Energy Policy 137 (2020) 111152

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Sequential investment in renewable energy technologies under policy uncertainty

Lars Hegnes Sendstad [a,*], Michail Chronopoulos [b,c]

[a] Department of Industrial Economics & Technology Management, Norwegian University of Science & Technology, 7491 Trondheim, Norway
[b] City, University of London, Cass Business School, EC1Y 8TZ London, UK
[c] Norwegian School of Economics, Department of Business & Management Science, 5045 Bergen, Norway

ARTICLE INFO

Keywords:
Investment analysis
Real options
Renewable energy
Policy uncertainty

ABSTRACT

Although innovation and support schemes are among the main forces that drive investment in renewable energy (RE) technologies, both involve considerable uncertainty. We develop a real options framework to analyse the impact of technological, policy and electricity price uncertainty on the decision to invest sequentially in successively improved versions of a RE technology. Technological uncertainty is reflected in the random arrival of innovations, and policy uncertainty in the likely provision or retraction of a subsidy that takes the form of a fixed premium on top of the electricity price. We show that greater likelihood of subsidy retraction (provision) lowers (raises) the incentive to invest, and, by comparing a stepwise to a lumpy investment strategy, we show how an embedded option to adopt an improved technology version mitigates the impact of subsidy retraction on investment timing. Specifically, we show how stepwise investment facilitates earlier technology adoption compared to lumpy investment, and that, under stepwise investment, technological uncertainty accelerates technology adoption, thus further offsetting the incentive to delay investment in the light of subsidy retraction.

1. Introduction

Investment in renewable energy (RE) technologies is considerably risky, since it is typically made in the light of various interacting uncertainties, including economic, technological and policy uncertainty. Indeed, not only innovations arrive at random points in time, but schemes that support their adoption are revised frequently, thus increasing the likelihood of unreliable long-term investment signals. Consequently, within an environment of increasing economic uncertainty, the challenge of timely technology adoption becomes rather formidable and not only threatens the viability of private firms, but also impacts upon the possible effectiveness of achieving in a timely way the new investment targets set by policy. For example, subsidies for RE technologies fuelled a boom in solar panel manufacturing in China and allowed solar production capacity to increase significantly. Combined with the decrease in the price of silicon, the main component of traditional solar panels, this reduced the competitive advantage of US companies, many of which either went bankrupt or were purchased by Chinese companies (The New York Times, 2013). Also, in Spain, promises of 10% annual returns boosted the solar industry in 2008, yet the subsequent reduction of subsidies at different points in time increased producers' reluctance to commit to future investments (The Economist, 2013). However, recent tenders for RE with subsidies, have induced a new investment boom (REN21, 2018).

Although the real options literature has grown considerably, models that analyse the implications of policy uncertainty on investment decisions are often narrowly specified, in that technological uncertainty is either ignored or not considered within the context of complex investment opportunities that involve embedded options (Yang et al., 2008; Boomsma and Linnerud, 2015; Ritzenhofen and Spinler, 2016; Zhang et al., 2016a). In turn, this implies that the value of the flexibility to adopt improved technology versions may be critical in terms of offsetting the impact of policy uncertainty, yet it is currently overlooked. Therefore, in this paper we develop a real options framework to address the following research questions: **i.** How does economic, policy and technological uncertainty interact to affect sequential investment decisions? **ii.** Does the likely arrival of improved technology versions increase the value of a project and mitigate the reluctance to invest due to policy uncertainty? and **iii.** Is the optimal investment policy under sequential investment significantly different than that under a lumpy investment strategy in the light of technological and policy uncertainty? These research questions are also motivated by Renewables 2018 global status report:

* Corresponding author.
E-mail addresses: lars.h.sendstad@ntnu.no (L.H. Sendstad), Michalis.Chronopoulos@city.ac.uk (M. Chronopoulos).

https://doi.org/10.1016/j.enpol.2019.111152
Received 27 March 2019; Received in revised form 24 November 2019; Accepted 26 November 2019
Available online 4 December 2019
0301-4215/

"... The interaction of policy, cost reductions and technology development has led to rapid change in the energy sector, prompting both proactive and reactive responses from policy makers." (REN21, 2018)

Hence, the contribution of this paper is threefold: **i.** we develop a real options framework for analysing how economic, technological and policy uncertainty interact to affect sequential investment in successively improved versions of a RE technology; **ii.** we show how an embedded option to adopt an improved technology version mitigates the impact of subsidy retraction on invest timing, by comparing a stepwise to a lumpy investment strategy; and **iii.** we derive insights on how policymakers can devise more efficient policy mechanisms and incentivise investment in RE technologies.

We assume that the subsidy takes the form of a fixed premium on top of the electricity price. Thus, it resembles a feed-in premium, which is one of the popular support schemes currently implemented in various forms in many countries (IRENA, 2018a). We find that greater likelihood of subsidy retraction postpones investment, yet the likely provision of a subsidy raises the investment incentive. Interestingly, we also find that the option to invest sequentially in improved technology versions raises the value of the investment opportunity, and mitigates the loss in project value due to subsidy retraction. Therefore, the implications of these new insights are important considering that many countries implement a variety of selective support schemes, without taking into account particular features of investment projects or considering how cautiously private firms may act in the light of the uncertainties due to innovation and frequent switches between policy regimes. Consequently, this paper also offers a direction for further research on the appropriate model specification for capturing features of low-carbon investments, e.g. irreversibility, delay and embedded options, that impinge upon the radical policy imperatives for structural change in electricity markets to meet ambitious sustainability targets.

We proceed by discussing some related work in Section 2 and introduce assumptions and notation in Section 3. In Section 4.1, we address the problem of optimal investment timing taking into account only price and technological uncertainty. We introduce policy uncertainty in Sections 4.2 and 4.3 in the form of sudden retraction and provision of a subsidy, and allow the sudden provision of a retractable subsidy in Section 4.4. Section 5 presents numerical results for each case via a case study on offshore wind, while Section 6 concludes the paper by offering policy insights and directions for further research.

2. Related work

The seminal work of McDonald and Siegel (1985) and Dixit and Pindyck (1994) has spawned a substantial literature in the area of investment under uncertainty. A strand of this literature illustrates the amenability of real options theory to emerging technologies, research and development (R&D) and the energy sector (Bastian-Pinto et al., 2010; Koussis et al., 2007; Rothwell, 2006; Siddiqui and Fleten, 2010; Lemoine, 2010; Farzan et al., 2015; Franklin, 2015). Nevertheless, analytical formulations of problems that address investment in emerging technologies either tackle the impact of technological uncertainty on investment timing ignoring the implications of policy uncertainty (Schwartz and Zozaya-Gorostiza, 2003) or allow for policy uncertainty without taking into account the sequential nature of investment in emerging technologies (Boomsma et al., 2012; Adkins and Paxson, 2016). However, since support schemes aim at facilitating the transition of emerging technologies through the steep part of the learning curve, uncertainty over the provision or retraction of a subsidy should be considered in combination with uncertainty over the arrival of innovations that these subsidies are designed to support.

Allowing for policy uncertainty, Boomsma et al. (2012) develop a real options model in order to investigate how different support schemes, including fixed feed-in tariff (FIT), premium FIT and RE certificate trading, as well as changes of a support scheme via Markov switching, impact investment behaviour. They find that the implications of the uncertainty associated with each support scheme can be crucial for both the time of investment and the size of a project. However, allowing changes in the level of a subsidy to follow a continuous-time stochastic process does not facilitate insights on the permanent or temporary termination of a support scheme. In the same line of work, Kim and Lee (2012) present a stochastic model for the evaluation and optimisation of FIT policies under different payoff structures. However, like Boomsma et al. (2012), their analysis overlooks the implications of technological uncertainty and how embedded options to adopt improved technology versions may impact investment behaviour under the different payoff structures of the FIT scheme.

A real options model for analysing how investors' behaviour is affected by different RE support schemes and the risk of their eventual termination is presented in Boomsma and Linnerud (2015). Their results indicate that the prospect of subsidy retraction increases the rate of investment if it is applied to new projects, yet slows down investment if it has a retroactive effect. In the same line of work, Chronopoulos et al. (2016) allow for discretion over project scale under sequential policy interventions and find that the likely retraction of a subsidy may facilitate investment, yet results in a smaller project. Also, the implications of a FIT for RE investment is emphasised in Ritzenhofen and Spinler (2016), who show that under a sufficiently attractive FIT regime, future regime changes have little impact on current investment projects, whereas under a free-market regime, in which investors are exposed to electricity price uncertainty, investment may be deferred or even withdrawn.

The importance of R&D investment for promoting the further development of solar power is emphasised in Zhang et al. (2016b), who develop a real options approach to assess the optimal levels of FIT within the Chinese power market. However, the interaction between technological and policy uncertainty is not taken into account. Also, an analysis of the implications of different kinds of subsidy support for investment timing and capacity sizing decisions is presented in Wen et al. (2017). Their model also investigates whether it is possible to align the firm's investment decisions to the social optimal ones. Results indicate that when the subsidy support is introduced from the beginning, it accelerates investment, and that, under a linear demand structure, the firm's investment decision and the social optimal decision cannot be aligned. However, there is a conditional subsidy regulation that aligns the firm's investment decision to the social optimal decision. Nevertheless, it remains unclear how embedded options to adopt improved technology versions may impact the firms investment and capacity sizing decisions, as well as the social welfare.

While policy-oriented real options papers offer important insights on the impact of policy uncertainty on investment timing, they tend to ignore technological uncertainty and how sequential investment opportunities may impact the optimal investment policy. In the area of sequential investment under uncertainty, Majd and Pindyck (1987) show how traditional valuation methods understate the value of a project by ignoring the flexibility embedded in the time to build. In the same line of work, Gollier et al. (2005) compare a sequence of modular nuclear power plants with a single nuclear power plant of large capacity. They find that the value of modularity may trigger investment in the initial module at an electricity price level below the net present value (NPV) threshold. Allowing for technological uncertainty, Chronopoulos and Siddiqui (2015) develop a framework for sequential technological adoption and analyse how economic and technological uncertainty impact the optimal technology adoption strategy and the associated investment rule. They find that, although economic uncertainty postpones investment, uncertainty over the arrival of innovations accelerates technology adoption.

Examples of early work that analyses the impact of technological uncertainty on the timing of technology adoption include Balcer and Lippman (1984), who find that the optimal timing of technology adoption is influenced by expectations about future technological changes

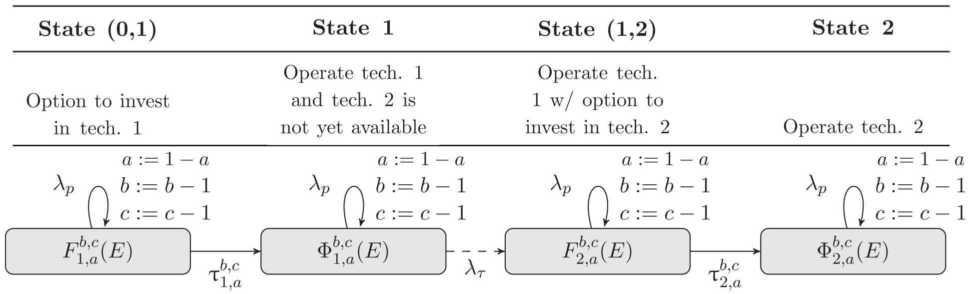

Fig. 1. State-transition diagram.

and that increasing technological uncertainty tends to delay adoption. Grenadier and Weiss (1997) develop a sequential investment model to study how the innovation rate and technological growth impact the optimal technology adoption strategy, and find that a firm may adopt an available technology although more valuable innovations may occur in the future. Farzin et al. (1998) assume that technological innovations follow a Poisson process and find that the NPV rule can be used as an investment criterion in most cases. However, Doraszelski (2001) revisits the framework of Farzin et al. (1998) and shows that a firm will always defer investment when it takes the value of waiting into account. Also, a discrete-time model for maintenance and replacement of a technology is presented in Mehrez et al. (2000).

We extend Chronopoulos and Siddiqui (2015) by introducing policy uncertainty in the form of sudden provision and retraction of a subsidy. Since technological uncertainty and increased intervention of government policy in trading arrangements may affect the optimal investment policy of private firms, we explore their combined impact in this paper. We assume that the electricity price follows a geometric Brownian motion (GBM) and that policy interventions and technological innovations follow independent Poisson processes. Thus, we confirm that greater likelihood of subsidy retraction (provision) lowers (raises) the investment incentive by decreasing (increasing) the expected value of the project. Also, we compare a stepwise to a lumpy investment strategy to show how an embedded option to adopt an improved technology version mitigates the impact of subsidy retraction on investment timing. Interestingly, we find that a stepwise investment strategy has a clear advantage over lumpy investment, as it results in earlier technology adoption. Additionally, we show how uncertainty over the arrival of an innovation induces earlier investment, thus creating an opposing force that further offsets the incentive to delay investment in the light of subsidy retraction.

3. Assumptions and notation

We consider a price-taking firm with a perpetual option to invest in $n = 1, 2$ successively improved versions of a RE technology, each with infinite lifetime, facing price, technological and policy uncertainty. Given a probability space $(\Omega, \mathcal{F}, \mathbb{P})$, we assume that technological and policy uncertainty follow independent Poisson processes, $\{M_t^i, t \geq 0\}$, where t is continuous and denotes time, and $\lambda_i \geq 0$ denotes the intensity of the Poisson process associated with technological innovations ($i = \tau$) or policy interventions ($i = p$). Intuitively, M_t^i counts the number of random events that occur at times $h_m^i, m \in \mathbb{N}$ between 0 and t, and $T_m^i = h_m^i - h_{m-1}^i$ is the time interval between subsequent Poisson events. Also, we assume that there is no operating cost, that the electricity price at time t, E_t, is independent of M_t^i (Boomsma and Linnerud, 2015), and that only the second technology is subject to technological uncertainty, i.e. the first technology that the firm invests in is the currently available version.

The electricity price follows a GBM (Boomsma et al., 2012), which is described in (1). We denote by μ the annual growth rate, by σ the annual volatility, by dZ_t the increment of the standard Brownian motion. Also, we assume that the firm is risk-neutral and denote the risk-free rate by ρ. With respect to our motivating examples, although energy prices are mean reverting, empirical evidence based on 127 years of data indicates that the rate of mean reversion is low enough, and, therefore, assuming a GBM for investment analysis is unlikely to lead to large errors (Pindyck, 1999).

$$dE_t = \mu E_t dt + \sigma E_t dZ_t, \quad E_0 \equiv E > 0 \tag{1}$$

We denote the investment cost of technology n by I_n ($I_2 > I_1$) and the corresponding output by D_n ($D_2 \geq D_1$). Note that D_n is assumed to be fixed on the basis that for a specific technology annual average production is unlikely to vary considerably. We let $a = 0, 1$ denote the current state of the subsidy in terms of being present ($a = 1$) or absent ($a = 0$), and assume that, in the future, the subsidy can be provided and retracted b and c times, respectively. We assume that the subsidy takes the form of a fixed premium, y, on top of the electricity price, E_t. Thus, the time of investment in technology n is denoted by $\tau_{n,a}^{b,c}$, while $\varepsilon_{n,a}^{b,c}$ is the corresponding optimal investment threshold. For example, if the subsidy is currently unavailable ($a = 0$) but will be provided permanently ($b = 1$ and $c = 0$) at a random point in time in the future, then the optimal time to invest in the second technology is $\tau_{2,0}^{1,0}$, while the corresponding optimal investment threshold is $\varepsilon_{2,0}^{1,0}$. Finally, $F_{n,a}^{b,c}(\cdot)$ is the maximised expected NPV from investing in technology n, while $\Phi_{n,a}^{b,c}(\cdot)$ is the expected value of the revenues of the active project inclusive of embedded options.

The firm's different states of operation are indicated in Fig. 1, where a transition due to a Poisson event (investment) is indicated by a dashed (solid) arrow. The value function and optimal investment threshold in each state are determined via backward induction, which are described below.

1. **State 2**: Initially, we assume that the firm operates technology 2, which is adopted at time $\tau_{2,a}^{b,c}$, and, thus, the firm holds the value function $\Phi_{2,a}^{b,c}(E)$.
2. **State (1,2)**: Next, we step back and assume that the firm holds the value function $F_{2,a}^{b,c}(E)$, consisting of the value from operating technology 1 and a single embedded option to invest in technology 2. The latter is exercised at time $\tau_{2,a}^{b,c}$, at which point the firm obtains the value function $\Phi_{2,a}^{b,c}(E)$, which is already determined in the previous step.
3. **State 1**: Before the arrival of the second technology, the firm operates technology 1 and holds an option to adopt technology 2 that has yet to become available. The firm's value function is $\Phi_{1,a}^{b,c}(E)$ and consists of the expected value from operating technology 1 and the embedded option to invest in technology 2, which is not available yet.
4. **State (0,1)**: Finally, we assume that the firm is not active and waits to adopt technology 1. Thus, before time $\tau_{1,a}^{b,c}$ the firm holds the value function $F_{1,a}^{b,c}(E)$, i.e. the option to invest in technology 1 with a single embedded option to invest technology 2, that has yet to become available.

