19). Therefore, while the value functions in states 1 and 2 are still defined by Equations 2 and 1, respectively, those in states 0 and E are as follows:

$$V_0^{sw}(P; C_0, C^E) = \begin{cases} A_1^{sw} P^{\beta_1} & \text{if } 0 \leq P < P_E^{sw} \\ F^{sw} P^{\beta_1} + G^{sw} P^{\beta_2} & \text{if } P_F^{sw} < P < P_G^{sw} \end{cases} \quad \text{(A-1)}$$

$$V_E^{sw}(P; C_0, C^E) = X^E \left(\frac{P}{\rho - \alpha} - \frac{C^E}{\rho} \right) + B^{sw} P^{\beta_1} \text{ for } 0 \leq P < P_{E1}^{sw} \quad \text{(A-2)}$$

Again, if $A_1 > A_1^{sw}$, then the approach of Section 2.1 may be used, i.e., there is no need to consider the existing RE technology. However, for small values of σ, it may be relevant, in

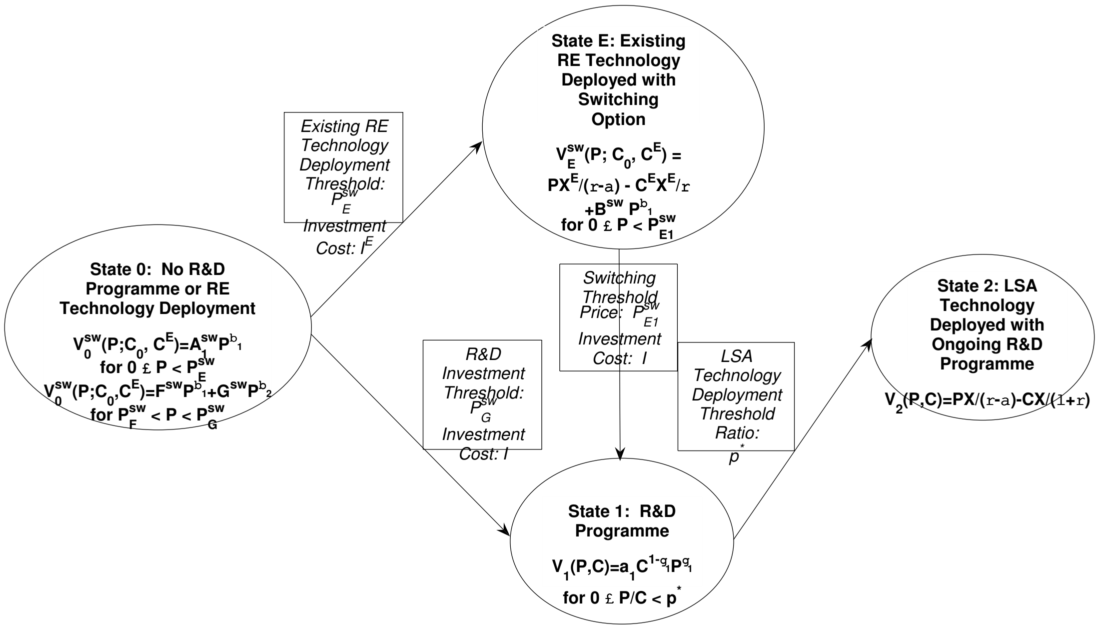

Figure 19: State transition diagram with a mutually exclusive existing RE technology option and a possibility to switch to the LSA technology. The government may choose either to deploy an existing RE technology or to start a major LSA R&D project. If the former avenue is selected, then the government may subsequently switch to the LSA R&D phase, from where it is then possible to deploy the LSA technology.

