Energy Policy 172 (2023) 113309

Contents lists available at ScienceDirect

Energy Policy

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

Don't stop me now: Incremental capacity growth under subsidy termination risk

Roel L.G. Nagy *, Stein-Erik Fleten, Lars H. Sendstad

Department of Industrial Economics and Technology Management, Norwegian University of Science and Technology, 7491 Trondheim, Norway

ARTICLE INFO

Keywords:
Investments
Capacity expansion
Incremental investment
Policy uncertainty
Real options

ABSTRACT

Once a subsidy scheme is close to reaching its goal or loses political support, it may be terminated. An important question for policy makers is how to minimize the negative impact of the risk of subsidy termination on industrial investment. We assume the social planner aims to increase capacity and welfare and uses a subsidy, which has an uncertain lifetime, for the purpose. We examine a monopolist supplying an uncertain demand, faced with the option to expand capacity by irreversibly investing in small increments. We find that the firm installs capacity expansions sooner and, consequently, installs a larger capacity than a firm without a subsidy. A firm's total investment during the subsidy's lifetime increases with both the subsidy size and the likelihood of subsidy withdrawal. However, this happens at the cost of less investment directly after the subsidy has been retracted. The optimal subsidy size strongly depends on the point in time at which the social planner aims to maximize the welfare — the further into the future, the larger the welfare optimal subsidy. Furthermore, the welfare optimal subsidy size strongly depends on the social planner's discretion over adjustments to the subsidy size.

1. Introduction

Subsidies are commonly used to mitigate market imperfections and consequently increase welfare. Alternatively, subsidies can be used to encourage investment to develop a technology that fulfills a social need and is not yet economically viable. As subsidies are used to reach a specific goal, they are usually terminated at some point. The profitability of investors' projects depends largely on a subsidy's lifetime; thus, it is important that investors account for the risks related to the termination of a subsidy. This is a challenge for many industries, as politicians typically cannot commit to long-term policies due to short election cycles. For a policy maker, it is important to account for an industry's response to the risk of subsidy termination as a firm's investment decisions are key to reaching the policy maker's targets. Examples of such transitions in which subsidy and subsidy termination play a role are renewable energy,[1] hydrogen[2] and agriculture.[3] Ganhammar (2021) provides evidence that regulatory uncertainty may disrupt the effect of energy policy in the Swedish–Norwegian certificate market because regulatory interventions increase the volatility in certificate prices.

* Corresponding author.
E-mail address: roel.nagy@ntnu.no (R.L.G. Nagy).

[1] The annual installed wind capacity in the United States (US) in the period 1997–2005 strongly depended on the production tax credit. Investment increased in the years before the tax credit expired, and has been low in the following years (The Economist, 2013). Stokes (2015) and Stokes and Warshaw (2017) point out the important role of public opinion on renewable energy policy in the US. Stokes and Warshaw (2017) address the withdrawal risk caused by public opinion: "Since 2011[,] several [US] states have weakened their renewable energy policies. Public opinion will probably be crucial for determining whether states expand or contract their renewable energy policies in the future".

[2] Already in the early 2000s, Van Benthem et al. (2006) mention that there was a broad consensus on hydrogen investment projects being eligible for government support, citing George W. Bush's State of the Union address in 2003 (Bush, 2003) and the then European Commission Chairman Romano Prodi (CORDIS Europa, 2004). More recently, the European Commission released the Hydrogen Strategy for a Climate-neutral Europe in 2020 (European Commission, 2020), as part of its European Green Deal. It mentions the availability of European Union (EU) funding as well 14 Member States having included hydrogen in their national infrastructure policy frameworks.

[3] The amount of subsidies in agriculture has declined compared that from the late 90 s to the period 2009–2011 in Europe (The Economist, 2012), while the EU has recently debated on limiting spending on agriculture (The Economist, 2019). In the UK, farmers are concerned about the consequences of missing out on the £3bn of annual subsidy under the EU's common agricultural policy after the UK has left the EU (The Economist, 2020). The uncertainty regarding the farmers' income affects their investment decisions; Musshoff and Hirschauer (2008) show that low volatility in the total gross margin differences encourages farmers to invest more in a new technology.

https://doi.org/10.1016/j.enpol.2022.113309
Received 27 June 2022; Received in revised form 5 October 2022; Accepted 17 October 2022
Available online 4 November 2022

A popular subsidy scheme in energy and renewables is the investment tax credit. An investment tax credit allows the investment to be fully or partially credited against the tax obligations or income of the investor (REN21, 2022, page 231). Investment tax credits constitute the most widespread policy instrument for renewable energy globally,[4] and are often implemented with the aim to increase the affordability and profitability of renewable energy production (IRENA et al., 2018, page 70). Recently, the United States used an investment tax credit, combined with the Renewable Fuel Standard 2 (RFS2) and California's Low Carbon Fuel Standard (LCFS), to increase production of Hydrotreated Vegetable Oil (HVO) (REN21, 2022, page 106). The popularity of investment tax credits may be explained by Bunn and Muñoz (2016), who show that "reducing capital cost through grants (e.g. capital allowances, capacity payments and/or fiscal benefits) is more effective [in attracting new investment in renewables] than through energy prices (e.g. green certificates)".