Note that at a given state, a policy intervention (loop arrows) changes the value of a, b and c via the recursive formulae $a := 1-a$, $b := b-1$ and $c := c-1$. For example, in the case of provision of a retractable subsidy we initially have $a = 0, b = 1$ and $c = 1$. Once the subsidy is provided, the updated value of a is $a := 1-0 = 1$ and for b is $b := 1-1 = 0$. Hence, until the second policy intervention, the new state is defined by $a = 1$, $b = 0$ and $c = 1$. Finally, following the retraction of the subsidy, we have $a := 1-1 = 0$, $b = 0$, as there are not further subsidy provisions, and $c := 1-1 = 0$.

4. Model

4.1. Benchmark case: Investment without policy uncertainty

We assume that the firm has the option to invest in each technology facing only price and technological uncertainty. Using backward induction, we first assume that the firm is operating the first technology holding the option to invest in the second one, that is already available, as indicated in (2). The first term on the right-hand side is the immediate cash flows from operating the first technology and the second term is the expected value of the option in the continuation region.

$$F_{2,a}^{0,0}(E) = D_1 E(1+ay)\,dt + e^{-\rho dt}\mathbb{E}_E\left[F_{2,a}^{0,0}(E+dE)\right] \tag{2}$$

By expanding the right-hand side of (2) using Itô's lemma, we obtain the ordinary differential equation (ODE) (3), where $\mathcal{L} = \frac{1}{2}\sigma^2 E^2 \frac{d^2}{dE^2} + \mu E\frac{d}{dE}$ denotes the differential generator.

$$(\mathcal{L}-\rho)\,F_{2,a}^{0,0}(E) + D_1 E(1+ya) = 0 \tag{3}$$

The solution of (3) is indicated in (4). The first term on the top part of (4) reflects the expected present value of the revenues from operating the first technology and the second term represents the option to invest in the second one, where $\beta_1 > 0$ is the positive root of the quadratic $\frac{1}{2}\sigma^2\beta(\beta-1)+\mu\beta-\rho = 0$. Also, the bottom part of (4) reflects the expected value from operating the second technology, i.e. $\Phi_{2,a}^{0,0}(E) = \frac{D_2 E_{2,a}^{0,0}(1+ay)}{\rho-\mu}$, reduced by the investment cost (all proofs can be found in the appendix).

$$F_{2,a}^{0,0}(E) = \begin{cases} \frac{D_1 E(1+ay)}{\rho-\mu} + A_{2,a}^{0,0}E^{\beta_1} & , E < \varepsilon_{2,a}^{0,0} \\ \Phi_{2,a}^{0,0}(E) - I_2 & , E \geq \varepsilon_{2,a}^{0,0} \end{cases} \tag{4}$$

The optimal investment threshold, $\varepsilon_{2,a}^{0,0}$, and the endogenous constant, $A_{2,a}^{0,0}$, are obtained analytically by applying value-matching and smooth-pasting conditions to the two branches of (4). These conditions are indicated in (A.2) and (A.3), respectively, and the expression for $\varepsilon_{2,a}^{0,0}$ and $A_{2,a}^{0,0}$ is indicated in (5).

$$\varepsilon_{2,a}^{0,0} = \frac{\beta_1}{\beta_1-1}\frac{I_2(\rho-\mu)}{\left(D_2-D_1\right)(1+ay)}$$
$$\text{and}\quad A_{2,a}^{0,0} = \left(\frac{1}{\varepsilon_{2,a}^{0,0}}\right)^{\beta_1}\left(\frac{\left(D_2-D_1\right)(1+ay)\,\varepsilon_{2,a}^{0,0}}{\rho-\mu} - I_2\right) \tag{5}$$

Although we do not consider the choice between the two technologies (Décamps et al., 2006), the feasibility of a compulsive strategy relies on the ratios between output produced and investment cost of the two technologies, as indicated in Proposition 1. Intuitively, this relationship reflects the assumption of the second technology being more advanced, in terms of producing greater output, yet also more costly than the first one. Formally, this trade-off is defined by the existence of $E^* > 0$ such that $\Phi_{1,a}^{0,0}(E) \geq \Phi_{2,a}^{0,0}(E)$ for $E \leq E^*$ and $\Phi_{1,a}^{0,0}(E) < \Phi_{2,a}^{0,0}(E)$ for $E > E^*$. Consequently, this definition implies that the NPV at the point of intersection between the expected NPVs of the two technologies is positive, and, therefore, both technologies present viable investment opportunities for different electricity price ranges. Otherwise, if the NPV at the point of intersection is negative then only the new technology presents a viable investment opportunity. This is also motivated by offshore wind projects, where new projects have a substantially higher yield but at a greater cost (see Section 5).

Proposition 1. *A trade-off between the two technologies exists if* $\frac{D_1}{I_1} > \frac{D_2}{I_2}$.

Next, we assume that the firm is in State 1, where it operates the first technology holding an embedded option to adopt the second one, which has yet to become available. We follow the approach of Dixit and Pindyck (1994, p. 202–205) to describe the dynamics of the value function $\Phi_{1,a}^{0,0}(E)$, as in (6). The first term on the right-hand side of (6) is the immediate profit from operating the first technology. As the second term indicates, with probability $\lambda_\tau dt$ the second technology will arrive and the firm will receive the value function $F_{2,a}^{0,0}(E)$, whereas, with probability $1-\lambda_\tau dt$, no innovation will occur and the firm will continue to hold the value function $\Phi_{1,a}^{0,0}(E)$.

$$\Phi_{1,a}^{0,0}(E) = D_1 E(1+ay)\,dt + e^{-\rho dt}\mathbb{E}_E\left\{\lambda_\tau dt F_{2,a}^{0,0}(E+dE) + \left(1-\lambda_\tau dt\right)\Phi_{1,a}^{0,0}(E+dE)\right\} \tag{6}$$

By expanding the right-hand side of (6) using Itô's lemma, we obtain the ordinary differential equation (7). Note that $F_{2,a}^{0,0}(E)$ is defined over two different intervals of E, i.e. $E < \varepsilon_{2,a}^{0,0}$ and $E \geq \varepsilon_{2,a}^{0,0}$. Consequently, (7) must be solved for each one of these two price intervals, separately.

$$(\mathcal{L}-\rho)\,\Phi_{1,a}^{0,0}(E) + \lambda_\tau\left[F_{2,a}^{0,0}(E) - \Phi_{1,a}^{0,0}(E)\right] + D_1 E(1+ya) = 0 \tag{7}$$

We solve (7) and obtain the expression for $\Phi_{1,a}^{0,0}(E)$ that is indicated in (8), where $A_{1,a}^{0,0} \leq 0$ and $B_{1,a}^{0,0} \geq 0$ are determined analytically via value-matching and smooth-pasting conditions between the two branches of (8) and are given in (A.4) and (A.5). The terms $\delta_1 > 1, \delta_2 < 0$ are the roots of the quadratic $\frac{1}{2}\sigma^2\delta(\delta-1)+\mu\delta-\left(\rho+\lambda_\tau\right) = 0$. The first term on the top part of (8) represents the expected present value of the revenues from operating the first technology, while the second term is the option to invest in the second one, adjusted via the third term because the second technology has yet to become available. The first two terms on the bottom part of (8) represent the expected profit from the two technologies. Notice that both the output and investment cost in the second technology are adjusted by λ_τ, since the second technology is not available yet. Similar formulations can be found in Huisman and Kort (2004) and Chronopoulos and Siddiqui (2015). The third term reflects the likelihood of the price dropping in the waiting region prior to the arrival of an innovation. Note that if $\lambda_\tau = 0$, then the second technology will never arrive and the firm will continue to operate the first technology indefinitely, which means that $\Phi_{1,a}^{0,0}(E) = \frac{D_1 E(1+ay)}{\rho-\mu}$ for all $E > 0$. In contrast, $\lambda_\tau \to \infty$ implies that the second technology will arrive within the next time interval, and, therefore, $\Phi_{1,a}^{0,0}(E) = F_{2,a}^{0,0}(E)$.

$$\Phi_{1,a}^{0,0}(E) = \begin{cases} \frac{D_1 E(1+ay)}{\rho-\mu} + A_{2,a}^{0,0}E^{\beta_1} + A_{1,a}^{0,0}E^{\delta_1}, \\ \quad E < \varepsilon_{2,a}^{0,0} \\ \frac{\left(\lambda_\tau D_2 + (\rho-\mu)D_1\right)E(1+ay)}{(\rho-\mu)\left(\rho-\mu+\lambda_\tau\right)} - \frac{\lambda_\tau I_2}{\rho+\lambda_\tau} + B_{1,a}^{0,0}E^{\delta_2}, \\ \quad E \geq \varepsilon_{2,a}^{0,0} \end{cases} \tag{8}$$

Finally, the value of the option to invest in State (0,1) is described in (9), where $\varepsilon_{1,a}^{0,0}$ and $C_{1,a}^{0,0} \geq 0$, are determined numerically via value-matching and smooth-pasting conditions between the two branches. The top part on the right-hand side of (9) is the value of the option to invest in the first technology, while the bottom part reflects the expected value of the active project, inclusive of the embedded option to invest in the second one, reduced by the investment cost.

$$F_{1,a}^{0,0}(E) = \begin{cases} C_{1,a}^{0,0}E^{\beta_1} & , E < \varepsilon_{1,a}^{0,0} \\ \Phi_{1,a}^{0,0}(E) - I_1 & , E \geq \varepsilon_{1,a}^{0,0} \end{cases} \tag{9}$$

4.2. Permanent subsidy retraction

We extend the previous framework by assuming that a subsidy is available and that it may be retracted permanently at a random point in time, T_1^p, i.e. $a = 1$, $b = 0$ and $c = 1$. Hence, the expected value of the revenues from operating the second technology is indicated in (10). The first term on the right-hand side is the expected present value of the revenues in the absence of the subsidy, while, the second term, is the expected value of the subsidy, that has an exponential lifetime and will be retracted at T_1^p.

$$\mathbb{E}_E\left[\int_0^\infty e^{-\rho t} D_2 E_t dt + \int_0^{T_1^p} e^{-\rho t} D_2 E_t y dt\right] = \frac{D_2 E}{\rho-\mu} + \mathbb{E}\left\{\frac{D_2 E y\left[1-e^{-(\rho-\mu)T_1^p}\right]}{\rho-\mu}\right\} \tag{10}$$

Since $T_1^p \sim \exp(\lambda_p)$, by evaluating the expectation of this expression with respect to T_1^p we obtain (11). Notice that the subsidy will never be retracted if $\lambda_p = 0$, whereas a greater λ_p raises the likelihood of subsidy retraction and lowers the expected NPV of the project.

$$\Phi_{2,1}^{0,1}(E) = \frac{D_2 E}{\rho-\mu} + \int_0^\infty \lambda_p e^{-\lambda_p T_1^p} \frac{D_2 E y\left[1-e^{-(\rho-\mu)T_1^p}\right]}{\rho-\mu} dT_1 = \frac{D_2 E}{\rho-\mu} + \frac{D_2 E y}{\rho-\mu+\lambda_p} \tag{11}$$

Next, we assume that the firm is in State(1,2), where it operates the first technology and holds a single embedded option to invest in the second one. The dynamics of the firm's value function are described in (12), where the first term on the right-hand side reflects the immediate profit from operating the first technology. As the second term indicates, the option to invest in the second technology will be exercised in the permanent absence of a subsidy with probability $\lambda_p dt$. By contrast, with probability $1-\lambda_p dt$, no policy intervention will take place and the firm will continue to hold the option to invest in the second technology in the presence of a retractable subsidy.

$$F_{2,1}^{0,1}(E) = D_1 E(1+y)dt + e^{-\rho dt}\mathbb{E}_E\left\{\lambda_p dt F_{2,0}^{0,0}(E+dE) + \left(1-\lambda_p dt\right) F_{2,1}^{0,1}(E+dE)\right\} \tag{12}$$

By expanding the right-hand side of (12) using Itô's lemma, we obtain (13).

$$(\mathcal{L}-\rho) F_{2,1}^{0,1}(E) + \lambda_p\left[F_{2,0}^{0,0}(E) - F_{2,1}^{0,1}(E)\right] + D_1 E(1+y) = 0 \tag{13}$$

The solution of (13) is described in (14), where $\varepsilon_{2,1}^{0,1}$ and $A_{2,1}^{0,1} \geq 0$ are determined via value-matching and smooth-pasting conditions, while $\eta_1 > 1, \eta_2 < 0$ are the roots of the quadratic $\frac{1}{2}\sigma^2\eta(\eta-1)+\mu\eta-\left(\rho+\lambda_p\right) = 0$. The first two terms in the top part of (14) represent the expected value of the revenues from operating the first technology, while the third term is the option to invest in the second one in the absence of a subsidy, adjusted via the fourth term since the subsidy is currently available.

$$F_{2,1}^{0,1}(E) = \begin{cases} \frac{D_1 E}{\rho-\mu} + \frac{D_1 E y}{\rho-\mu+\lambda_p} + A_{2,0}^{0,0} E^{\beta_1} + A_{2,1}^{0,1} E^{\eta_1} & , E < \varepsilon_{2,1}^{0,1} \\ \Phi_{2,1}^{0,1}(E) - I_2 & , E \geq \varepsilon_{2,1}^{0,1} \end{cases} \tag{14}$$

Next, we step back to State 1, where an innovation has not taken place yet, but may occur over the time interval dt with probability $\lambda_\tau dt$. The dynamics of $\Phi_{1,1}^{0,1}(E)$ are described in (15), where the first term on the right-hand side represents the immediate profit from operating the first technology and the second term reflects the expected value in the continuation region. If the subsidy is retracted with probability $\lambda_p dt$, then either an innovation will take place with probability $\lambda_\tau dt$ and the firm will receive the value function $F_{2,0}^{0,0}(E)$, or no innovation will take place with probability $1-\lambda_\tau dt$ and the firm will continue to operate the first technology in the absence of a subsidy. Similarly, if no policy intervention occurs with probability $1-\lambda_p dt$, then the firm will either receive the value function $F_{2,1}^{0,1}(E)$ with probability $\lambda_\tau dt$, or it will continue to hold the value function $\Phi_{1,1}^{0,1}(E)$ with probability $1-\lambda_\tau dt$.

$$\begin{aligned}\Phi_{1,1}^{0,1}(E) &= D_1 E(1+y)dt \\ &+ e^{-\rho dt}\mathbb{E}_E\Big\{\lambda_p dt\left[\lambda_\tau dt F_{2,0}^{0,0}(E+dE) + \left(1-\lambda_\tau dt\right)\Phi_{1,0}^{0,0}(E+dE)\right] \\ &+ \left(1-\lambda_p dt\right)\left[\lambda_\tau dt F_{2,1}^{0,1}(E+dE) + \left(1-\lambda_\tau dt\right)\Phi_{1,1}^{0,1}(E+dE)\right]\Big\}\end{aligned} \tag{15}$$

By expanding the right-hand side of (15) using Itô's lemma, we obtain (16).

$$(\mathcal{L}-\rho)\Phi_{1,1}^{0,1}(E) + \lambda_p\left[\Phi_{1,0}^{0,0}(E) - \Phi_{1,1}^{0,1}(E)\right] + \lambda_\tau\left[F_{2,0}^{0,1}(E) - \Phi_{1,1}^{0,1}(E)\right] + D_1 E(1+y) = 0 \tag{16}$$

The expression of $\Phi_{1,1}^{0,1}(E)$ is indicated in (17), where $A_{1,1}^{0,1} \leq 0$ and $B_{1,1}^{0,1} \leq 0$ are determined numerically via value-matching and smooth-pasting conditions, while $\theta_1 > 1, \theta_2 < 0$ are the roots of the quadratic $\frac{1}{2}\sigma^2\theta(\theta-1) + \mu\theta - \left(\rho+\lambda_p+\lambda_\tau\right) = 0$. The first two terms in the top part of (17) represent the expected revenues from operating the first technology, while the third term is the option to invest in the second one, adjusted via the fourth term due to policy uncertainty. The fifth term reflects the loss in option value due to the absence of the second technology, and is adjusted via the last term due to policy uncertainty. The first three terms in the bottom part of (17) represent the expected revenues from investing in the second technology, while the last two terms reflect the likelihood of the price dropping in the waiting region before the arrival of the second technology, adjusted for policy uncertainty.