which case the last term in Equation A-2 is the value of the option to switch to state 1 by paying the full investment cost of the LSA R&D programme. The endogenous constant, B^{sw}, and the switching threshold price, P_{E1}^{sw}, are found numerically via the following value-matching and smooth-pasting conditions:

$$\begin{aligned} V_E^{sw}(P_{E1}^{sw};C_0,C^E) - I^E &= V_1(P_{E1}^{sw},C_0) - I - I^E \\ \Rightarrow X^E\left(\frac{P_{E1}^{sw}}{\rho-\alpha} - \frac{C^E}{\rho}\right) + B^{sw}(P_{E1}^{sw})^{\beta_1} - I^E &= a_1(C_0)^{1-\gamma_1}(P_{E1}^{sw})^{\gamma_1} - I - I^E \end{aligned} \tag{A-3}$$

$$\begin{aligned} \left.\frac{dV_E^{sw}}{dP}\right|_{P=P_{E1}^{sw}} &= \left.\frac{\partial V_1}{\partial P}\right|_{P=P_{E1}^{sw},C=C_0} \\ \Rightarrow \quad \frac{X^E}{\rho-\alpha} + \beta_1 B^{sw}(P_{E1}^{sw})^{\beta_1-1} &= \gamma_1 a_1(C_0)^{1-\gamma_1}(P_{E1}^{sw})^{\gamma_1-1} \end{aligned} \tag{A-4}$$

The endogenous constant, A_1^{sw}, and the existing RE technology deployment threshold price, P_E^{sw}, are found by value-matching and smooth-pasting conditions involving $V_0^{sw}(P;C_0,C^E)$ and $V_E^{sw}(P;C_0,C^E)$ as follows:[10]

$$\begin{aligned} V_0^{sw}(P_E^{sw};C_0,C^E) &= V_E^{sw}(P_E^{sw};C_0,C^E) - I^E \\ \Rightarrow \quad A_1^{sw}(P_E^{sw})^{\beta_1} &= X^E\left(\frac{P_E^{sw}}{\rho-\alpha} - \frac{C^E}{\rho}\right) + B^{sw}(P_E^{sw})^{\beta_1} - I^E \end{aligned} \tag{A-5}$$

$$\begin{aligned} \left.\frac{dV_0^{sw}}{dP}\right|_{P=P_E^{sw}} &= \left.\frac{dV_E^{sw}}{dP}\right|_{P=P_E^{sw}} \\ \Rightarrow \quad \beta_1 A_1^{sw}(P_E^{sw})^{\beta_1-1} &= \frac{X^E}{\rho-\alpha} + \beta_1 B^{sw}(P_E^{sw})^{\beta_1-1} \end{aligned} \tag{A-6}$$

Solving Equations A-5 and A-6 simultaneously, we obtain the following closed-form solutions:

$$P_E^{sw} = \left(\frac{\beta_1(\rho-\alpha)}{X^E(\beta_1-1)}\right)\left[\frac{C^E X^E}{\rho} + I^E\right] \tag{A-7}$$

[10] We assume here that investment is sequential, i.e., $P_E^{sw} < P_{E1}^{sw}$. Otherwise, it is optimal to invest directly in the LSA R&D programme at a cost of $(I^E + I)$.

$$A_1^{sw} = B^{sw} + \frac{(P_E^{sw})^{1-\beta_1} X^E}{\beta_1(\rho - \alpha)} \tag{A-8}$$

In other words, $P_E^{sw} = P_E^{ex}$ and $A_1^{sw} = B^{sw} + A_1^{ex}$.

Finally, the two endogenous constants, F^{sw} and G^{sw}, and threshold prices, P_F^{sw} and P_G^{sw}, are determined by the following value-matching and smooth-pasting conditions between $V_0^{sw}(P; C_0, C^E)$ and $V_E^{sw}(P; C_0, C^E)$ as well as between $V_0^{sw}(P; C_0, C^E)$ and $V_1(P, C_0)$:

$$\begin{aligned} V_0^{sw}(P_F^{sw}; C_0, C^E) &= V_E^{sw}(P_F^{sw}; C_0, C^E) - I^E \\ \Rightarrow F^{sw}(P_F^{sw})^{\beta_1} + G^{sw}(P_F^{sw})^{\beta_2} &= X^E \left(\frac{P_F^{sw}}{\rho - \alpha} - \frac{C^E}{\rho} \right) + B^{sw}(P_F^{sw})^{\beta_1} - I^E \end{aligned} \tag{A-9}$$

$$\begin{aligned} \left.\frac{dV_0^{sw}}{dP}\right|_{P=P_F^{sw}} &= \left.\frac{dV_E^{sw}}{dP}\right|_{P=P_F^{sw}} \\ \Rightarrow \quad \beta_1 F^{sw}(P_F^{sw})^{\beta_1-1} + \beta_2 G^{sw}(P_F^{sw})^{\beta_2-1} &= \frac{X^E}{\rho-\alpha} + \beta_1 B^{sw}(P_F^{sw})^{\beta_1-1} \end{aligned} \tag{A-10}$$

$$\begin{aligned} V_0^{sw}(P_G^{sw}; C_0, C^E) &= V_1(P_G^{sw}, C_0) - I \\ \Rightarrow F^{sw}(P_G^{sw})^{\beta_1} + G^{sw}(P_G^{sw})^{\beta_2} &= a_1(C_0)^{1-\gamma_1}(P_G^{sw})^{\gamma_1} - I \end{aligned} \tag{A-11}$$

$$\begin{aligned} \left.\frac{dV_0^{sw}}{dP}\right|_{P=P_G^{sw}} &= \left.\frac{\partial V_1}{\partial P}\right|_{P=P_G^{sw}, C=C_0} \\ \Rightarrow \beta_1 F^{sw}(P_G^{sw})^{\beta_1-1} + \beta_2 G^{sw}(P_G^{sw})^{\beta_2-1} &= \gamma_1 a_1 (C_0)^{1-\gamma_1}(P_G^{sw})^{\gamma_1-1} \end{aligned} \tag{A-12}$$

For completeness, we perform a numerical example with the same data as in Section 3.2 and without technical uncertainty. We consider the case in which either deployment of the existing RE technology (with a subsequent option to deploy the LSA technology directly) or direct deployment of the LSA technology is possible. In terms of Figure 19, we suppose that the arrow from state E leads to state 2, i.e., there is no intermediate R&D stage for the LSA technology. At the initial long-term electricity price of \$60/MWh, we obtain that it is optimal to deploy the existing RE technology and wait for the opportunity to switch to deployment of the LSA technology when the long-term electricity price reaches \$187.25/MWh. The expected NPV of this alternative energy programme with the switching option is \$4.68 billion, which is more than a \$1 billion increase relative to the example in Section 3.2 with direct deployment of the LSA technology.

Intuitively, the subsequent option to switch to the LSA technology (even without the intermediate R&D stage) facilitates the deployment of the existing RE technology as this decision is now reversible. Indeed, until the electricity price reaches suitably high levels for deployment of the LSA technology to become viable, the government planner is able to benefit from the cost savings of using the existing RE technology. The option value and expected NPV curves in Figure 20 indicate how the situation changes from that illustrated in Figure 16 without the switching option: the region for immediate investment in the existing RE technology widens, the indifference zone between the two alternative energy projects occurs at a much higher electricity price and is narrower, and, finally, the threshold for switching to the LSA technology from the existing RE technology is much higher. In particular, $P_E^{sw} = 39.39$ as before, but $[P_F^{sw}, P_G^{sw}] = [149.37, 157.79]$ and $P_{E1}^{sw} = 187.25$. Figure 21 illustrates how these thresholds behave with varying estimates of the long-term electricity price volatility.