We examine the impact of an investment tax credit on industrial capacity growth. We consider a market with uncertain demand and a supply side, comprising a single, risk-neutral, profit-maximizing firm that holds the option to invest in irreversible capacity expansions.[5] No stock can be created. The investments are eligible for a subsidy, and face the risk of a potential future subsidy retraction. We examine the effect of the risk of subsidy termination on the firm's investment decision. The cost of investment is dependent on the availability of a subsidy. We consider an investment cost subsidy in the form of a percentage coverage of the investment cost. This represents a general class of subsidies including investment tax credits and capital subsidies. The subsidy is implemented by a social planner, who aims to reach a capacity target or maximize welfare, and decides on the subsidy size. We assume the subsidy is merely a welfare transfer, i.e., any subsidy payment to the firm is a cost to society, which means that the net cost of implementing the subsidy is zero.

This setting is applicable to, for example, a country's renewable energy capacity, in which many projects gradually increase the country's or industry's total capacity. In this study, we seek to answer the following open research questions: (i) How is the rate of capacity expansion affected by an investment cost subsidy under the prospect of policy termination and how does the rate of expansion change after subsidy termination? (ii) How does the prospect of policy termination affect the social planner's ability to increase total surplus, and (iii) how should the social planner set their subsidy size optimally to maximize total surplus?

In answering the first question, we find that a monopolist faced with an investment cost subsidy subject to withdrawal risk expands sooner while the subsidy is available and, consequently, installs a larger aggregate capacity during the subsidy's lifetime than a monopolist without the subsidy. Once the subsidy is withdrawn, the monopolist stops investment until demand – and consequently output prices – has grown sufficiently to attract investment without subsidy. This means that a policy maker aiming to reach a capacity target must implement a subsidy that is sufficiently large such that the target is reached during the subsidy's lifetime. If the target is not reached during the subsidy's lifetime, the target will be reached at the same time as in the scenario in which a subsidy is never implemented.

When we examine our second question, we find that the social planner can increase welfare by implementing a subsidy even when the subsidy is subject to withdrawal risk. While the subsidy is in effect, an optimally set subsidy can positively impact welfare in the long run. The welfare increases as the subsidy attracts more investment, which increases the consumer surplus that accumulates over time. However, in the short term, the welfare under a subsidy is lower than that without due to the cost of subsidizing investment.

Third, we find that the optimal subsidy size increases with the monopolist's capacity and decreases with the risk of subsidy withdrawal. The optimal subsidy strongly depends on whether the social planner can adjust the subsidy size throughout the lifetime of the subsidy as well as the time at which the social planner aims to maximize the surplus. We find that a social planner sets a larger subsidy if they aim to maximize welfare far in the future, to the detriment of short-term welfare.

Numerous studies analyze the effects of support schemes in renewables on investment and/or welfare. The topic of policy making for renewable energy is especially interesting as investors may need a progressively higher level of support over time, due to the high risk and low return of renewable energy projects (Muñoz and Bunn, 2013). Furthermore, Gan et al. (2007) state that the policy instruments in the US and Europe in the early 2000s provide insufficient incentive for the long-term development of new, green technologies, which are important in reaching long-term policy goals. As support schemes are considered crucial for inducing investments in energy, it is also important, from a policy maker's viewpoint, to implement efficient and effective policies. Both theoretical (Kydland and Prescott, 1977; Nordhaus, 2007; Gerlagh et al., 2009; Stern, 2018; Keen, 2020; Stern et al., 2022) and empirical (Stern, 2006; García-Álvarez et al., 2018; Rossi et al., 2019; Liski and Vehviläinen, 2020) studies attempt to determine the optimal government policy or subsidy design — with a strong focus on attracting investments in renewable energy or reaching targets in battling climate change. Liski and Vehviläinen (2020) propose a policy design leading to energy producers' incurring most of the cost of the subsidy that supports clean technologies instead of the consumers. Real options are also often applied to investment in the energy sector, see Fernandes et al. (2011) for a literature review. Kozlova (2017) provides an extensive literature review of renewable energy investment under uncertainty using real options, which also considers the literature on energy policy. We contribute to this literature in that we study an uncertain market accounting for policy risk. We focus on the long-term perspective and show that the social planner's time at which a policy target should be reached is key in determining what the optimal policy is.