$$\Phi_{1,1}^{0,1}(E) = \begin{cases} \frac{D_1 E}{\rho-\mu} + \frac{D_1 E y}{\rho-\mu+\lambda_p} + A_{2,0}^{0,0}E^{\beta_1} + A_{2,1}^{0,1}E^{\eta_1} \\ \quad + A_{1,0}^{0,0}E^{\delta_1} + A_{1,1}^{0,1}E^{\theta_1}, \qquad E < \varepsilon_{2,1}^{0,1} \\ \frac{\lambda_\tau D_2 E + (\rho-\mu) D_1 E}{(\rho-\mu)\left(\rho-\mu+\lambda_\tau\right)} + \frac{\left[\lambda_\tau D_2 + \left(\rho-\mu+\lambda_p\right) D_1\right] E y}{\left(\rho-\mu+\lambda_p\right)\left(\rho-\mu+\lambda_p+\lambda_\tau\right)} \\ \quad - \frac{\lambda_\tau I_2}{\rho+\lambda_\tau} + B_{1,0}^{0,0}E^{\delta_2} + B_{1,1}^{0,1}E^{\theta_2}, \qquad E \geq \varepsilon_{2,1}^{0,1} \end{cases} \tag{17}$$

Next, we step back to State (0,1), and, following the same approach as in (12), the dynamics of the option to invest in the first technology are described in (18).

$$(\mathcal{L}-\rho) F_{1,1}^{0,1}(E) + \lambda_p\left[F_{1,0}^{0,0}(E) - F_{1,1}^{0,1}(E)\right] = 0 \tag{18}$$

The expression of $F_{1,1}^{0,1}(E)$ is indicated in (19), where $\varepsilon_{1,1}^{0,1}$ and $C_{1,1}^{0,1} \geq 0$ are obtained numerically via value-matching and smooth-pasting conditions. The first term in the top part of (19) is the option to invest in the absence of a subsidy, adjusted via the second term, since the subsidy is currently available. The bottom part represents the expected value from operating the first technology inclusive of the embedded option to invest in the second one.

$$F_{1,1}^{0,1}(E) = \begin{cases} C_{1,0}^{0,0}E^{\beta_1} + C_{1,1}^{0,1}E^{\eta_1} & , E < \varepsilon_{1,1}^{0,1} \\ \Phi_{1,1}^{0,1}(E) - I_1 & , E \geq \varepsilon_{1,1}^{0,1} \end{cases} \tag{19}$$

Alternatively, to facilitate the analysis of how λ_p and λ_τ impact the optimal investment policy, $F_{1,1}^{0,1}(E)$ can be expressed as in (20) for $E < \varepsilon_{1,1}^{0,1} < \varepsilon_{2,1}^{0,1}$. The optimal investment threshold can be obtained numerically by applying the first-order necessary condition (FONC) to (20) and equating the marginal benefit (MB) of delaying investment to the marginal cost (MC) as in (21).

$$F_{1,1}^{0,1}(E)=\left(\frac{E}{\varepsilon_{1,1}^{0,1}}\right)^{\beta_1}\left[\Phi_{1,1}^{0,1}\left(\varepsilon_{1,1}^{0,1}\right)-I_1-C_{1,1}^{0,1}\varepsilon_{1,1}^{0,1^{\eta_1}}\right],\quad E<\varepsilon_{1,1}^{0,1} \tag{20}$$

The left-hand side of (21) reflects the MB of delaying investment and the right-hand side is the MC. Formally, the MB (MC) consists of terms that offer a positive (negative) contribution to $\partial F_{1,1}^{0,1}(E)/\partial\varepsilon_{1,1}^{0,1}$. Specifically, the first two terms on the left-hand side of (21) consist of the stochastic discount factor multiplied by the incremental project value created by waiting until the price is higher. These terms are positive, decreasing functions of the electricity price, as waiting longer allows the project to start at a higher initial price, yet the rate at which this benefit accrues diminishes due to the effect of discounting. The third term represents the reduction in the MC of waiting due to saved investment cost. Similarly, the first two terms on the right-hand side reflect the discounted opportunity cost of forgone cash flows. The fourth and third term on the left- and right-hand side, respectively, reflect the loss in option value, since the second technology is not available yet. Specifically, the fourth term on the left-hand side is the MB from postponing the loss in value, whereas the third term on the right-hand side is the MC from a potentially greater impact of the loss from waiting for a higher threshold price. The last two terms on the left- and the right-hand side reflect the necessary adjustments due to policy uncertainty.

$$\begin{aligned}&\left(\frac{E}{\varepsilon_{1,1}^{0,1}}\right)^{\beta_1}\left[\frac{D_1}{\rho-\mu}+\frac{D_1 y}{\rho-\mu+\lambda_p}+\frac{\beta_1 I_1}{\varepsilon_{1,1}^{0,1}}-\beta_1 A_{1,0}^{0,0}\varepsilon_{1,1}^{0,1^{\delta_1-1}}-\beta_1 A_{1,1}^{0,1}\varepsilon_{1,1}^{0,1^{\theta_1-1}}\right.\\&\qquad\left.+\left[\beta_1 C_{1,1}^{0,1}+\eta_1 A_{2,1}^{0,1}\right]\varepsilon_{1,1}^{0,1^{\eta_1-1}}\right]\\&=\left(\frac{E}{\varepsilon_{1,1}^{0,1}}\right)^{\beta_1}\left[\frac{\beta_1 D_1}{\rho-\mu}+\frac{\beta_1 D_1 y}{\rho-\mu+\lambda_p}-\delta_1 A_{1,0}^{0,0}\varepsilon_{1,1}^{0,1^{\delta_1-1}}-\theta_1 A_{1,1}^{0,1}\varepsilon_{1,1}^{0,1^{\theta_1-1}}\right.\\&\qquad\left.+\left[\eta_1 C_{1,1}^{0,1}+\beta_1 A_{2,1}^{0,1}\right]\varepsilon_{1,1}^{0,1^{\eta_1-1}}\right]\end{aligned} \tag{21}$$

As shown in Proposition 2, greater likelihood of subsidy retraction lowers the MC by more than the MB, thereby raising the incentive to postpone investment. Intuitively, the incentive to invest early in order to take advantage of the subsidy for a longer period is mitigated completely by the rapid reduction in the value of the active project due to subsidy retraction. However, as shown in Chronopoulos and Siddiqui (2015), an increase in the innovation rate while holding λ_p fixed lowers the optimal investment threshold. Hence, in relation to the second research question, the likely arrival of an improved technology version creates an opposing force that mitigates the impact of subsidy retraction on the incentive to invest. Despite this opposing force, a higher likelihood of subsidy retraction raises the optimal investment threshold when λ_τ is fixed.

Proposition 2. *Greater likelihood of subsidy retraction raises the optimal investment threshold.*

To emphasise the implications of a stepwise investment strategy, we also consider the alternative option of lumpy investment, where the firm incurs the cost I_1+I_2 in a single step to develop a project producing output of D_2. Proposition 3 indicates that adopting a lumpy investment strategy results in later technology adoption compared to a stepwise investment strategy. Consequently, with respect to the third research question, the option to adopt an improved technology version alters the optimal investment policy relative to the case of lumpy investment, by increasing the incentive to invest earlier in an existing technology and expand capacity at a later point once an innovation becomes available.

Proposition 3. *Stepwise investment induces earlier technology adoption than a lumpy investment strategy as long as $\frac{I_1}{I_2}>y$.*

4.3. Provision of a permanent subsidy

Here, we assume that a subsidy will be provided permanently at a random point in time, i.e. $a=0$, $b=1$ and $c=0$. Hence, like in Section 4.2, we assume that there is a single policy intervention and denote the random time at which it takes place by T_1^p. The expected present value of the revenues from operating the second technology is indicated in (22), and, according to the right-hand side, it consists of the expected value of the project in the absence of the subsidy (first term) and the extra value of the subsidy (second term) that will be provided at time T_1^p.

$$\mathbb{E}_E\left[\int_0^\infty e^{-\rho t}D_2E_t dt+\int_{T_1^p}^\infty e^{-\rho t}D_2E_t y dt\right]=\frac{D_2E}{\rho-\mu}+\mathbb{E}\left\{\frac{D_2Eye^{-(\rho-\mu)T_1^p}}{\rho-\mu}\right\} \tag{22}$$

Since $T_1^p\sim\exp(\lambda_p)$, taking the expectation of this expression with respect to T_1^p yields (23).

$$\Phi_{2,0}^{1,0}(E)=\frac{D_2E}{\rho-\mu}+\frac{\lambda_p D_2 E y}{\left(\rho-\mu+\lambda_p\right)(\rho-\mu)} \tag{23}$$

Stepping back to State (1,2), the dynamics of the option to invest in the second technology are described in (24).

$$(\mathcal{L}-\rho)F_{2,0}^{1,0}(E)+\lambda_p\left[F_{2,1}^{0,0}(E)-F_{2,0}^{1,0}(E)\right]+D_1E=0 \tag{24}$$

The expression of $F_{2,0}^{1,0}(E)$ is indicated in (25), where $\varepsilon_{2,0}^{1,0}$, $A_{2,0}^{1,0}\le 0$, $B_{2,0}^{2,0}\ge 0$, and $C_{2,0}^{1,0}\ge 0$, are determined numerically via value-matching and smooth-pasting conditions between the three branches. Note that, unlike the case of sudden subsidy retraction, $F_{2,0}^{1,0}(E)$ is now defined over three different regions of E: (i) if $E<\varepsilon_{2,1}^{0,0}$, then the firm would not invest even in the presence of a subsidy, (ii) if $\varepsilon_{2,1}^{0,0}\le E<\varepsilon_{2,0}^{1,0}$, then the firm would invest immediately if the subsidy is provided, and (iii) if $E\ge\varepsilon_{2,0}^{1,0}$, then investment will take place immediately even in the absence of the subsidy. Intuitively, compared to (14), the extra region reflects the implications of subsidy provision in terms of the expected increase in the firm's profits, and, in turn, the likelihood of investment when the subsidy is not available but rather a future promise.

$$F_{2,0}^{1,0}(E)=\begin{cases}\dfrac{D_1E}{\rho-\mu}+\dfrac{\lambda_p y D_1 E}{(\rho-\mu)\left(\rho-\mu+\lambda_p\right)}+A_{2,1}^{0,0}E^{\beta_1}+A_{2,0}^{1,0}E^{\eta_1}, & E<\varepsilon_{2,1}^{0,0}\\ \dfrac{\lambda_p D_2 E(1+y)+(\rho-\mu)D_1E}{(\rho-\mu)\left(\rho-\mu+\lambda_p\right)}-\dfrac{\lambda_p I_2}{\rho+\lambda_p}+B_{2,0}^{1,0}E^{\eta_2}+C_{2,0}^{1,0}E^{\eta_1}, & \\ \qquad \varepsilon_{2,1}^{0,0}\le E<\varepsilon_{2,0}^{1,0} & \\ \Phi_{2,0}^{1,0}(E)-I_2, \quad E\ge\varepsilon_{2,0}^{1,0} & \end{cases} \tag{25}$$

The dynamics of the value of the active project before the arrival of the second technology in State 1 are described in (26).

$$\begin{aligned}&(\mathcal{L}-\rho)\Phi_{1,0}^{1,0}(E)+\lambda_p\left[\Phi_{1,1}^{0,0}(E)-\Phi_{1,0}^{1,0}(E)\right]\\&\quad+\lambda_\tau\left[F_{2,0}^{1,0}(E)-\Phi_{1,0}^{1,0}(E)\right]+D_1E=0\end{aligned} \tag{26}$$

Notice that (26) must be solved separately for each of the expressions of $F_{2,1}^{0,0}(E)$, $\Phi_{1,1}^{0,0}(E)$, and $F_{2,0}^{1,0}(E)$ that are indicated in (4), (8) and (25), respectively. Thus, $\Phi_{1,0}^{1,0}(E)$ is also defined over three different regions of E. Following the same approach as in Section 4.2, we obtain the expression for $\Phi_{1,0}^{1,0}(E)$ that is described in (27), where $A_{1,0}^{1,0}$, $B_{1,0}^{1,0}$, $C_{1,0}^{1,0}$ and $D_{1,0}^{1,0}$ are determined via value-matching and smooth-pasting conditions between the three branches. Each branch reflects the expected value of the first technology with an embedded option to invest in the second one. The second technology is not available yet and the corresponding investment option will not be exercised if the electricity price is low, i.e. $E<\varepsilon_{2,1}^{0,0}$ (top branch), however, it will be exercised instantly if the subsidy is provided (middle branch) or immediately regardless of the subsidy (bottom branch).

$$\Phi_{1,0}^{1,0}(E)=\begin{cases}\dfrac{D_1E}{\rho-\mu}+\dfrac{\lambda_pD_1Ey}{(\rho-\mu)\left(\rho-\mu+\lambda_p\right)} \\ \quad +A_{2,1}^{0,0}E^{\beta_1}+A_{2,0}^{1,0}E^{\eta_1}+A_{1,1}^{0,0}E^{\delta_1}+A_{1,0}^{1,0}E^{\theta_1}, & E<\varepsilon_{2,1}^{0,0} \\ \left[\dfrac{\left[\lambda_\tau D_2+(\rho-\mu)D_1\right]}{\rho-\mu+\lambda_\tau}+\dfrac{\lambda_\tau D_2}{\rho-\mu+\lambda_p}\right] \\ \times\dfrac{\lambda_pE(1+y)}{(\rho-\mu)^2\left(1+\frac{\lambda_p+\lambda_\tau}{\rho-\mu}\right)}+\dfrac{D_1E}{\rho-\mu+\lambda_p} \\ -\left(\dfrac{1}{\rho+\lambda_\tau}+\dfrac{1}{\rho+\lambda_p}\right)\dfrac{\lambda_\tau\lambda_pI_2}{\rho+\lambda_p+\lambda_\tau} \\ \quad +B_{2,0}^{1,0}E^{\eta_2}+C_{2,0}^{1,0}E^{\eta_1}+B_{1,1}^{0,0}E^{\delta_2} \\ +B_{1,0}^{1,0}E^{\theta_2}+C_{1,0}^{1,0}E^{\theta_1}, & \varepsilon_{2,1}^{0,0}\le E<\varepsilon_{2,0}^{1,0} \\ \left[\dfrac{\lambda_p(1+y)}{\rho-\mu+\lambda_\tau}+\dfrac{\lambda_py}{\rho-\mu+\lambda_p}+1\right]\dfrac{\lambda_\tau D_2E}{(\rho-\mu)^2\left(1+\frac{\lambda_p+\lambda_\tau}{\rho-\mu}\right)} \\ \quad +\left[\dfrac{\lambda_py}{(\rho-\mu)\left(1+\frac{\lambda_p+\lambda_\tau}{\rho-\mu}\right)}+1\right] \\ \times\dfrac{D_1E}{\rho-\mu+\lambda_\tau}-\dfrac{\lambda_\tau I_2}{\rho+\lambda_\tau}+B_{1,1}^{0,0}E^{\delta_2}+D_{1,0}^{1,0}E^{\theta_2}, & E\ge\varepsilon_{2,0}^{1,0}\end{cases} \tag{27}$$

Like in (26), the dynamics of the option to invest in the first technology with a single embedded option to upgrade to the second one are described in (28).

$$(\mathcal{L}-\rho)F_{1,0}^{1,0}(E)+\lambda_p\left[F_{1,1}^{0,0}(E)-F_{1,0}^{1,0}(E)\right]=0 \tag{28}$$

The expression of $F_{1,0}^{1,0}(E)$ is indicated in (29), where $\varepsilon_{1,0}^{1,0}$, $G_{1,0}^{1,0}$, $H_{1,0}^{1,0}$, and $J_{1,0}^{1,0}$, are determined numerically via value-matching and smooth-pasting conditions between the three branches. The first term in the top branch of (29) reflects the value of the option to invest in the presence of a subsidy, adjusted via the second term due to policy uncertainty. The first two terms in the second branch represent the expected value of the project if the subsidy is provided, while the third term is the option to invest in the second technology, adjusted for technological uncertainty via the fourth term. The last two terms reflect the likelihood of the price either dropping below $\varepsilon_{1,1}^{0,0}$ or increasing beyond $\varepsilon_{1,0}^{1,0}$.