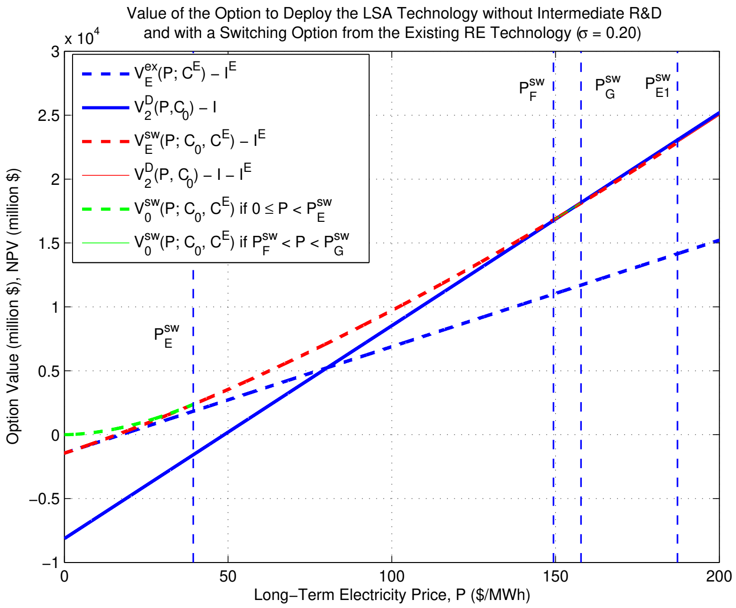

Figure 20: Value of option to deploy the LSA technology without intermediate R&D when an existing RE technology is available with a switching option ($\sigma = 0.20$). The broken blue line is the expected NPV of the (small) existing RE technology, while the solid blue line is the expected NPV of the deployable LSA technology. Representing the value of the option to switch to the LSA technology after the existing RE technology has been selected is the broken red curve, while the solid red line is the expected NPV of the deployed LSA technology after the existing RE technology was already used. Finally, the broken green curve is the value of the option to invest in the existing RE technology with a subsequent option to switch to the LSA technology, and the solid green curve is the value of the option to invest in either the existing RE or the LSA technology.

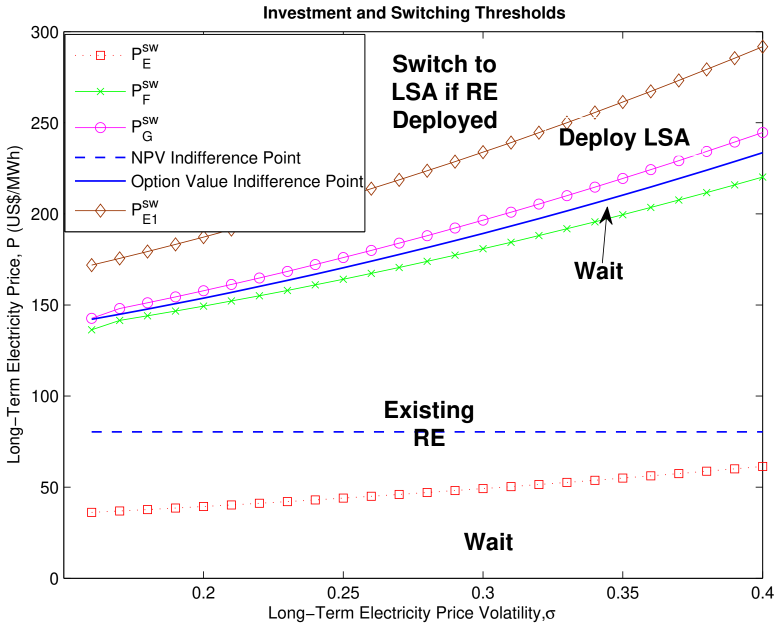

Figure 21: Investment thresholds with direct deployment of the LSA technology when an existing RE technology is available with a switching option. Unlike the case without the switching option, the existing RE project is always selected at moderate levels of the long-term electricity price. The waiting region increases with uncertainty, and the LSA technology is deployed at high long-term electricity prices as before, but these regions are relatively narrower than before. Finally, if the existing RE technology is deployed, then the switch to the LSA technology is made at even higher electricity price levels than for those at which the LSA technology would have been deployed.