Real options theory is also frequently applied to studying investment problems under (market) uncertainty to determine the optimal subsidy and/or tax (e.g., Pennings (2000), Yu et al. (2007), Danielova and Sarkar (2011), Boomsma et al. (2012), Rocha Armada et al. (2012), Sarkar (2012), Feil et al. (2013), Barbosa et al. (2016), Ritzenhofen and Spinler (2016), Azevedo et al. (2021), Tsiodra and Chronopoulos (2021), and Hu et al. (2022)), and sometimes accounting for policy change (Dixit and Pindyck (1994, Chapter 9), Hassett and Metcalf (1999), Boomsma and Linnerud (2015), Chronopoulos et al. (2016) and Nagy et al. (2021)). Dixit and Pindyck (1994, Chapter 9), Hassett and Metcalf (1999), and Nagy et al. (2021) all examine the case of a monopolist facing a one-time investment decision under a lump-sum subsidy subject to withdrawal risk. They conclude that the firm invests sooner under the subsidy if the likelihood of subsidy withdrawal is larger. Nagy et al. (2021) includes capacity choice and concludes that a firm opts for earlier investment, but also at a lower investment size. Boomsma and Linnerud (2015) derive a similar conclusion if a support scheme is non-retroactively terminated, but also find that "the prospect of [support scheme] termination will slow down investments if it is retroactively applied".

A specific branch of literature examines incremental investment, stepwise investment, or capacity expansion as a real options model; see, for example, Dixit and Pindyck (1994, Chapter 11), Bar-Ilan and Strange (1999), Panteghini (2005), Chronopoulos et al. (2016), and Gryglewicz and Hartman-Glaser (2020). In this literature, an industry or firm invests more than once, which means that the capacity

[4] An estimated amount of 30 to 40 countries used investment or production tax credits to support renewable energy installations over the past decade (IRENA et al., 2018, page 69).

[5] This casts us in a setting of real options, where each investment increment can be seen as an American call option on marginal production capacity.

can be adjusted upward over time. Dixit and Pindyck (1994, Chapter 11) and Bar-Ilan and Strange (1999) assume production to follow a Cobb–Douglas function, and that the industry maximizes its own total profit, implicitly assuming that it acts as a monopolist. Bar-Ilan and Strange (1999) find that demand uncertainty affects an industry's investment size differently when investment is incremental compared to when it is lumpy. This implies that one cannot directly derive the results for incremental investment under policy from models that study lumpy investment under policy uncertainty. Panteghini (2005) finds that for a two-stage investment project, a tax does not provide any incentives for the firm to change its behavior, i.e., the taxation is neutral. Gryglewicz and Hartman-Glaser (2020) examine the role of incentive costs in the value and exercise of an option in a model in which incremental capital is assumed to be stochastic. The decision maker decides on the optimal investment rate, which determines the incremental capital trend. The costs of accumulating capital affects the relationship between managerial hazard and the option value and exercise.

Closely related to our study is Chronopoulos et al. (2016), who examine the effect of the subsidy withdrawal risk of a price premium on a monopolist's investment timing and size, where investment is either lumpy or stepwise. When investment occurs in two steps, they find that the firm invests in a larger aggregate capacity than when the investment is lumpy, as the firm has more flexibility to adjust its capacity over time. They mention the assumption of the electricity price being independent of the size of the project as a limitation of their work.[6] We extend the analysis by Chronopoulos et al. (2016) by relaxing this assumption as well as examining the effect of policy on a social planner's targets. The combination of an option to implement multiple capacity expansions and a subsidy subject to withdrawal risk has scarcely been examined in the literature, and we revisit this setting. Furthermore, unlike Chronopoulos et al. (2016) and previously mentioned literature, we examine total surplus as a welfare measure to study the policy maker's point of view.

In short, this study contributes to the literature in three ways. First, we examine how subsidies affect incremental investment in contrast to the literature on lumpy investment, and how this impacts social welfare. By assuming the industry invests incrementally instead of lumpy, we take a long-term perspective instead of looking at a one-time decision. We show that a subsidy can increase total welfare in a dynamic monopoly and attain a first-best solution, even if the lifetime of the subsidy is uncertain. Our second contribution lies in providing new insights by examining the long-term effects of a subsidy as well as what happens after subsidy withdrawal. An investment cost subsidy is an effective tool for accelerating investment; however, this effect tapers off over time. Third, we show that the policy maker's time horizon plays a crucial role in determining the welfare optimal policy.

The remainder of this paper is structured as follows: The model is presented in Section 2. In Section 3, we derive the optimal investment decisions with and without subsidy withdrawal risk. We also study the optimal investment from a social planner's perspective, as well as derive the optimal subsidy. Section 4 provides a numerical case study, while Section 5 concludes.