$$F_{1,0}^{1,0}(E)=\begin{cases}C_{1,1}^{0,0}E^{\beta_1}+G_{1,0}^{1,0}E^{\eta_1} & ,E<\varepsilon_{1,1}^{0,0} \\ \dfrac{\lambda_pD_1E(1+y)}{(\rho-\mu)\left(\rho-\mu+\lambda_p\right)}-\dfrac{\lambda_pI_1}{\rho+\lambda_p}+A_{2,1}^{0,0}E^{\beta_1} \\ \quad +\dfrac{\lambda_p}{\lambda_p-\lambda_\tau}A_{1,1}^{0,0}E^{\delta_1}+H_{1,0}^{1,0}E^{\eta_2}+J_{1,0}^{1,0}E^{\eta_1} & ,\varepsilon_{1,1}^{0,0}\le E<\varepsilon_{1,0}^{1,0} \\ \Phi_{1,0}^{1,0}(E)-I_1 & ,E\ge\varepsilon_{1,0}^{1,0}\end{cases} \tag{29}$$

Although it is not possible to express the value of the option to invest as in (20), we analyse the impact of λ_p on $\varepsilon_{1,0}^{1,0}$ by applying the FONC to the value-matching condition between the bottom two branches of (29), and, thus, obtain (30). The first term on the left-hand side represents the extra benefit from allowing the project to start at a higher threshold price, the second term reflects the reduction in the MC due to saved investment cost and the third term is the MB from being able to delay investment should the electricity price drop below $\varepsilon_{1,1}^{0,0}$. The first term on the right-hand side is the MC of the forgone cash flows, while the second term represents the MC associated with the absence of the second technology. The fourth term on the left-hand side reflects the increase in MB due to the likelihood of a subsidy, whereas the third term on the right-hand is the corresponding MC of waiting because the subsidy is not available yet.

$$\left(\frac{E}{\varepsilon_{1,0}^{1,0}}\right)^{\eta_1}\left[\frac{D_1}{\rho-\mu+\lambda_p}+\frac{\eta_1\rho I_1}{\left(\rho+\lambda_p\right)\varepsilon_{1,0}^{1,0}}\right.$$
$$\left.+\theta_1A_{1,0}^{1,0}\varepsilon_{1,0}^{1,0\,\theta_1-1}+\left(\eta_1-\eta_2\right)H_{1,0}^{1,0}\varepsilon_{1,0}^{1,0\,\eta_2-1}\right]$$
$$=\left(\frac{E}{\varepsilon_{1,0}^{1,0}}\right)^{\eta_1}\left[\frac{\eta_1D_1}{\rho-\mu+\lambda_p}-\frac{\left(\delta_1-\eta_1\right)\lambda_\tau}{\lambda_\tau-\lambda_p}A_{1,1}^{0,0}\varepsilon_{1,0}^{1,0\,\delta_1-1}+\eta_1A_{1,0}^{1,0}\varepsilon_{1,0}^{1,0\,\theta_1-1}\right] \tag{30}$$

As shown in Proposition 4, greater likelihood of subsidy provision lowers the MB by more than the MC, thereby decreasing the optimal investment threshold. In combination with technological uncertainty, this result further emphasises how the optimal investment policy under stepwise investment differs from that under lumpy investment. Indeed, holding λ_p fixed, an increase in λ_τ raises the investment incentive, i.e. reduces the investment threshold, thus making the impact of subsidy provision even more pronounced.

Proposition 4. *Greater likelihood of subsidy provision lowers the optimal investment threshold.*

The relative loss in option value due to subsidy provision ($a=0,b=1,c=0$) or retraction ($a=1,b=0,c=1$) is $\frac{F_{1,1}^{0,0}(E)-F_{1,a}^{b,c}(E)}{F_{1,1}^{0,0}(E)}$. For example, under sudden subsidy provision, $\lambda_p=0$ means that the subsidy will never be provided and the relative loss in option value is maximised. By contrast, a greater λ_p increases the likelihood of permanent subsidy provision and lowers the relative loss in option value. The range of possible value for the relative loss in option value is indicated in Proposition 5.

Proposition 5. $\frac{F_{1,1}^{0,0}(E)-F_{1,a}^{b,c}(E)}{F_{1,1}^{0,0}(E)}\in\left[0,1-\frac{1}{(1+y)^{\beta_1}}\right]$.

4.4. Provision of a retractable subsidy

Unlike Section 4.3, here, we assume that the subsidy that was provided at time T_1^p may be retracted at time T_2^p, i.e. $a=0$, $b=1$ and $c=1$. Consequently, once the subsidy is provided, the firm receives the value of a retractable subsidy, which is already described in (11). The expected value of the project can be calculated as indicated in (31). Unlike (22), the second term on the left-hand side of (31) indicates that the subsidy is only available until time T_2^p. Using the properties of the Erlang distribution for the joint density of T_1^p and T_2^p, we can express the expected value of the active project as in (31).

$$\mathbb{E}_E\left[\int_0^\infty e^{-\rho t}D_2E_tdt+\int_{T_1^p}^{T_2^p}e^{-\rho t}D_2E_tydt\right]$$
$$=\frac{D_2E}{\rho-\mu}+\mathbb{E}\left\{\frac{D_2Ey\left[e^{-(\rho-\mu)T_1^p}-e^{-(\rho-\mu)T_2^p}\right]}{\rho-\mu}\right\}$$
$$=\frac{D_2E}{\rho-\mu}+\frac{D_2Ey}{\rho-\mu}\left[\int_0^\infty\lambda_pe^{-\lambda_pT_1^p}e^{-(\rho-\mu)T_1^p}dT_1^p\right.$$
$$\left.-\int_0^\infty\lambda_p^2T_2^pe^{-\lambda_pT_2^p}e^{-(\rho-\mu)T_2^p}dT_2^p\right] \tag{31}$$

The analytical expression of (31) is indicated in (32). Unlike Section 4.3, the subsidy is now available for a smaller time period, and, thus, its expected value is reduced, since $\frac{\lambda_p}{\left(\rho-\mu+\lambda_p\right)^2}\le\frac{\lambda_p}{(\rho-\mu)\left(\rho-\mu+\lambda_p\right)}$.

$$\Phi_{2,0}^{1,1}(E)=\frac{D_2E}{\rho-\mu}+\frac{\lambda_pD_2Ey}{\left(\rho-\mu+\lambda_p\right)^2} \tag{32}$$

Next, in State (1,2), the firm operates the first technology and holds a single embedded investment option. The dynamics of the value function $F_{2,0}^{1,1}(E)$ are described in (33), which must be solved for each expression of $F_{2,1}^{0,1}(E)$, that is indicated in (14). The expression for $F_{2,0}^{1,1}(E)$ is indicated in (D.1).

$$(\mathcal{L}-\rho)\,F_{2,0}^{1,1}(E)+\lambda_p\left[F_{2,1}^{0,1}(E)-F_{2,0}^{1,1}(E)\right]+D_1 E=0 \tag{33}$$

Stepping back to State 1, the dynamics of the value function $\Phi_{1,0}^{1,1}(E)$ are indicated in (34), and the expression of $\Phi_{1,0}^{1,1}(E)$ is indicated in (D.2).

$$(\mathcal{L}-\rho)\,\Phi_{1,0}^{1,1}(E)+\lambda_p\left[\Phi_{1,1}^{0,1}(E)-\Phi_{1,0}^{1,1}(E)\right] + \lambda_\tau\left[F_{2,0}^{1,1}(E)-\Phi_{1,0}^{1,1}(E)\right]+D_1 E=0 \tag{34}$$

Finally, in State (0,1), the dynamics of the value of the option to invest in the first technology are described in (35). Solving (35) for each expression of $F_{1,1}^{0,1}(E)$ indicated in (19), we obtain (D.3).

$$(\mathcal{L}-\rho)\,F_{1,0}^{1,1}(E)+\lambda_p\left[F_{1,1}^{0,1}(E)-F_{1,0}^{1,1}(E)\right]=0 \tag{35}$$

As it will be shown numerically, the likely retraction of the subsidy lowers the investment incentive compared to the case of permanent subsidy provision. This happens because the reduction in the lifetime of the subsidy renders it less valuable and raises the incentive to delay investment.

5. Case study

We illustrate the impact of price, policy and technological uncertainty on the optimal investment policy via a case study on offshore wind, which has experienced a tremendous growth over the last twenty years. Particularly impressive is the output increase over this time period, which is mostly driven by greater hub-heights, sweep area and average capacity. These factors have increased the capital cost of such projects considerably. Indeed, a typical offshore-wind turbine has a capacity of 4 MW today compared to only 2 MW in 2000. Also, the capacity factor, i.e. the average electricity generated divided by the capacity, has increased from 30% twenty years ago to 42% today (IRENA, 2018b). Hence, we can expect a typical offshore-wind turbine to yield 14.5 GWh per year today (4 MW×0.42 × 24h×365d) compared to 10 GWh in 2000. According to IRENA (2018b), the total cost of an offshore-wind turbine is approximately 4000 EUR/kW, and, with a capacity of 4 MW, the total installation cost is 16 million EUR, while less advanced platforms cost around 5.4 million EUR for a 2 MW capacity.

The relevant parameter values are indicated in Table 1. Apart from I_n and D_n that are obtained from IRENA (2018b), the remaining parameter values are based on stylised assumptions. However, μ and σ can be estimated from historic electricity prices, r can be estimated from government bonds and λ_τ can be estimated by fitting a Poisson process to historical data on innovation (https://ens.dk/en). Also, information on historic policy changes that can be used to gauge policymakers' commitment to current subsidies can be found at www.res-legal.eu/. The support scheme we consider is akin to a premium FIT, i.e. a fixed proportion on top of the electricity price (Couture et al., 2010). [For example, under the FIT scheme in Germany the subsidy has been set to 15 EUR/MWh],[1] and since market prices were around 50 EUR/MWh in early 2019, the subsidy amounts to 30% of the electricity price.[2] Also, we consider a context where rapid technological innovation renders existing technologies obsolete so that only a new technology presents a viable investment opportunity after the first one has already been adopted.

[1] A detailed description of the subsidy scheme in Germany can be found in http://www.res-legal.eu/search-by-country/germany/single/s/res-e/t/promotion/aid/premium-tariff-i-market-premium/lastp/135/.

[2] Market prices are available at https://www.epexspot.com/en/market-data/elix.

Table 1
Parameter values.

Parameter	Description	Benchmark values
D_2	Output for technology 2	14.5 GWh per year
I_2	Investment cost for technology 2	16 mEUR
D_1	Output for technology 1	5 GWh per year
I_1	Investment cost for technology 1	5 mEUR
y	Subsidy level	30%
r	Risk-free rate	2%
μ	Electricity price growth parameter	0%
σ	Volatility electricity price	20%
λ_p	Policy uncertainty	$\lambda_p \in [0, 1]$
λ_τ	Technological uncertainty	$\lambda_\tau \in [0, 1]$

Fig. 2 illustrates the project and option value as well as the optimal investment threshold for the second technology in the case of permanent subsidy retraction (left panel) and permanent subsidy provision (right panel). As the left panel illustrates, greater likelihood of subsidy retraction lowers the expected value of both the investment opportunity and the active project. This increases the incentive to delay investment and raises the optimal investment threshold. However, greater likelihood of subsidy provision raises the expected value of the option to invest and lowers the optimal investment threshold.

Fig. 3 illustrates the impact of technological and policy uncertainty on the optimal investment threshold in the second (left panel) and the first technology (right panel) under sudden subsidy retraction. As both panels illustrate, greater price uncertainty raises the opportunity cost of investment, and, in turn, the value of waiting, thereby increasing the incentive to postpone investment. Also, the threat of permanent subsidy retraction decreases the firm's incentive to invest and raises the optimal investment threshold, as shown in Proposition 2. However, the right panel illustrates the interaction between economic, technological and policy uncertainty, and indicates that stepwise investment facilitates earlier technology adoption compared to lumpy investment and that an increase in λ_τ makes this result even more pronounced. Intuitively, as λ_τ increases, the time interval between subsequent technology versions decreases. Consequently, in the attempt to maintain a compulsive strategy, a firm would be more willing to adopt the current technology version sooner before the new technology version is released. Furthermore, when the second technology is uncertain, i.e. for $0<\lambda_\tau<\infty$, an earlier adoption of the first technology facilitates the arrival of the second one. Hence, the firm has an incentive to adopt the first technology earlier to increase the expected NPV of the second one. From a technical standpoint, an increase in λ_τ while holding λ_p fixed raises the value of the embedded option, and, in turn, the incentive to invest. However, for a given λ_p, the impact of λ_τ on the optimal investment threshold in the first technology is not monotonic. This happens because in the presence of the embedded option ($\lambda_\tau \to \infty$) the project and option value for the first technology are greater compared to the case $\lambda_\tau = 0$, yet the optimal investment threshold is not affected. This implies that, the firm behaves myopically when adopting the first technology given that the second one is available, as shown in Chronopoulos and Siddiqui (2015). This is why we observe the non-monotonic behaviour, whereby the optimal investment threshold decreases (increases) with higher λ_τ when λ_τ is small (large).

This result emphasises how modular capacity expansion in the light of technological uncertainty can have a critical impact on the decision to invest compared to a lumpy investment strategy and has important implications for both private firms and policymakers. Indeed, the former can take into account the impact of policy uncertainty on the value of the project and the option to invest, and, thus, make more informed investment and operational decisions. Similarly, the latter can devise more effective policy mechanisms by balancing the adverse impact of subsidy retraction on investment timing in terms of decelerating investment against the value of stepwise investment that induces earlier technology adoption. Note that the value of stepwise

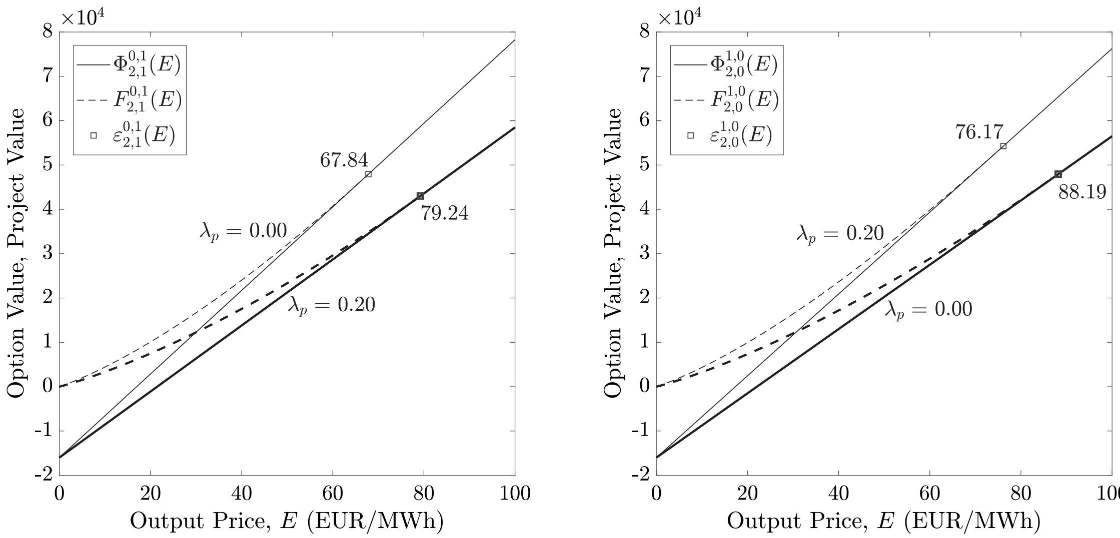

Fig. 2. Option and project value for investment in the second technology under permanent subsidy retraction (left) and permanent subsidy provision (right) for $\lambda_p = 0.00, 0.2$ and $\sigma = 0.20$. Greater likelihood of subsidy retraction (provision) lowers (raises) the expected value of the project and decreases (increases) the investment incentive.