2. Model

We propose a theoretical framework that examines a single firm's optimal investment decision under uncertain subsidy support. The firm aims to maximize its profits. We assume that the monopolist currently produces K units and can invest in small, fixed-size projects. The future revenue stream from the production is uncertain. The monopolist's total capacity increases gradually as it installs its projects.

The output price is denoted by $P(X,K)$ and given by

$$P(X,K) = X(1-\eta K), \tag{1}$$

where η is a positive constant.[7] The output price depends on both K, the monopolist's total production capacity, and $X(t)$, which represents exogenous shocks. The exogenous shocks are assumed to follow a geometric Brownian motion process given by

$$dX(t) = \mu X(t)dt + \sigma X(t)dW(t),\ X(0) = x, \tag{2}$$

where μ is the drift rate, σ the uncertainty parameter, and $dW(t)$ the increment of a Wiener process.

The cost of installing one unit of capacity is set equal to κ. The size of the next expansion is given by dK. Hence, assuming the current capacity to be K, increasing the production capacity leads to a new capacity of $K + dK$ at an investment cost of $\kappa \cdot dK$ when no subsidy is in effect. A subsidy provides a discount at a rate, θ, on the investment cost; thus, the investment costs are then equal to $(1-\theta)\kappa \cdot dK$.

Initially, the subsidy is assumed to be available; however, it can be withdrawn due to a random event, such as the depletion of the public budget or a change in government. We assume that the monopolist's perceived likelihood of subsidy retraction follows an exponential jump process with parameter λ. This implies that the monopolist's perceived probability of subsidy retraction in the next time interval, dt, is equal to λdt.

Next, we derive the monopolist's objective that maximizes its profit. Without loss of generality, we assume a current production capacity of $K(0) = k$. The monopolist chooses when to install its expansions, i, $i \in \mathbb{N}$, which means that it chooses the investment times, τ_i, where $\tau_i \le \tau_j$ for all $i \le j$. We denote the capacity after the ith expansion by K_i:

$$K_i = K_{i-1} + dK = k + i \cdot dK. \tag{3}$$

The monopolist maximizes the producer surplus (PS). Its objective is given by

$$\begin{aligned} V &= \sup_{\tau_1,\tau_2,\dots} PS(X,K) \\ &= \sup_{\tau_1,\tau_2,\dots} \sum_{i=1}^{\infty} \mathbb{E}\left[\int_{\tau_{i-1}}^{\tau_i} P(X(t),K_i)\cdot K_i \cdot e^{-rt}dt \right. \\ &\qquad \left. -(1-\theta\cdot \mathbb{1}_{\xi(\tau_i)})\kappa\cdot dK\cdot e^{-r\tau_i} \,\middle|\, X(\tau_{i-1}),\xi(\tau_{i-1}) \right], \end{aligned} \tag{4}$$

where $\tau_0 = 0$ indicates the start of the planning horizon, and $\mathbb{1}_{\xi(t)}$ is an indicator function that assumes a value of 1 if the subsidy is still available at time t and zero otherwise. As the subsidy is available at the start of the planning horizon, we have $\xi(0) = 1$.

We show that the problem in which the monopolist maximizes their total profits as defined in (4) is equivalent to that in which

[6] Chronopoulos et al. (2016) emphasize that the limitation of their assumption is especially visible when considering installation of large projects. We assume market power, as one can expect that aggregate capacity and price are strongly linked in any industry. For the energy industry specifically, there are several examples of countries in which market power lead to prices being affected. See Karthikeyan et al. (2013) for a thorough review on market power in the electricity market in different countries, or Nagy et al. (2021) for a detailed reflection on market power on the energy market.

[7] The inverse demand function in (1) is a special case of the one used by Dixit and Pindyck (1994, Chapter 11), which assumes $P = XD(K)$, with an unspecified demand function, $D(K)$, and is frequently used in the literature (see, e.g., Pindyck (1988), He and Pindyck (1992), and Huisman and Kort (2015)).

they maximize the added value of each extra unit of capacity. The monopolist's objective in (4) can be rewritten to.[8]

$$V = \mathbb{E}\left[\int_0^\infty P(X(t),k)\cdot k\cdot e^{-rt}dt \,\middle|\, X(0)=x,\xi(0)=1\right] + \sum_{i=1}^{\infty}\sup_{\tau_i}\left\{ \mathbb{E}\left[\int_{\tau_i}^{\infty}\left(P(X(t),K_i)\cdot dK + \Delta P_i(X(t))\cdot K_{i-1}\right)\cdot e^{-rt}dt - (1-\theta\cdot \mathbb{1}_{\xi(\tau_i)})\kappa\cdot dK\cdot e^{-r\tau_i}\,\middle|\, X(\tau_{i-1}),\xi(\tau_{i-1})\right]\right\}, \tag{5}$$

where $\Delta P_i(X(t))$ is the price change from increasing the capacity for the ith time when the value of the demand shock is given by $X(t)$, i.e., $\Delta P_i(X(t)) = P(X(t),K_i) - P(X(t),K_{i-1})$. The equivalence of the objective functions in (4) and (5) holds for any demand function satisfying the Markov property.