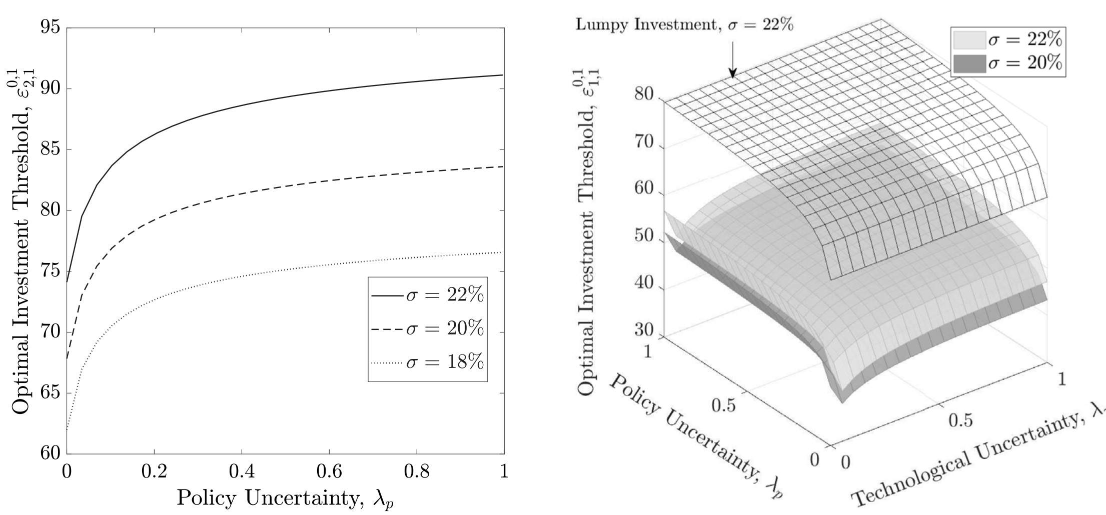

Fig. 3. Impact of λ_p and λ_τ on the optimal investment threshold in the second (left) and the first technology (right) under sudden subsidy retraction. A higher innovation rate raises the value of the project and the incentive to invest, thereby mitigating the impact of subsidy retraction.

investment in terms of the timing of technology adoption is two-fold: First, stepwise investment facilitates earlier technology adoption as it entails an initial investment cost that is lower than that under lumpy investment. Second, greater likelihood of technological innovation lowers the optimal investment threshold for the first technology for a given level of λ_p, thus further increasing the discrepancy between the lumpy and the stepwise investment investment threshold.

The practical relevance of the results of Fig. 3 is also indicated in Table 2. Notice that an increase in λ_p for $\lambda_\tau = 0$ increases the incentive to delay investment and raises the optimal investment threshold. For example, an increase of λ_p from 0 to 0.12 when $\lambda_\tau = 0$ raises $\varepsilon^{0,1}_{0,1}$ from 43.5 to 49.67. However, an increase in λ_τ from 0 to 0.0181 for $\lambda_p = 0.12$ results in a decrease in $\varepsilon^{0,1}_{0,1}$ to its initial value, i.e. 43.5. Hence, the implications of subsidy retraction in terms of delaying investment can be completely offset by incentivising greater R&D efforts. The implications of this result are relevant from a policymaking perspective considering how private firms often own a portfolio of technologies with different innovation rates, e.g. wind, solar, etc. Hence, quantifying the extent to which sequential investment opportunities accelerate technology adoption enables the design of policy commitments, so that the delay in technology adoption that policy uncertainty motivates is offset by the greater incentive to invest due to the likely arrival of an improved technology version. Also, from a policymaking standpoint, the comparison between lumpy and stepwise investment is critical in terms of balancing the benefit of installing a greater capacity at a later date (lumpy investment) over an earlier investment but in a smaller initial project (stepwise investment).

Unlike the case of sudden subsidy retraction, the left panel of Fig. 4 indicates that greater likelihood of subsidy provision accelerates the adoption of the second technology, as shown in Proposition 4. As the right panel illustrates, this result also holds for the first technology, however, the interaction between policy and technological uncertainty is such that greater likelihood of innovation further accelerates investment in the first technology. Note that under a compulsive technology adoption strategy the firm invests in each technology that becomes available. Thus, an increase in λ_τ raises the value of the embedded

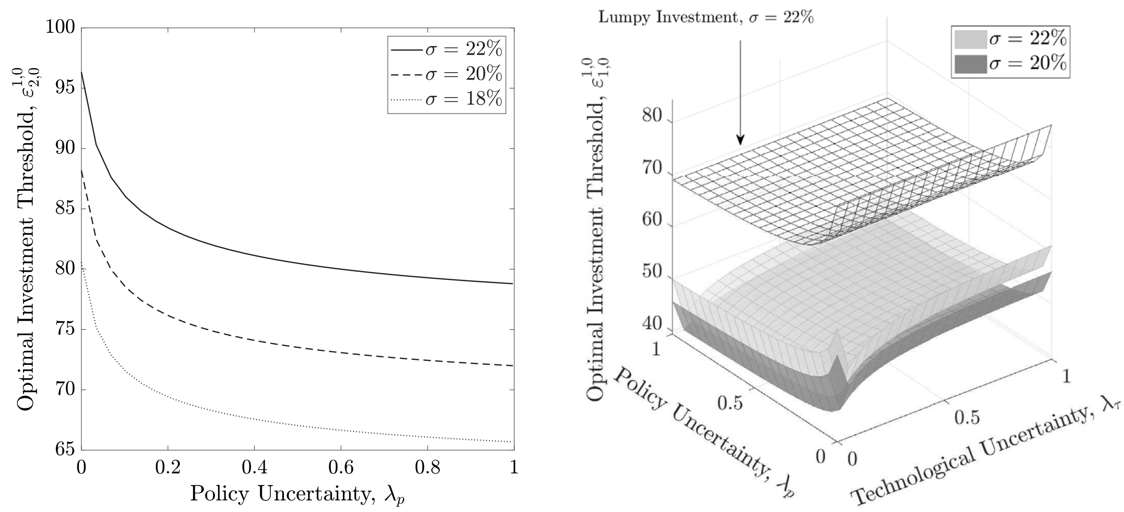

Fig. 4. Impact of λ_p and λ_τ on the optimal investment threshold in the second (left) and the first technology (right) under sudden subsidy provision. The likely arrival of a new technology raises the incentive to invest in the existing one and makes the impact of subsidy provision more pronounced.

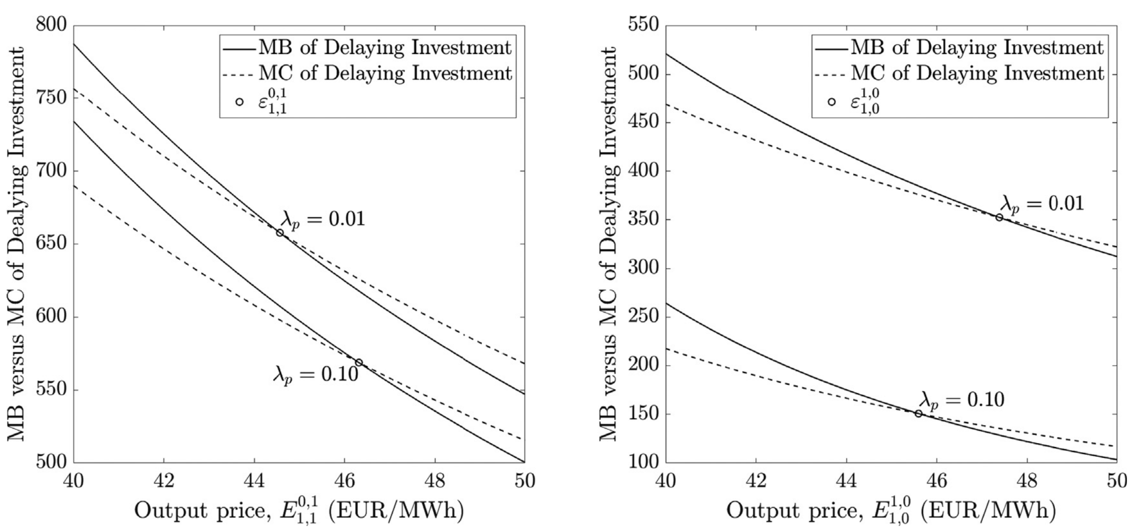

Fig. 5. Impact of λ_p on the MB and MC of delaying investment for a permanent sudden retraction (left) and a permanent provision (right) for $\lambda_\tau = 0.02$ and $\sigma = 0.20$.

Table 2
Comparison between lumpy and stepwise investment.

Impact of λ_p on investment threshold				Reduction in $\varepsilon_{0,1}^{0,1}$ due to innovation		
λ_p	λ_τ	Lumpy investment	$\varepsilon_{0,1}^{0,1}$	λ_p	λ_τ	$\varepsilon_{0,1}^{0,1}$
0.00	0.0	64.95	43.50	0.00	–	–
0.12	–	73.86	49.67	0.12	0.0181	43.50
0.24	–	76.16	51.19	0.24	0.0012	49.67
0.36	–	77.37	51.99	0.36	0.0006	51.19
0.48	–	78.16	52.51	0.48	0.0004	51.99
0.60	–	78.72	52.87	0.60	0.0002	52.51

option to invest in the second technology, and, in turn, the value of the option to invest in the first one.

Fig. 5 illustrates how the impact of policy uncertainty on the optimal investment threshold can be decomposed with respect to the MB and MC of delaying investment. Notice that greater likelihood of subsidy retraction (left panel) lowers both the MB and the MC curve, yet the latter shifts down by more than the former, and, as a result, the two curves intersect at a higher threshold. Intuitively, the extra cost from delaying investment is reflected partly in the loss in value due to the absence of the second technology. This loss becomes more pronounced as both the electricity price and the likelihood of subsidy retraction increase. By contrast, greater likelihood of subsidy provision decreases both the MB and MC, yet the MB decreases by more, thereby decreasing the marginal value of delaying investment, and, in turn, the optimal investment threshold (right panel).

As shown in Proposition 5 and illustrated in Fig. 6, the relative loss in option value due to sudden subsidy retraction or provision obtains values within the interval $\left[0, 1 - \frac{1}{(1+\gamma)^{\beta_1}}\right]$, which, for the parameter value of Table 1, becomes $[0, 35\%]$. Within this interval, an increase in the likelihood of subsidy retraction (provision) from $\lambda_p = 2\%$ to $\lambda_p = 4\%$ raises (lowers) the relative loss in options value, as illustrated in the left (right) panel of Fig. 6 via the upward (downward) shift of the curves. Also, as both panels illustrate, the impact of λ_τ on the relative loss in option value is non-monotonic. Note that both $F_{1,1}^{0,0}(E)$ and $F_{1,1}^{1,0}(E)$ reflect options to invest in an existing technology with

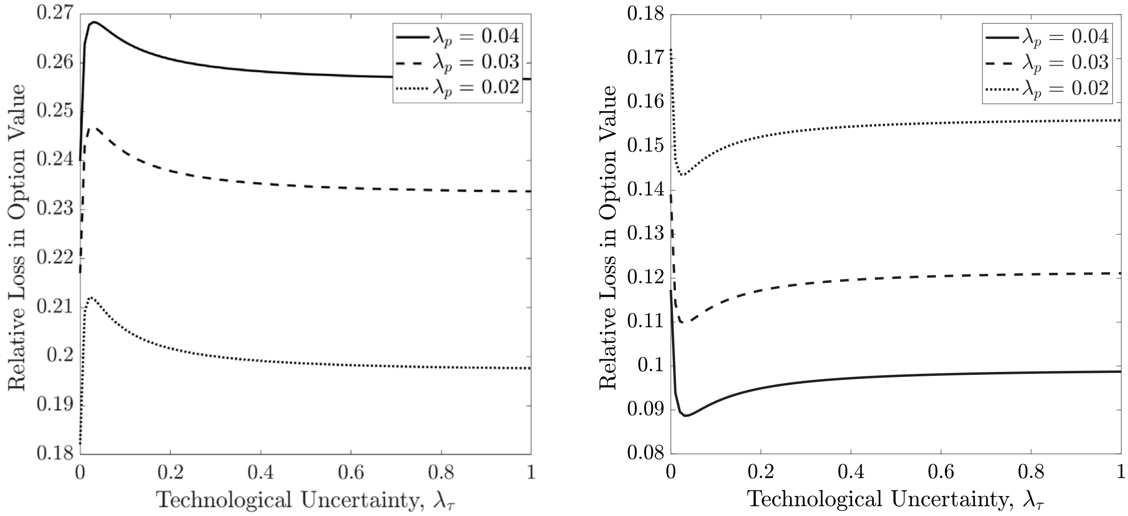

Fig. 6. Impact of λ_p and λ_τ on the relative loss in options value under permanent subsidy retraction (left) and permanent subsidy provision (right), for $\sigma = 0.20$. The likely arrival of a more advanced technology version raises (lowers) the relative loss in option value due to subsidy retraction (provision).

a single embedded option to adopt an improved technology version. Hence, as λ_τ increases, the value of the embedded option increases in both cases. However, since $F_{1,1}^{0,0}(E)$ includes a permanent subsidy, it increases proportionally by more than $F_{1,1}^{1,0}(E)$, which explains the increase in the relative loss in option value for low value of λ_τ. This increase stops as soon as $F_{1,1}^{0,0}(E)$ approaches its maximum value. At the same time, $F_{1,1}^{1,0}(E)$ continues to increase yet at a lower rate, which results in a slight decrease in the relative loss in option value until it also reached its maximum and the relative loss remains constant.

Fig. 7 illustrates how the likely retraction of a subsidy following its initial provision impacts the optimal investment policy and the relative loss in option value. Compared to the case of permanent subsidy provision (thin curves), the retraction of the subsidy lowers the expected value of the project, and, in turn, the expected value of the investment opportunity, thereby increasing the incentive to postpone investment. This is in line with Karneyeva and Wüstenhagen (2017), who find that retroactive policy changes in Italy increased perceived policy risk, and, in turn, the value of the remaining feed-in tariffs. In the right panel, the arrows indicate the direction of increasing policy interventions, specifically, the shift from permanent provision of a subsidy to provision of a retractable subsidy. Notice that, for each value of λ_p, the relative loss in option value under the sudden provision of a retractable subsidy (thick curves) is greater than the relative loss in option value in the case of sudden provision of a permanent subsidy (thin curves). Thus, the right panel illustrates the adverse impact of sequential policy interventions in terms of reducing the expected value of the firm's option to invest.

Fig. 8 illustrates the impact of λ_p and λ_τ on the optimal investment threshold in the case of provision of a permanent and a retractable subsidy. As both panels illustrate, $\lambda_p = 0$ implies that the subsidy will never be provided, and, therefore, $\epsilon_{2,0}^{1,1} = \epsilon_{2,0}^{1,0}$. However, an increase in λ_p implies that the value due the provision of the subsidy is reduced due to the likelihood of a subsequent retraction. Consequently, relative to the case of permanent subsidy provision, the likelihood that the subsidy will be available temporarily decreases the investment incentive and raises the optimal investment threshold, i.e. $\epsilon_{2,0}^{1,1} > \epsilon_{2,0}^{1,0}$. This also implies that the impact of λ_p on the optimal investment threshold is non-monotonic when the subsidy is only temporarily available. Indeed, for low values of λ_p, $\epsilon_{2,0}^{1,1}$ decreases due to the likely provision of the subsidy. However, a further increase in λ_p shortens the period in which the subsidy is available, thus increasing the incentive to postpone investment. Furthermore, note that despite the likely withdrawal of a subsidy, the mere prospect of subsidy provision induces earlier adoption than no subsidy at all, as can be seen by comparing the surface to the line when $\lambda_p = 0$. Interestingly, even though the subsidy is assumed to be available under lumpy investment, a stepwise investment approach leads to earlier technology adoption despite the uncertainty over subsidy provision. This happens because the expected value of the investment cost associated with the second technology is lower relative to case of lumpy investment due to the effect of discounting.

Nevertheless, as the right panel illustrates, the possibility to upgrade an existing technology by adopting a more advanced version creates an opposing force that mitigates the impact of subsidy retraction. In relation to the interaction between technological and policy uncertainty, this result is crucial from the perspective of policymakers and private firms. Indeed, within a volatile economic environment, support schemes that aim to stimulate investment in RE technologies are likely to be revised frequently. Hence, taking into account how private firms may respond to frequent revisions of a support scheme when a project entails embedded investment options, will facilitate informed revisions of support schemes and decisions upon the rate of policy interventions that do not risk the timing of the required investments in RE and maintain it within desired limits.

6. Conclusions and policy implications

The implications of the structural transformation of the power sector for both market participants and policymakers are considered to be crucial as they are expected to change substantially the wholesale market dynamics (Sensfuß et al., 2008). Within this environment, private firms are required to make accurate investment decisions, while policymakers must take into account how private firms respond to different sources of uncertainty in order to incentivise investment. The objective of the analysis is to provide complementary insights to the well-established energy systems models by addressing the behavioural impact of incentives upon market agents. These insights are particularly relevant to the energy sector, where frequent revisions of support schemes create uncertain responses to incentives, while technological innovations create sequential investment opportunities. The results of the analysis can be summarised into the following three main lessons:

i. Greater likelihood of subsidy retraction (provision) postpones (accelerates) investment. The implications of this result are crucial

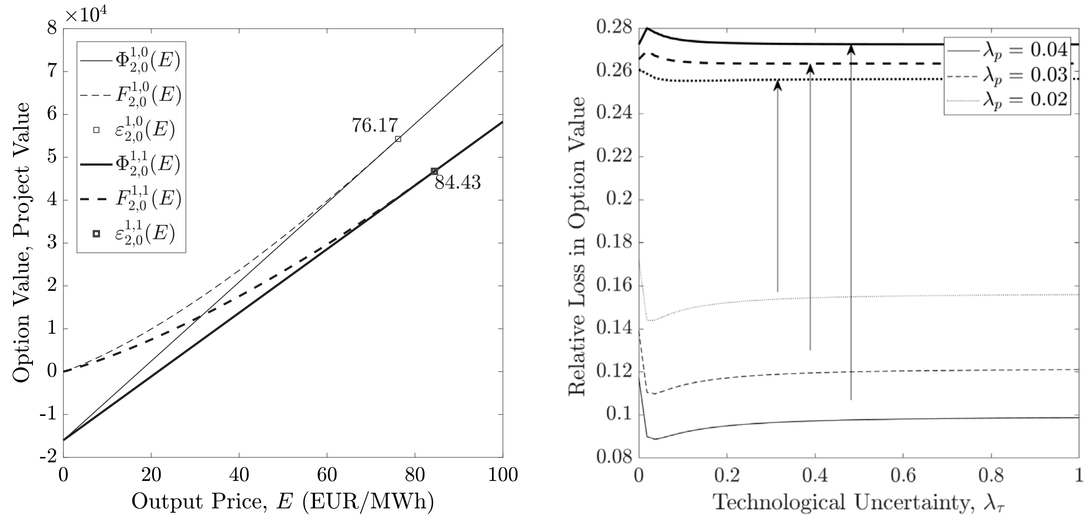

Fig. 7. Option and project value for investment in the second technology under the provision of a permanent and a retractable subsidy for $\lambda_p = 0.2$ and $\sigma = 0.2$ (left) and relative loss in option value (right). The likely retraction of a subsidy following its initial provision increases the incentive to postpone investment (left) and raises the relative loss in option value (right).

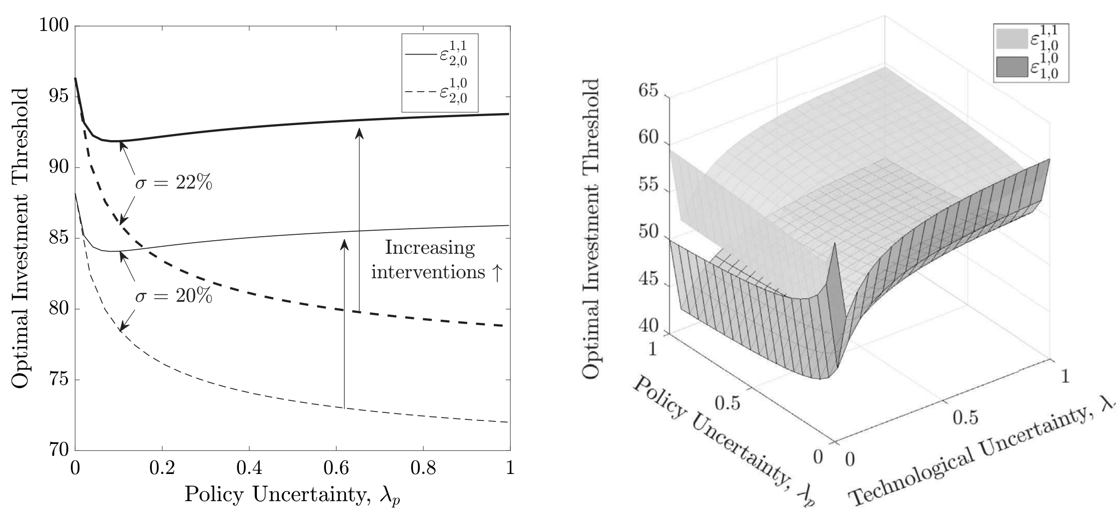

Fig. 8. Impact of λ_p and λ_τ on the optimal investment threshold in the second (left) and the first technology version (right) under sudden provision of a permanent and a retractable subsidy, for $\sigma = 0.22$. The likely retraction of a subsidy following its initial provision decreases the expected value of the project and increases the incentive to postpone investment. However, the option to adopt an improved technology version mitigates the impact of subsidy retraction.

from a policy-making standpoint as it quantifies how market participants would act upon their flexibility to delay investment in the light of economic, technological and policy uncertainty. Indeed, discretion over investment timing impacts upon the possible effectiveness of achieving timely the investment targets set by policy. For example, under the Paris Agreement, the EU's nationally determined contribution is to reduce greenhouse gas emissions by at least 40% by 2030 compared to 1990 (The Independent, 2018a).

ii. The flexibility to proceed in stages enables efficient technological risk management, which offers a critical advantage over a lumpy investment strategy as it accelerates investment, and this result is more pronounced in the light of technological uncertainty. This implies that the possibility to invest in an improved version of a RE technology mitigates the impact of policy uncertainty in the case of subsidy retraction, and makes the impact of subsidy provision more pronounced. Consequently, the decision to provide or retract a subsidy should account for the added value of the flexibility to upgrade an existing RE technology and the rate at which it will become available to ensure the efficient use of scarce resources. Indeed, through new auction-based systems, governments have almost eliminated subsidy payments for offshore-wind, which has demonstrated tremendous efficiency improvements (IEA, 2017).

iii. Sequential policy interventions should be designed so as to minimise the likelihood of an adverse impact on the optimal timing of technology adoption. For example, the retraction of a subsidy following its initial provision results in later technology adoption relative to the case of permanent subsidy provision. Quantifying the delay caused by the retraction of a subsidy makes it possible to design its duration in a way that maintains the timing of technology adoption within acceptable limits. This may also prevent undesirable market reactions, such as the 56% decrease in RE investment after the announcement of RE subsidy cuts in the UK (The Independent, 2018b).

Extensions of this framework may include the development of a two-factor model in order to investigate how the correlation between price and policy uncertainty impacts the optimal investment policy. Additionally, empirical research regarding the rate of policy interventions would provide crucial insights not only on the appropriate model specification, but also on how to configure model parameters in order to model realistic situations within the RE industry. Finally, to relax the assumption of a GBM, a mean-reverting process could be implemented within the same framework, while allowing for different technology adoption strategies, e.g. leapfrog and laggard, would enable further investigation of how the dominant strategy is affected by technological and policy uncertainty.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Lars Hegnes Sendstad: Methodology, Formal analysis, Writing - original draft, Visualization. **Michail Chronopoulos:** Conceptualization, Validation, Writing - review & editing, Supervision.

Acknowledgements

The authors are grateful for helpful suggestions from Petter Bjerksund, Stein-Erik Fleten, Verena Hagspiel, Peter Kort and Frode Kjærland. Additionally, we would like to express our gratitude for feedback from participants of the Annual International Real Options Conference 2015, InvestExl's project meeting, FIBE 2016 and NFB Research School Conference 2015. We also acknowledge support from the Research Council of Norway through project 268093 and 274569.

Appendix A. Benchmark Case

The dynamics of the value function $F^{0,0}_{2,a}(E)$ are described in (2). And by using Itô's lemma, we expand the right-hand side of (2), and, thus, we obtain (A.1).

$$\frac{1}{2}\sigma^2 E^2 F^{0,0''}_{2,a}(E) + \mu E F^{0,0'}_{2,a}(E) - \rho F^{0,0}_{2,a}(E) + D_1 E\,(1+ya) = 0 \tag{A.1}$$

Notice that the solution of the homogeneous part of (A.1) is $F^{0,0}_{2,a}(E) = A^{0,0}_{2,a}E^{\beta_1} + B^{0,0}_{2,a}E^{\beta_2}$. However, $E \to 0 \Rightarrow B^{0,0}_{2,a}E^{\beta_2} \to \infty$, and, therefore, $B^{0,0}_{2,a} = 0$. The expression for $F^{0,0}_{2,a}(E)$ is indicated in (4). Also, $\varepsilon^{0,0}_{2,a}$ and $A^{0,0}_{2,a}$ are indicated in (5) and are determined analytically via the value-matching and smooth-pasting conditions indicated in (A.2) and (A.3), respectively.

$$\frac{D_2\varepsilon^{0,0}_{2,a}(1+ay)}{\rho-\mu} - I_2 = \frac{D_1\varepsilon^{0,0}_{2,a}(1+ay)}{\rho-\mu} + A^{0,0}_{2,a}\varepsilon^{0,0\beta_1}_{2,a} \tag{A.2}$$

$$\frac{D_2(1+ay)}{\rho-\mu} = \frac{D_1(1+ay)}{\rho-\mu} + \beta_1 A^{0,0}_{2,a}\varepsilon^{0,0\beta_1-1}_{2,a} \tag{A.3}$$

Also, the endogenous constants $A^{0,0}_{1,a}$ and $B^{0,0}_{1,a}$ are indicated in (A.4) and (A.5) and are determined by applying value-matching and smooth-pasting conditions to (8). Note that $A^{0,0}_{1,a} \le 0$, since the third term in the top part of (8) reflects the reduction in option value (second term) because the second technology has yet to become available. Also, $B^{0,0}_{1,a} \ge 0$ since the third term in the bottom part of (8) reflects the likelihood of the price dropping in the waiting region.

$$A^{0,0}_{1,a} = \frac{\varepsilon^{0,0-\delta_1}_{2,a}}{\delta_2-\delta_1}\left[\frac{\lambda_\tau\left(\delta_2-1\right)\left(D_2-D_1\right)(1+ya)\,\varepsilon^{0,0}_{2,a}}{(\rho-\mu)\left(\rho-\mu+\lambda_\tau\right)} - \frac{\delta_2\lambda_\tau I_2}{\lambda_\tau+\rho} + \left(\beta_1-\delta_2\right)A^{0,0}_{2,a}\varepsilon^{0,0\beta_1}_{2,a}\right] \le 0 \tag{A.4}$$

$$B^{0,0}_{1,a} = \frac{\varepsilon^{0,0-\delta_2}_{2,a}}{\delta_1-\delta_2}\left[\frac{\lambda_\tau\left(1-\delta_1\right)\left(D_2-D_1\right)(1+ya)\,\varepsilon^{0,0}_{2,a}}{(\rho-\mu)\left(\rho-\mu+\lambda_\tau\right)} + \frac{\delta_1\lambda_\tau I_2}{\lambda_\tau+\rho} - (\beta_1-\delta_1)A^{0,0}_{2,a}\varepsilon^{0,0\beta_1}_{2,a}\right] \ge 0 \tag{A.5}$$

Proposition 1. *A trade-off between the two technologies exists if* $\frac{D_1}{I_1} > \frac{D_2}{I_2}$.

Proof. The electricity price, α, where the expected NPVs of the profits of the two technologies are equal is given in (A.6).

$$\frac{D_1\alpha\,(1+ay)}{\rho-\mu} - I_1 = \frac{D_2\alpha\,(1+ay)}{\rho-\mu} - I_2 \Rightarrow \alpha = \frac{\left(I_1-I_2\right)(\rho-\mu)}{\left(D_1-D_2\right)(1+ay)} \tag{A.6}$$

Since the value function must be positive at α, we have:

$$\frac{\left(I_1-I_2\right)(\rho-\mu)}{\left(D_1-D_2\right)(1+ay)}\,\frac{D_1\,(1+ay)}{\rho-\mu} - I_1 > 0$$
$$\iff \left(I_1-I_2\right)D_1 - \left(D_1-D_2\right)I_1 < 0$$

Hence, the condition becomes: $I_1 D_2 \langle I_2 D_1 \iff D_1/I_1 \rangle D_2/I_2$. ■

Appendix B. Permanent subsidy retraction

Proposition 2. *Greater likelihood of subsidy retraction raises the optimal investment threshold.*

Proof. Since technological and policy uncertainty are modelled as independent Poisson processes, the impact of greater λ_p on the optimal investment threshold would be qualitatively the same for each value of λ_τ, as demonstrated in the right panel of Figs. 3 and 4. For example, considering the first technology in the absence of the second one ($\lambda_\tau = 0$), greater λ_p lowers the expected value of the active project as indicated in (B.1).

$$\frac{\partial}{\partial\lambda_p}\Phi^{0,1}_{1,1}(E) = \frac{\partial}{\partial\lambda_p}\left[\frac{D_1 E}{\rho-\mu} + \frac{D_1 E y}{\rho-\mu+\lambda_p}\right] < 0 \tag{B.1}$$

Also, to demonstrate the additive impact of λ_p on the expected value of the active project for $\lambda_\tau > 0$, we consider the case $\lambda_\tau \to \infty$ and the option to invest in the second technology, $F^{0,1}_{2,1}(E)$, for $E < \varepsilon^{0,1}_{2,1}$, which is indicated in the top part of (14). As shown in (B.2), the impact of λ_p on $F^{0,1}_{2,1}(E)$ consists of the impact on the expected value from operating the first technology (first term) and the impact on the option to invest in the second one (second term). Like in (B.1), greater λ_p lowers the expected value from operating the first technology. Also, greater λ_p lowers the expected value of the embedded option since $A^{0,1}_{2,1}E^{\eta_1}$ reflects the added value from the subsidy which decreases with greater λ_p.

$$\frac{\partial}{\partial\lambda_p}F^{0,1}_{2,1}(E) = \underbrace{\frac{\partial}{\partial\lambda_p}\left[\frac{D_1 E}{\rho-\mu} + \frac{D_1 E y}{\rho-\mu+\lambda_p}\right]}_{<0} + \underbrace{\frac{\partial}{\partial\lambda_p}\left[A^{0,0}_{2,0}E^{\beta_1} + A^{0,1}_{2,1}E^{\eta_1}\right]}_{<0} \tag{B.2}$$

Consequently, to facilitate the exposition of the derivation we will show that that greater likelihood of subsidy retraction raises the optimal investment threshold for $\lambda_\tau = 0$. First, note that, based on the general expression of β_1, η_1, δ_1 and θ_1 indicated in (B.3), where $d = \mu - 0.5\sigma^2$, we have the following relationships: $\theta_1 \ge \eta_1 \ge \beta_1 \ge 1$ and $\theta_1 \ge \delta_1 \ge \beta_1 \ge 1$, while $\frac{\partial \eta_1}{\partial \lambda_p} > 0$, $\frac{\partial \delta_1}{\partial \lambda_\tau} > 0$, $\frac{\partial \theta_1}{\partial \lambda_p} > 0$, and $\frac{\partial \theta_1}{\partial \lambda_\tau} > 0$.

$$\begin{aligned} \beta_1 &= \frac{-d + \sqrt{d^2 + 2\sigma^2 \rho}}{\sigma^2} \\ \eta_1 &= \frac{-d + \sqrt{d^2 + 2\sigma^2 (\rho + \lambda_p)}}{\sigma^2} \\ \delta_1 &= \frac{-d + \sqrt{d^2 + 2\sigma^2 (\rho + \lambda_\tau)}}{\sigma^2} \\ \theta_1 &= \frac{-d + \sqrt{d^2 + 2\sigma^2 (\rho + \lambda_\tau + \lambda_p)}}{\sigma^2} \end{aligned} \tag{B.3}$$

If $\lambda_\tau = 0$, then (21) simplifies to (B.4). This happens because $\delta_1 = \beta_1 \Rightarrow -A_{1,1}^{0,1} = A_{2,1}^{0,1}$, and, therefore, the terms involving $A_{2,1}^{0,1}$, $A_{1,1}^{0,1}$ and $A_{1,0}^{0,0}$ cancel out.

$$\begin{aligned} &\left(\frac{E}{\varepsilon_{1,1}^{0,1}}\right)^{\beta_1} \left[\frac{D_1}{\rho-\mu} + \frac{D_1 y}{\rho - \mu + \lambda_p} + \frac{\beta_1 I_1}{\varepsilon_{1,1}^{0,1}} + \beta_1 C_{1,1}^{0,1} \varepsilon_{1,1}^{0,1\,\eta_1 - 1}\right] \\ &= \left(\frac{E}{\varepsilon_{1,1}^{0,1}}\right)^{\beta_1} \left[\frac{\beta_1 D_1}{\rho-\mu} + \frac{\beta_1 D_1 y}{\rho - \mu + \lambda_p} + \eta_1 C_{1,1}^{0,1} \varepsilon_{1,1}^{0,1\,\eta_1 - 1}\right] \end{aligned} \tag{B.4}$$

We start by subtracting the right- from the left-hand side of (B.4) as indicated in (B.5), where $C_{1,1}^{0,1} \varepsilon_{1,1}^{0,1\,\eta_1-1} = \frac{D_1}{\rho-\mu} + \frac{D_1 y}{\rho-\mu+\lambda_p} - \frac{I_1}{\varepsilon_{1,1}^{0,1}} - C_{1,0}^{0,0} \varepsilon_{1,1}^{0,1\,\beta_1-1}$.