Using the rewritten form of the objective in (5), we solve the monopolist's problem of maximizing their total profit by solving multiple, independent, optimization problems that maximize the added value of each capacity expansion. This approach is preferred as it avoids dealing with dependencies between different capacity expansions and, hence, is easier than directly solving (4). The optimal times for the capacity expansions are derived in the next section.

In the remainder of this section, we derive an expression for the objective of the social planner, who maximizes total surplus (TS). The social planner cannot invest directly in the market itself, but decides on the size of the subsidy that is available to the monopolist. By doing so, the social planner can try to align the monopolist's investment with the welfare optimal investment. The total surplus comprises the sum of the producer and consumer (CS) surpluses, i.e.,

$$TS = PS + CS. \tag{6}$$

The consumer surplus is defined as the difference between the price consumers are willing to pay and the price they actually pay.

The social planner's objective under the demand function (1) is given by,[9]

$$TS(X,K) = \mathbb{E}\left[\int_0^\infty X(t)\cdot\left(1-\frac{1}{2}\eta k\right)\cdot k\cdot e^{-rt}dt \,\middle|\, X(0)=x\right] + \sum_{i=1}^{\infty}\mathbb{E}\left[\int_{\tau_i}^{\infty}\left(X(t)\cdot(1-\eta K_i)+\eta X(t)\cdot dK\right)\cdot dK\cdot e^{-rt}dt - \kappa\cdot dK\cdot e^{-r\tau_i}\,\middle|\, X(\tau_{i-1})\right]. \tag{7}$$

The maximization of the total surplus can be rewritten as the sum of the maximizations of the added value of each independent extra unit of capacity, as stated in (7). Therefore, we can solve the problem of the maximization of the total surplus by solving multiple, independent, maximization problems, which are easier to solve.

3. Investment and subsidy

In this section, we derive the optimal capacity expansion threshold as well as the welfare optimal policy. We derive the optimal investment threshold for both the monopolist and the social planner in Section 3.1. For the monopolist, we examine both the scenarios with and without subsidy. In Section 3.2, we consider the position of the social planner deciding on the subsidy. The social planner sets their subsidy such that it maximizes total surplus, considering that the monopolist decides on when to invest.

[8] The derivation and discussion of the firm's objective function in (5) can be found in Appendix A.1

[9] The derivation of the consumer surplus and the social planner's objective in (7) and a discussion of the social planner's objective can be found in Appendix A.2.

3.1. Optimal investment

We first derive the optimal investment threshold for the monopolist when there is no subsidy in place. For this, we maximize the marginal revenue of the expansion.

Let V_1 (V_0) denote the value of the option to expand capacity with(out) the subsidy. The value of the monopolist's investment without subsidy under the demand function (1) is given by

$$V_0(X_0,K) = \frac{x(1-\eta k)k}{r-\mu} + \sum_{i=1}^{\infty}\left(\frac{x}{X_0^i}\right)^{\beta_{01}}\cdot\left(\frac{X_0^i\left(1-\eta(2K_i-dK)\right)}{r-\mu}-\kappa\right)dK, \tag{8}$$

where X_0^i denotes the monopolist's optimal timing threshold without a subsidy, to implement the ith capacity expansion. For convenience, we denote X_0 as the vector containing all X_0^i. Moreover, β_{01} is the positive solution to $\frac{1}{2}\sigma^2\beta^2+(\mu-\frac{1}{2}\sigma^2)\beta-r=0$. β_{01} can be interpreted as a measure of the wedge between the monopolist's optimal investment threshold and the investment costs. $\beta_{01}>1$ holds and the value of β_{01} depends on the market uncertainty, σ, market growth rate, μ, and the discount rate, r.

We derive the optimal threshold at which to implement the ith capacity expansion without a subsidy using the same approach as Dixit and Pindyck (1994, Chapter 11). The expression for the optimal expansion threshold without a subsidy is given by Proposition 1.

Proposition 1. *The optimal investment threshold without a subsidy is given by*

$$X_0^i(K_i) = \frac{\beta_{01}}{\beta_{01}-1}\cdot\frac{(r-\mu)\kappa}{1-2\eta K_i}. \tag{9}$$

The proofs of all corollaries and propositions can be found in Appendix B.

Next, considering the scenario in which a subsidy is available, the value of the monopolist's investment is given by

$$V_1(X_1,K) = \frac{x(1-\eta k)k}{r-\mu} + \sum_{i=1}^{\infty}\left(\frac{x}{X_1^i}\right)^{\beta_{11}}\cdot\left(\frac{X_1^i\left(1-\eta(2K_i-dK)\right)}{r-\mu}-(1-\theta)\kappa\right)dK, \tag{10}$$

where X_1^i denotes the monopolist's optimal timing threshold, under a subsidy, for the ith capacity expansion. For convenience, we denote X_1 and X_0 as the vector containing all X_1^i and X_0^i respectively. Furthermore, β_{11} is the positive solution to $\frac{1}{2}\sigma^2\beta^2+(\mu-\frac{1}{2}\sigma^2)\beta-(r+\lambda)=0$. β_{11} can be interpreted as a measure of the wedge between the monopolist's optimal investment threshold and the investment costs when the subsidy is available. The equation is similar to the expression for β_{01}, with the only difference being that β_{11} depends on λ. We have that $\beta_{11}>\beta_{01}$ as the likelihood of subsidy withdrawal decreases the wedge because there is a risk that investment costs significantly increase.

An implicit expression for the optimal expansion threshold under subsidy is given by Proposition 2.

Proposition 2. *The optimal investment threshold for the ith capacity expansion under a subsidy, X_1^i, is given by*

$$\frac{\beta_{11}-\beta_{01}}{\beta_{11}}\cdot\frac{dA_{01}(K_i)}{dK}\cdot(X_1^i)^{\beta_{01}} + \frac{\beta_{11}-1}{\beta_{11}}\cdot\frac{X_1^i(1-2\eta K_i)}{r-\mu} - (1-\theta)\kappa = 0. \tag{11}$$

To the best of our knowledge, the implicit Eq. (11) does not have an analytical solution. In Section 4, we numerically solve this expression.

We can derive how the optimal investment threshold changes with respect to the policy parameters. The following corollary states how the optimal investment decision is affected by subsidy retraction risk.

Corollary 1. *The optimal investment timing, X_1^i, is negatively affected by the subsidy retraction risk, λ.*

From Corollary 1, one may be tempted to conclude that the best situation for a social planner interested in maximizing investment during the subsidy's lifetime is a situation in which the subsidy withdrawal risk is large.[10] However, the larger withdrawal risk does not only lower the firm's investment threshold under the subsidy, but it also shortens the expected lifespan of the subsidy. The shorter the lifespan of the subsidy, the less time there is for the capacity to grow. Therefore, the total impact of a higher subsidy withdrawal risk on the monopolist's capacity is ambiguous. We examine this impact, as well as the situation after subsidy withdrawal, in detail in Section 4.

Corollary 2. *The optimal investment timing, X_1^i, is negatively affected by the subsidy size, θ.*

The result that a larger investment cost subsidy accelerates investment is a well-known one in different settings; for example, in the case of lumpy investment both with policy uncertainty (Dixit and Pindyck, 1994; Hassett and Metcalf, 1999; Nagy et al., 2021) and without policy uncertainty (Pennings, 2000; Rocha Armada et al., 2012; Azevedo et al., 2021).

An important advice for a social planner interested in maximizing investment during a subsidy's lifetime follows from Corollary 2. Such a social planner should set the subsidy as large as possible, as this incentivizes capacity growth. Although this maximizes the investment during the subsidy's lifetime, it is also important for a policy maker to know the impact of their policy after withdrawal.

Next, we solve the investment problem from the perspective of the social planner, who maximizes total surplus. The maximization of the total surplus can be rewritten into smaller optimization problems in which the added value of an each capacity expansion is maximized, as shown in Eq. (7).

Let V_S denote the value of the option to expand capacity for the social planner. The total surplus of the investment under the demand function (1) is given by

$$V_S(X_S, K) = \frac{x(2-\eta k)k}{2(r-\mu)} + \sum_{i=1}^{\infty} \left(\frac{x}{X_S^i}\right)^{\beta_{01}} \cdot \left(\frac{X_S^i\big(2-\eta(2K_i - dK)\big)}{2(r-\mu)} - \kappa\right) dK, \tag{12}$$

where X_S^i denotes the social planner's optimal timing threshold to implement the ith capacity expansion. The optimal social threshold at which to expand capacity is stated in Proposition 3.