$$\begin{aligned} &\frac{D_1}{\rho-\mu} + \frac{D_1 y}{\rho-\mu+\lambda_p} + \frac{\beta_1 I_1}{\varepsilon_{1,1}^{0,1}} + \beta_1 \left[\frac{D_1}{\rho-\mu} + \frac{D_1 y}{\rho-\mu+\lambda_p}\right. \\ &\left. - \frac{I_1}{\varepsilon_{1,1}^{0,1}} - C_{1,0}^{0,0} \varepsilon_{1,1}^{0,1\,\beta_1-1}\right] - \frac{\beta_1 D_1}{\rho-\mu} - \frac{\beta_1 D_1 y}{\rho-\mu+\lambda_p} \\ &- \eta_1 \left[\frac{D_1}{\rho-\mu} + \frac{D_1 y}{\rho-\mu+\lambda_p} - \frac{I_1}{\varepsilon_{1,1}^{0,1}} - C_{1,0}^{0,0} \varepsilon_{1,1}^{0,1\,\beta_1-1}\right] = 0 \end{aligned} \tag{B.5}$$

Next, we rewrite (B.5) as in (B.6).

$$\frac{D_1}{\rho-\mu} + \frac{(1-\eta_1) D_1 y}{\rho-\mu+\lambda_p} - \beta_1 C_{1,0}^{0,0} \varepsilon_{1,1}^{0,1\,\beta_1-1} - \eta_1 \left[\frac{D_1}{\rho-\mu} - \frac{I_1}{\varepsilon_{1,1}^{0,1}} - C_{1,0}^{0,0} \varepsilon_{1,1}^{0,1\,\beta_1-1}\right] = 0 \tag{B.6}$$

Finally, we set

$$\begin{aligned} M = \frac{\partial}{\partial \lambda_p} \Bigg[&\frac{D_1}{\rho-\mu} + \frac{(1-\eta_1) D_1 y}{\rho-\mu+\lambda_p} - \beta_1 C_{1,0}^{0,0} \varepsilon_{1,1}^{0,1\,\beta_1-1} \\ &- \eta_1 \left[\frac{D_1}{\rho-\mu} - \frac{I_1}{\varepsilon_{1,1}^{0,1}} - C_{1,0}^{0,0} \varepsilon_{1,1}^{0,1\,\beta_1-1}\right]\Bigg] \end{aligned} \tag{B.7}$$

with the objective to show that $M > 0$, as this would imply that the MC of delaying investment decreases by more than the MB with greater λ_p, and, therefore, greater likelihood of subsidy retraction increases the marginal value of delaying investment, and, in turn, the optimal investment threshold.

$$M = \frac{\partial}{\partial \lambda_p} \frac{(1-\eta_1) D_1 y}{\rho-\mu+\lambda_p} - \left[\frac{D_1}{\rho-\mu} - \frac{I_1}{\varepsilon_{1,1}^{0,1}} - C_{1,0}^{0,0} \varepsilon_{1,1}^{0,1\,\beta_1-1}\right] \frac{\partial \eta_1}{\partial \lambda_p} \geq 0 \tag{B.8}$$

Note that $\frac{\partial}{\partial \lambda_p} \frac{(1-\eta_1) D_1 y}{\rho-\mu+\lambda_p} = \frac{D_1 y}{(\rho-\mu+\lambda_p)^2} \left[\eta_1 - 1 - (\rho - \mu + \lambda_p) \frac{\partial \eta_1}{\partial \lambda_p}\right]$ and, thus, we can rewrite M as in (B.9).

$$M = \frac{D_1 y \left[\eta_1 - 1 - (\rho-\mu+\lambda_p) \frac{\partial \eta_1}{\partial \lambda_p}\right]}{(\rho-\mu+\lambda_p)^2} - \left[\frac{D_1}{\rho-\mu} - \frac{I_1}{\varepsilon_{1,1}^{0,1}} - C_{1,0}^{0,0} \varepsilon_{1,1}^{0,1\,\beta_1-1}\right] \frac{\partial \eta_1}{\partial \lambda_p} \geq 0 \tag{B.9}$$

Multiplying both sides of the inequality by $\varepsilon_{1,1}^{0,1}$ we obtain:

$$\begin{aligned} &\left[C_{1,0}^{0,0} \varepsilon_{1,1}^{0,1\,\beta_1} - \left(\frac{D_1 \varepsilon_{1,1}^{0,1}}{\rho-\mu} - I_1\right)\right] \frac{\partial \eta_1}{\partial \lambda_p} \\ &+ \frac{D_1 y \varepsilon_{1,1}^{0,1}}{(\rho-\mu+\lambda_p)^2} \left[\eta_1 - 1 - (\rho-\mu+\lambda_p) \frac{\partial \eta_1}{\partial \lambda_p}\right] \geq 0 \end{aligned} \tag{B.10}$$

Note that the first term in (B.10) is positive since $\frac{\partial \eta_1}{\partial \lambda_p} > 0$ while the expression within the brackets can be written as $F_{1,0}^{0,0}\left(\varepsilon_{1,1}^{0,1}\right) - \left(\Phi_{1,0}^{0,0}\left(\varepsilon_{1,1}^{0,1}\right) - I_1\right)$ and we know that $F_{1,0}^{0,0}\left(\varepsilon_{1,1}^{0,1}\right) > \Phi_{1,0}^{0,0}\left(\varepsilon_{1,1}^{0,1}\right) - I_1$ for $\varepsilon_{1,1}^{0,1} < \varepsilon_{1,0}^{0,0}$, i.e. the expected option value is greater than the expected NPV at a price level lower than the optimal one. The second term is also positive since $\frac{D_1 y \varepsilon_{1,1}^{0,1}}{(\rho-\mu+\lambda_p)^2} > 0$ while $\eta_1 - 1 - (\rho-\mu+\lambda_p) \frac{\partial \eta_1}{\partial \lambda_p} \geq 0$ requires that $\eta_1 - 1 \geq \sqrt{\frac{\rho+\lambda_p}{2\sigma^2}}$ or equivalently that $\sqrt{\frac{\rho+\lambda_p}{2\sigma^2}} \leq \sqrt{4 \cdot \frac{\rho+\lambda_p}{2\sigma^2} + \left(\frac{\mu}{\sigma^2} - \frac{1}{2}\right)^2} - \left(\frac{\mu}{\sigma^2} + \frac{1}{2}\right)$. For low values of μ (as in Table 1), $\frac{\mu}{\sigma^2} \simeq 0$ and the last condition simplifies to $\frac{\rho+\lambda_p}{2\sigma^2} > \frac{1}{3}\sqrt{\frac{\rho+\lambda_p}{2\sigma^2}}$, which holds. ■

Proposition 3. *Stepwise investment induces earlier technology adoption than a lumpy investment strategy as long as* $\frac{I_1}{I_2} > y$.

Proof. The objective is to show that the lumpy investment threshold, denoted by $\varepsilon_{.,1}^{0,0}$, is greater than the optimal investment threshold in the first technology under stepwise investment. We will show this result for the case of subsidy retraction. Following a similar process, the same result can be shown for the case of subsidy provision as well. In this comparison, we ignore technological and policy uncertainty based on the following reasoning:

- Technological uncertainty does not impact the optimal investment threshold when a firm holds a single investment opportunity, as is the case with lumpy investment, only the corresponding option and project value (Chronopoulos and Siddiqui, 2015).
- Also, with respect to the stepwise investment strategy, technological uncertainty accelerates investment in the first technology. Consequently, in view of showing that $\varepsilon_{1,1}^{0,1} < \varepsilon_{.,1}^{0,0}$, we may ignore technological uncertainty as greater λ_τ decreases $\varepsilon_{1,1}^{0,1}$ relative to $\varepsilon_{.,1}^{0,0}$.
- From Proposition 2, we know that greater likelihood of subsidy retraction raises the optimal investment threshold. Hence, it suffices to show that $\varepsilon_{1,1}^{0,1} < \varepsilon_{.,1}^{0,0}$ at the extreme values of λ_p, i.e. for $\lambda_p = 0$ and $\lambda_p \to \infty$. In the latter case, the subsidy will be retracted immediately, and, therefore, the optimal investment threshold in both cases is obtained analytically, thus facilitating the comparison".

First, we consider the case of $\lambda_p = 0$ for both lumpy and stepwise investment and the comparison between the optimal thresholds is indicated in (B.11).

$$\begin{aligned} \varepsilon_{.,1}^{0,0} > \varepsilon_{1,1}^{0,0} &\Leftrightarrow \frac{\beta_1}{\beta_1 - 1} \frac{(I_2 + I_1)(\rho-\mu)}{D_2 (1+y)} \\ &> \frac{\beta_1}{\beta_1 - 1} \frac{I_1 (\rho-\mu)}{D_1 (1+y)} \Leftrightarrow \frac{I_1 + I_2}{D_2} > \frac{I_1}{D_1} \end{aligned} \tag{B.11}$$

From Proposition 1 we know that $\frac{I_1}{D_1} < \frac{I_2}{D_2} < \frac{I_1+I_2}{D_2}$ and therefore (B.11) holds.

Next, we assume that $\lambda_p \to \infty$ for the case of stepwise investment and show that $\varepsilon_{.,1}^{0,0} > \varepsilon_{1,0}^{0,0}$.

$$\frac{\beta_1}{\beta_1 - 1} \frac{(I_2 + I_1)(\rho-\mu)}{D_2 (1+y)} > \frac{\beta_1}{\beta_1 - 1} \frac{I_1 (\rho-\mu)}{D_1} \Leftrightarrow \frac{I_2 + I_1}{D_2 (1+y)}$$

$$> \frac{I_1}{D_1} \Leftrightarrow \frac{D_1}{I_1} > \frac{D_2\,(1+y)}{I_2+I_1} \tag{B.12}$$

Note that (B.12) holds due to Proposition 1 if the subsidy is close to zero, yet will not necessarily hold if $a = 1$. However, by using Proposition 1 we have $\varepsilon^{0,0}_{\cdot,1} > \varepsilon^{0,1}_{1,1}$ as long as $\frac{I_1}{I_2} > y$. ■

Appendix C. Provision of a permanent subsidy

Proposition 4. *Greater likelihood of subsidy provision lowers the optimal investment threshold.*

Proof. Like in Proposition 2, we show this result for the case $\lambda_\tau = 0$ to facilitate the exposition of the derivation. If $\lambda_\tau = 0$, then (30) can be rewritten as in (C.1), since $\theta_1 = \eta_1$.

$$\left(\frac{E}{\varepsilon^{1,0}_{1,0}}\right)^{\eta_1}\left[\frac{D_1}{\rho-\mu+\lambda_p}+\frac{\eta_1\rho I_1}{\left(\rho+\lambda_p\right)\varepsilon^{1,0}_{1,0}}+\left(\eta_1-\eta_2\right)H^{1,0}_{1,0}\varepsilon^{1,0^{\eta_2-1}}_{1,0}\right] = \left(\frac{E}{\varepsilon^{1,0}_{1,0}}\right)^{\eta_1}\left[\frac{\eta_1 D_1}{\rho-\mu+\lambda_p}\right] \tag{C.1}$$

By inserting the expression for $H^{1,0}_{1,0} = \frac{1}{(\eta_1-\eta_2)\varepsilon^{0,0^{\eta_2}}_{1,1}}\left(\left(\eta_1-\beta_1\right)C^{0,0}_{1,1}\varepsilon^{0,0^{\beta_1}}_{1,1} - \left(\eta_1-1\right)\frac{\lambda_p D_1\varepsilon^{0,0}_{1,1}(1+y)}{(\rho-\mu)(\rho-\mu+\lambda_p)} + \eta_1\frac{\lambda_p I_1}{\rho+\lambda_p}\right)$ in (C.1), subtracting the left from the right-hand side and taking the derivative with respect to λ_p, we obtain (C.2).

$$L = \frac{\partial}{\partial\lambda_p}\left[\frac{\left(\eta_1 D_1(\rho-\mu)+\lambda_p D_1\right)\left[\varepsilon^{0,0^{1-\eta_2}}_{1,1}(1+y)-\varepsilon^{1,0^{1-\eta_2}}_{1,0}\right]}{(\rho-\mu)(\rho-\mu+\lambda_p)} + \frac{\eta_1\rho I_1\left[\varepsilon^{1,0^{-\eta_2}}_{1,0}-\varepsilon^{0,0^{-\eta_2}}_{1,1}\right]}{\rho+\lambda_p}\right] + (\eta_1-\eta_2)H^{1,0}_{1,0}\log\left(\frac{\varepsilon^{1,0}_{1,0}}{\varepsilon^{0,0}_{1,1}}\right)\frac{\partial\eta_2}{\partial\lambda_p} \tag{C.2}$$

The objective is to show that $L < 0$, as this would imply that the MB of delaying investment decreases by more than the MC with greater λ_p, and, therefore, that greater likelihood of subsidy provision lowers the marginal value of delaying investment, and, in turn, the optimal investment threshold. Below, we consider each term of (C.2) separately.

- We start with the second term on the right-hand side of (C.2) and determine its partial derivative with respect to λ_p as in (C.3).

$$\frac{\partial}{\partial\lambda_p}\frac{\eta_1}{\rho+\lambda_p} = \frac{\frac{\partial\eta_1}{\partial\lambda_p}(\rho+\lambda_p)-\eta_1}{(\rho+\lambda_p)^2} < \frac{\frac{\partial\eta_1}{\partial\lambda_p}(\rho+\lambda_p)-\sqrt{\frac{\rho+\lambda_p}{\sigma^2}}}{(\rho+\lambda_p)^2} \tag{C.3}$$

  Note that $\frac{\partial\eta_1}{\partial\lambda_p} = \frac{1}{\sigma^2\sqrt{\left(\frac{\mu}{\sigma^2}-\frac{1}{2}\right)^2+\frac{2(\rho+\lambda_p)}{\sigma^2}}}$ and by inserting the expression of $\frac{\partial\eta_1}{\partial\lambda_p}$ in the numerator of (C.3) we obtain: $\frac{\partial\eta_1}{\partial\lambda_p}(\rho+\lambda_p) - \sqrt{\frac{\rho+\lambda_p}{\sigma^2}} < 0 \Leftrightarrow \left(\frac{\mu}{\sigma^2}-\frac{1}{2}\right)^2 + \frac{(\rho+\lambda_p)}{\sigma^2} < 0$, which holds.
- Next, we determine the partial derivative of the first term on the right-hand side of (C.2) with respect to λ_p, as indicated in (C.4).

$$\frac{\partial}{\partial\lambda_p}\frac{\eta_1 D_1(\rho-\mu)+\lambda_p D_1}{(\rho-\mu)(\rho-\mu+\lambda_p)} = \frac{D_1\left[\frac{\partial\eta_1}{\partial\lambda_p}(\rho+\lambda_p-\mu)-\eta_1+1\right]}{(\rho-\mu)(\rho-\mu+\lambda_p)^2} \tag{C.4}$$

  Similarly, we can show that $\frac{\partial\eta_1}{\partial\lambda_p}(\rho+\lambda_p-\mu)-\eta_1+1 < 0$, that $\varepsilon^{0,0^{1-\eta_2}}_{1,1}(1+y)-\varepsilon^{1,0^{1-\eta_2}}_{1,0} < 0$, and that $\varepsilon^{0,0}_{1,1}(1+y) = \varepsilon^{0,0}_{1,0}$.
- Finally, the third term on the right-hand side of (C.2) is negative because $\frac{\partial\eta_2}{\partial\lambda_p} < 0$, while the other terms are positive.

Consequently, the MB of delaying investment decreases by more than the MC with greater λ_p, which lowers the marginal value of delaying investment, thereby raising the investment incentive. ■

Proposition 5. $\frac{F^{0,0}_{1,1}(E)-F^{b,c}_{1,a}(E)}{F^{0,0}_{1,1}(E)} \in \left[0, 1-\frac{1}{(1+y)^{\beta_1}}\right]$.

Proof. For the case of permanent subsidy retraction ($a = 1, b = 0, c = 1$), the relative loss in option value is outlined in (C.5).

$$\frac{F^{0,0}_{1,1}(E)-F^{0,1}_{1,1}(E)}{F^{0,0}_{1,1}(E)} = \frac{\left(C^{0,0}_{1,1}-C^{0,0}_{1,0}\right)E^{\beta_1}-C^{0,1}_{1,1}E^{\eta_1}}{C^{0,0}_{1,1}E^{\beta_1}} \tag{C.5}$$

We will determine the expression of the relative loss in options for $\lambda_p = 0$ and $\lambda_p \to \infty$.