Proposition 3. *The optimal investment threshold for a social planner is given by*

$$X_S^i(K_i) = \frac{\beta_{01}}{\beta_{01}-1} \cdot \frac{(r-\mu)\kappa}{1-\eta K_i}. \tag{13}$$

We examine the difference between the social planner's and monopolist's investments by comparing the optimal social investment threshold in (13) with the firm's optimal threshold without a subsidy in (9). The social planner increases the capacity earlier than the monopolist, as a larger aggregate capacity positively impacts the consumer surplus. The monopolist, meanwhile, keeps the output price high by maintaining the capacity lower than is optimal level from a social planner's viewpoint. The social planner uses the subsidy to align the monopolist's decision with the welfare optimal investment. The optimal subsidy from the social planner's viewpoint is examined in the next section.

[10] Due to Donald Trump's hard stance against renewables (The New York Times, 2019; Center for American Progress, 2020; Forbes, 2020), favoring coal and fossil fuels (The Economist, 2018), we call this the Trumpian strategy.

3.2. Optimal subsidy

This subsection examines how the subsidy should be set to maximize the total surplus, given the monopolist's investment decisions. First, we study the situation in which the social planner can alter the subsidy size after each investment until the subsidy is terminated. We refer to this as the *flexible* subsidy. Next, we assume that the social planner can only set the subsidy at the beginning, and that it remains at that size until the subsidy is abolished. This subsidy is referred to as the *fixed* subsidy.

We start with the welfare optimal flexible subsidy and use $\theta_\lambda^*(K)$ to denote the welfare optimal subsidy size for a given subsidy withdrawal level, λ, and a current capacity of K. The following proposition states how the social planner who maximizes total surplus should set their flexible subsidy.

Proposition 4. *To maximize surplus, the social planner should set their subsidy size equal to*

$$\theta_\lambda^*(K) = 1 - \frac{1}{\beta_{11}(\beta_{01}-1)} \cdot \left[\beta_{01}(\beta_{11}-1)\cdot\frac{1-2\eta K}{1-\eta K} - (\beta_{11}-\beta_{01})\cdot\left(\frac{1-2\eta K}{1-\eta K}\right)^{\beta_{01}}\right], \tag{14}$$

where $K < \frac{1}{2\eta}$ is the monopolist's current capacity, while β_{01} and β_{11} are the positive solutions to the equations, $\frac{1}{2}\sigma^2\beta^2 + (\mu - \frac{1}{2}\sigma^2)\beta - r = 0$ and $\frac{1}{2}\sigma^2\beta^2 + (\mu - \frac{1}{2}\sigma^2)\beta - (r+\lambda) = 0$, respectively.

If there is no subsidy withdrawal risk (i.e., the subsidy is never withdrawn, $\lambda = 0$), the expression for the optimal subsidy size simplifies. The social planner who maximizes surplus sets their subsidy size equal to

$$\theta_{\lambda=0}^*(K) = \frac{\eta K}{1-\eta K}. \tag{15}$$

Eq. (15) implies that the social planner should increase their subsidy to keep additional investment attractive for the monopolist as the capacity grows. The monopolist has a strong incentive to keep prices high by maintaining supply low. However, unlike the monopolist, the social planner has an incentive to increase capacity as the consumer surplus does increase with capacity. The subsidy is used as a tool to decrease investment costs to such a level that the monopolist has an incentive to increase capacity even when output prices are low.

Furthermore, Eq. (15) shows that the optimal subsidy rate is increasing in the market power parameter, η. A firm with considerable market power invests only very little to keep prices high. The social planner wants to attract more investment as it will increase consumer surplus; thus, a significant subsidy is used to incentivize the firm to invest more.

Interestingly, the welfare optimal subsidy under a non-zero subsidy withdrawal risk depends on the demand uncertainty, σ, while the welfare optimal subsidy under a zero subsidy withdrawal risk does not. The social planner can optimally set the subsidy size at each point in time and only needs to account for the firm's market power today if the subsidy is available forever. However, if the subsidy may be terminated in the future, they must consider what may happen after subsidy withdrawal. As the firm's future investment depends on the demand uncertainty, it also impacts the optimal policy.

Corollary 3 shows the effect of the monopolist's capacity on the welfare optimal subsidy size for any level of subsidy retraction risk.

Corollary 3. *The welfare optimal subsidy size, $\theta_\lambda^*(K)$, is positively affected by the monopolist's capacity, K.*

The social planner should install a larger subsidy when the monopolist's capacity is larger. This holds even when there is subsidy withdrawal risk. Corollary 3 implies that a social planner only needs a small subsidy to align the monopolist's investment with the welfare

Table 1
Parameter values used.

Notation	Parameter	Value
r	Risk-free interest rate	5%
μ	Price trend	2%
σ	Price volatility	10%
x	demand shock at $t = 0$	10
η	Slope of linear demand function	0.005
dK	Size of the capacity expansion	1 unit/year
κ	Variable investment cost	300 €/dK

optimal investment in an emerging market, but needs a large subsidy to perfectly align the monopolist's investment when the monopolist has already installed a large capacity.