- Notice that $\lambda_p = 0 \Rightarrow F^{0,0}_{1,1}(E) = F^{0,1}_{1,1}(E) \Rightarrow \frac{F^{0,0}_{1,1}(E)-F^{0,1}_{1,1}(E)}{F^{0,0}_{1,1}(E)} = 0$.
- By contrast, as λ_p increases, the relative loss increases since $C^{0,1}_{1,1} \to 0$. Also, notice that $\varepsilon^{0,0}_{2,1} = \frac{\varepsilon^{0,0}_{2,0}}{1+y}$, $A^{0,0}_{2,1} = A^{0,0}_{2,0}(1+y)^{\beta_1}$, and, $\varepsilon^{0,0}_{1,1} = \frac{\varepsilon^{0,0}_{1,0}}{1+y}$. Thus, $A^{0,0}_{1,1} = (1+y)^{\delta_1}A^{0,0}_{1,0}$, and by substituting $\varepsilon^{0,0}_{1,1}$, $A^{0,0}_{1,1}$ and $A^{0,0}_{2,1}$ in the expression for $C^{0,0}_{1,1}$, we obtain:

$$C^{0,0}_{1,1} = (1+y)^{\beta_1}\frac{1}{\varepsilon^{0,0^{\beta_1}}_{1,1}}\left(\frac{D_1\varepsilon^{0,0}_{1,0}}{\rho-\mu}-I_1+A^{0,0}_{2,0}\varepsilon^{0,0^{\beta_1}}_{1,0}+A^{0,0}_{1,0}\varepsilon^{0,0^{\delta_1}}_{1,0}\right) = (1+y)^{\beta_1}C^{0,0}_{1,0} \tag{C.6}$$

  Hence, $\frac{C^{0,0}_{1,1}}{C^{0,0}_{1,0}} = (1+y)^{\beta_1}$, and, thus, $\frac{F^{0,0}_{1,1}(E)-F^{0,1}_{1,1}(E)}{F^{0,0}_{1,1}(E)} = \frac{\left[(1+y)^{\beta_1}C^{0,0}_{1,0}-C^{0,0}_{1,0}\right]E^{\beta_1}-0}{C^{0,0}_{1,1}E^{\beta_1}} = 1-\frac{1}{(1+y)^{\beta_1}}$.

Following similar steps, we can derive the relative loss in option value for the case of permanent subsidy provision. ■

Appendix D. Provision of a retractable subsidy

By solving (33), we obtain (D.1). The first two terms in the top part reflect the expected profit from operating the first technology. The third term represents the option to invest in the second technology in the permanent absence of a subsidy, adjusted via the last term, since the subsidy will be provided and subsequently retracted. Similarly, the first three terms in the middle part represent the expected profit from operating the second technology, while the last two terms represent the likelihood of the price either dropping in the waiting region or rising above $\varepsilon^{1,1}_{2,0}$.

$$F^{1,1}_{2,0}(E) = \begin{cases} \frac{D_1 E}{\rho-\mu}+\frac{\lambda_p D_1 E y}{\left(\rho-\mu+\lambda_p\right)^2}+A^{0,0}_{2,0}E^{\beta_1} + \left[\frac{\lambda_p A^{0,1}_{2,1}}{\frac{1}{2}\sigma^2-\eta_1\sigma^2-\mu}\ln E + A^{1,1}_{2,0}\right]E^{\eta_1} & , E < \varepsilon^{0,1}_{2,1} \\ \frac{\lambda_p D_2 E+(\rho-\mu)D_1 E}{(\rho-\mu)\left(\rho-\mu+\lambda_p\right)}+\frac{\lambda_p D_2 E y}{\left(\rho-\mu+\lambda_p\right)^2} - \frac{\lambda_p}{\rho+\lambda_p}I_2 + B^{1,1}_{2,0}E^{\eta_2}+C^{1,1}_{2,0}E^{\eta_1} & , \varepsilon^{0,1}_{2,1} \le E < \varepsilon^{1,1}_{2,0} \\ \Phi^{1,1}_{2,0}(E) - I_2 & , E \ge \varepsilon^{1,1}_{2,0} \end{cases} \tag{D.1}$$

Similarly, by solving (34) for each expression of $F^{1,1}_{1,0}(E)$ that is indicated in (D.1), we obtain (D.2). Note that $A^{1,1}_{1,0}$, $B^{1,1}_{1,0}$, $C^{1,1}_{1,0}$ and $D^{1,1}_{1,0}$ are determined via value-matching and smooth-pasting conditions between the three branches.

$$\Phi_{1,0}^{1,1}(E)=\begin{cases}\frac{D_1E}{\rho-\mu}+\frac{\lambda_pD_1Ey}{(\rho-\mu+\lambda_p)^2}+A_{2,0}^{0,0}E^{\beta_1}+A_{1,0}^{0,0}E^{\delta_1}+A_{1,0}^{1,1}E^{\theta_1}\\ +\frac{\lambda_pA_{1,1}^{0,1}\ln E}{\frac{1}{2}\sigma^2-\theta_1\sigma^2-\mu}E^{\theta_1}+\left(\frac{\lambda_p}{\lambda_\tau}A_{2,1}^{0,1}+A_{2,0}^{1,1}\right)E^{\eta_1}\\ +\frac{\lambda_\tau\lambda_pA_{2,1}^{0,1}E^{\eta_1}}{(\theta_2-\theta_1)\left(\frac{1}{2}\sigma^2-\eta_1\sigma^2-\mu\right)\frac{1}{2}\sigma^2}\\ \times\left[\frac{(\eta_1-\theta_1)\ln E-1}{(\eta_1-\theta_1)^2}-\frac{(\eta_1-\theta_2)\ln E-1}{(\eta_1-\theta_2)^2}\right], & E<\varepsilon_{2,1}^{0,1}\\ \left[\frac{\lambda_\tau D_2+(\rho-\mu)D_1}{(\rho-\mu)(\rho-\mu+\lambda_\tau)}+\frac{[\lambda_\tau D_2+(\rho-\mu+\lambda_p)D_1]y}{(\rho-\mu+\lambda_p)(\rho-\mu+\lambda_p+\lambda_\tau)}\right.\\ +\frac{\lambda_\tau D_2}{(\rho-\mu)(\rho-\mu+\lambda_p)}\\ \left.+\frac{\lambda_\tau D_2y}{(\rho-\mu+\lambda_p)^2}\right]\frac{\lambda_pE}{(\rho-\mu+\lambda_p+\lambda_\tau)}\\ +\frac{D_1E}{(\rho-\mu+\lambda_p)}+B_{1,0}^{0,0}E^{\delta_2}+\frac{\lambda_pB_{1,1}^{0,1}\ln E}{\frac{1}{2}\sigma^2-\theta_2\sigma^2-\mu}E^{\theta_2}\\ -\frac{(2\rho+\lambda_p+\lambda_\tau)\lambda_\tau\lambda_pI_2}{(\rho+\lambda_p+\lambda_\tau)(\rho+\lambda_p)(\rho+\lambda_\tau)}+B_{2,0}^{1,1}E^{\eta_2}\\ +C_{2,0}^{1,1}E^{\eta_1}+B_{1,0}^{1,1}E^{\theta_2}+C_{1,0}^{1,1}E^{\theta_1}, & \varepsilon_{2,1}^{0,1}\le E<\varepsilon_{2,0}^{1,1}\\ \frac{\lambda_\tau D_2E+(\rho-\mu)D_1E}{(\rho-\mu)(\rho-\mu+\lambda_\tau)}+\frac{\lambda_p[\lambda_\tau D_2+(\rho-\mu+\lambda_p)D_1]Ey}{(\rho-\mu+\lambda_p)(\rho-\mu+\lambda_p+\lambda_\tau)^2}\\ +\frac{\lambda_p\lambda_\tau D_2Ey}{(\rho-\mu+\lambda_p)^2(\rho-\mu+\lambda_p+\lambda_\tau)}\\ +B_{1,0}^{0,0}E^{\delta_2}+\frac{\lambda_pB_{1,1}^{0,1}\ln E}{\frac{1}{2}\sigma^2-\theta_1\sigma^2-\mu}E^{\theta_2}-\frac{\lambda_\tau I_2}{\rho+\lambda_\tau}+D_{1,0}^{1,1}E^{\theta_2}, & E\ge\varepsilon_{2,0}^{1,1}\end{cases}\tag{D.2}$$

Finally, the expression of $F_{1,0}^{1,1}(E)$ is indicated in (D.3), where $\varepsilon_{1,0}^{1,1}$, $G_{1,0}^{1,1}$, $H_{1,0}^{1,1}$, and $J_{1,0}^{1,1}$ are determined via value-matching and smooth-pasting conditions between the three branches. The first term on the top branch of (D.3) is the option to invest in the permanent presence of a subsidy, adjusted via the second term due to policy uncertainty. The second branch reflects the expected project value if the subsidy becomes available, and the bottom branch is expected project value when the price is high enough so that investment is optimal even in the absence of a subsidy.

$$F_{1,0}^{1,1}(E)=\begin{cases}C_{1,1}^{0,0}E^{\beta_1}+\left(\frac{\lambda_pC_{1,1}^{0,1}}{\frac{1}{2}\sigma^2-\eta_1\sigma^2-\mu}\ln E+G_{1,0}^{1,1}\right)E^{\eta_1} & ,E<\varepsilon_{1,1}^{0,1}\\ \frac{\lambda_pD_1E}{(\rho-\mu)(\rho-\mu+\lambda_p)}+\frac{\lambda_pD_1Ey}{(\rho-\mu+\lambda_p)^2}\\ -\frac{\lambda_pI_1}{\rho+\lambda_p}+A_{2,0}^{0,0}E^{\beta_1}-\frac{\lambda_p}{\lambda_\tau}A_{1,1}^{0,1}E^{\theta_1}\\ +\frac{\lambda_pA_{2,1}^{0,1}\ln E}{\frac{1}{2}\sigma^2-\theta_1\sigma^2-\mu}E^{\eta_1}+\frac{\lambda_p}{\lambda_p-\lambda_\tau}A_{1,0}^{0,0}E^{\delta_1}\\ +H_{1,0}^{1,1}E^{\eta_2}+J_{1,0}^{1,1}E^{\eta_1} & ,\varepsilon_{1,1}^{0,1}\le E<\varepsilon_{1,0}^{1,1}\\ \Phi_{1,0}^{1,1}(E)-I_1 & ,E\ge\varepsilon_{1,0}^{1,1}\end{cases}\tag{D.3}$$

References

Adkins, R., Paxson, D., 2016. Subsidies for renewable energy facilities under uncertainty. Manch. Sch. 84 (2), 222–250.
Balcer, Y., Lippman, S., 1984. Technological expectations and adoption of improved technology. J. Econom. Theory 34, 292–318.
Bastian-Pinto, C., Brandão, L., de Lemos Alves, M., 2010. Valuing the switching flexibility of the ethanol-gas flex fuel car. Ann. Oper. Res. 176 (1), 333–348.
Boomsma, T.K., Linnerud, K., 2015. Market and policy risk under different renewable electricity support schemes. Energy 89, 435–448.
Boomsma, T.K., Meade, N., Fleten, S.E., 2012. Renewable energy investments under different support schemes: A real options approach. European J. Oper. Res. 220 (1), 225–237.
Chronopoulos, M., Hagspiel, V., Fleten, S.E., 2016. Stepwise green investment under policy uncertainty. Energy J. 37 (4), 87–108.
Chronopoulos, M., Siddiqui, A., 2015. When is it better to wait for a new version? Optimal replacement of an emerging technology under uncertainty. Ann. Oper. Res. 235 (1), 177–201.
Couture, T.D., Cory, K., Kreycik, C., Williams, E., 2010. Policymaker's Guide to Feed-in Tariff Policy Design. National Renewable Energy Lab. (NREL), CO, United States.
Décamps, J.P., Mariotti, T., Villeneuve, S., 2006. Irreversible investment in alternative projects. Econom. Theory 28 (2), 425–448.
Dixit, A.K., Pindyck, R.S., 1994. Investment Under Uncertainty. Princeton University Press, Princeton, NJ, US.
Doraszelski, U., 2001. The net present value method versus the option value of waiting: A note on Farzin et al. (1998). J. Econom. Dynam. Control 25 (8), 1109–1115.
Farzan, F., Mahani, K., Gharieh, K., Jafari, M.A., 2015. Microgrid investment under uncertainty: a real option approach using closed form contingent analysis. Ann. Oper. Res. 235 (1), 259–276.
Farzin, Y.H., Huisman, K.J.M., Kort, P.M., 1998. Optimal timing of technology adoption. J. Econom. Dynam. Control 22 (5), 779–799.
Franklin, S.L., 2015. Investment decisions in mobile telecommunications networks applying real options. Ann. Oper. Res. 226 (1), 201–220.
Gollier, C., Proult, D., Thais, F., Walgenwitz, G., 2005. Choice of nuclear power investments under price uncertainty: Valuing modularity. Energy Econ. 27 (4), 667–685.
Grenadier, S.R., Weiss, A.M., 1997. Investment in technological innovations: An option pricing approach. J. Financ. Econ. 44 (3), 397–416.
Huisman, K.J.M., Kort, K.M., 2004. Strategic technology adoption taking into account future technological improvements: A real options approach. European J. Oper. Res. 159 (3), 705–728.
IEA, 2017. World energy outlook 2017. 14 November.
IRENA, 2018a. Renewable energy policies in a time of transition. 1 April.
IRENA, 2018b. Renewable power generation costs in 2017. 1 January.
Karneyeva, Y., Wüstenhagen, R., 2017. Solar feed-in tariffs in a post-grid parity world: The role of risk, investor diversity and business models. Energy Policy 106, 445–456.
Kim, K.K., Lee, C.G., 2012. Evaluation and optimization of feed-in tariffs. Energy policy 49, 192–203.
Koussis, N., Martzoukos, S.H., Trigeorgis, L., 2007. Real R & D options with time-to-learn and learning-by-doing. Ann. Oper. Res. 151 (1), 29–55.
Lemoine, D.M., 2010. Valuing plug-in hybrid electric vehicles' battery capacity using a real options framework. Energy J. 2, 113–143.
Majd, S., Pindyck, R.S., 1987. Time to build, option value, and investment decisions. J. Finan. Econ. 18 (1), 7–27.
McDonald, R.L., Siegel, D.R., 1985. Investment and the valuation of firms when there is an option to shut down. Internat. Econom. Rev. 26 (2), 331–349.

Mehrez, A., Rabinowitz, G., Shemesh, E., 2000. A discrete maintenance and replacement model under technological breakthrough expectations. Ann. Oper. Res. 99 (1), 351–372.

Pindyck, R.S., 1999. The long-run evolution of energy prices. Energy J. 20, 1–27.

REN21, 2018. Renewables 2018 Global Status Report. 11 September.

Ritzenhofen, I., Spinler, S., 2016. Optimal design of feed-in-tariffs to stimulate renewable energy investments under regulatory uncertainty – A real options analysis. Energy Econ. 53, 76–89.

Rothwell, G., 2006. A real options approach to evaluating new nuclear power plants. Energy J. 27 (1), 37–53.

Schwartz, E.S., Zozaya-Gorostiza, C., 2003. Investment under uncertainty in information technology: Acquisition and development projects. Manage. Sci. 49 (1), 57–70.

Sensfuß, F., Ragwitz, M., Genoese, M., 2008. The merit-order effect: A detailed analysis of the price effect of renewable electricity generation on spot market prices in Germany. Energy Policy 36 (8), 3076–3084.

Siddiqui, A., Fleten, S.E., 2010. How to proceed with competing alternative energy technologies: A real options analysis. Energy Econ. 32 (4), 817–830.

The Economist, 2013. The cost del sol. 20 July.

The Independent, 2018a. Climate change: EU proposes plan to go carbon-neutral by 2050. 28 November.

The Independent, 2018b. Wind and solar power investment crashed after government cut funding, show new figures. 16 January.

The New York Times, 2013. Chinese firm buys an american solar technology start-up. 9 January.

Wen, X., Hagspiel, V., Kort, P.M., 2017. Subsidized capacity investment under uncertainty. Working paper, CentER Discussion Paper Series No: 2017–2043.

Yang, M., Blyth, W., Bradley, R., Bunn, D., Clarke, C., Wilson, T., 2008. Evaluating the power investment options with uncertainty in climate policy. Energy Econ. 30 (4), 1933–1950.

Zhang, M.M., Zhou, P., Zhou, D.Q., 2016a. A real options model for renewable energy investment with application to solar photovoltaic power generation in China. Energy Econ. 59, 213–226.

Zhang, M.M., Zhou, D.Q., Zhou, P., Liu, G.Q., 2016b. Optimal feed-in tariff for solar photovoltaic power generation in China: A real options analysis. Energy Policy 97, 181–192.