Corollary 4 discusses the effect of the subsidy retraction risk on the welfare optimal subsidy size for any level of the monopolist's capacity.

Corollary 4. *The welfare optimal subsidy size, $\theta^*_\lambda(K)$, is negatively affected by the subsidy retraction risk, λ.*

It follows from Corollary 4 that a social planner should install a smaller subsidy when the withdrawal risk is larger. The social planner aligns the timing of the monopolist's investment and the optimal social investment. The gap in timing between the two investments decreases when the subsidy withdrawal risk is larger. The monopolist installs an additional unit of capacity sooner as they are afraid to lose the subsidy if they wait longer.

The welfare optimal policy depends on the firm's capacity level and must be updated after each investment. We now relax the assumption that the social planner can change the subsidy size after each increment of the firm, and assume that the social planner sets a fixed subsidy size at the start of the time horizon. We derive the optimal fixed subsidy size via simulation. For a given λ, the welfare optimal subsidy size, $\tilde{\theta}^*_\lambda$, is the subsidy size at which the average total surplus over all simulations is maximized.

4. Numerical study

In this section, we discuss the effect of a subsidy and the likelihood of its withdrawal on the decision to expand capacity and illustrate the relevant dynamics in a numerical example.[11] The data used in the numerical example, displayed in Table 1, are meant for illustrative purposes.

In Section 4.1, we first illustrate Propositions 1–3 for the non-subsidized firm's, the subsidized firm's and the social planner's optimal investment threshold in our numerical example. Next, we illustrate the findings of Corollaries 1 and 2. Finally, we examine the capacity growth under the optimal decision of a non-subsidized firm and compare it to a subsidized firm. In Section 4.2, we compare the welfare optimal subsidy size assuming the social planner aims to maximize the total surplus at fixed point of time in the future. We also compare the welfare under this policy to the welfare optimal policy when the social planner has an infinite time horizon (see Proposition 4).

4.1. Industry: Investment and capacity growth

First, we are interested in the rate at which the monopolist expands their production capacity during the lifetime of the subsidy for different withdrawal risk levels and subsidy sizes. We revisit the analytical results illustrating how a non-subsidized firm (Proposition 1), a subsidized firm (Proposition 2) and a social planner (Proposition 3) optimally invest via a numerical example. In Fig. 1(a), we illustrate the result of Corollary 1 and plot the optimal investment threshold, X_1 (see Proposition 2), as a function of the current capacity, K, for different levels of the subsidy termination intensity, λ, while keeping the subsidy size, θ, fixed. The effect of different subsidy sizes while keeping the withdrawal risk, λ, fixed, is examined in Fig. 1(b). Fig. 1(b) illustrates the result of Corollary 2. For comparison, we also plot X_0 (see Proposition 1), which is the optimal investment threshold without a subsidy and without subsidy termination risk, as well as X_S (see Proposition 3), the optimal social investment threshold, in both figures.

We observe that the monopolist invests sooner with a subsidy than without it for a given capacity, as the investment cost is lower with a subsidy. In Fig. 1(b), we see that the larger the subsidy, the lower the firm's investment threshold — consistent with the result stated in Corollary 2. As investment is cheaper, the firm is inclined to invest at a lower threshold, which means earlier investment, ceteris paribus. In Fig. 1(a), we also observe that the firm's investment threshold decreases with the subsidy withdrawal risk — consistent with the result stated in Corollary 1.

In addition to the investment threshold for a given level of capacity, these figures also have a second interpretation, related to the monopolist's capacity. The supremum of the demand shock, X, over time provides us with the monopolist's current capacity.[12] Our results indicate that the monopolist installs a larger aggregate capacity for as long as the subsidy is alive if the subsidy withdrawal risk is larger. This results from the fact that increasing the capacity is cheaper under a subsidy and that the firm fears that this subsidy will disappear sooner. We also conclude that the monopolist's optimal capacity for a given demand shock level is higher under a subsidy than without. The monopolist has an incentive to increase capacity early to guarantee that the capacity expansion is subsidized.

This is in stark contrast with both Chronopoulos et al. (2016) and Nagy et al. (2021). Chronopoulos et al. (2016) examine the retraction risk of a price premium and find that a greater likelihood of a permanent subsidy retraction increases the incentive to invest, but *lowers* the installed capacity. Nagy et al. (2021) examine a single firm having the option to undertake a lumpy investment subject to an investment cost subsidy, and find that the subsidized firm invests in a *smaller* capacity than a firm without a subsidy. In the case of a capacity expansion decision, as in this study, the firm still has the flexibility to extend capacity after investment, which leads to the difference in the results.

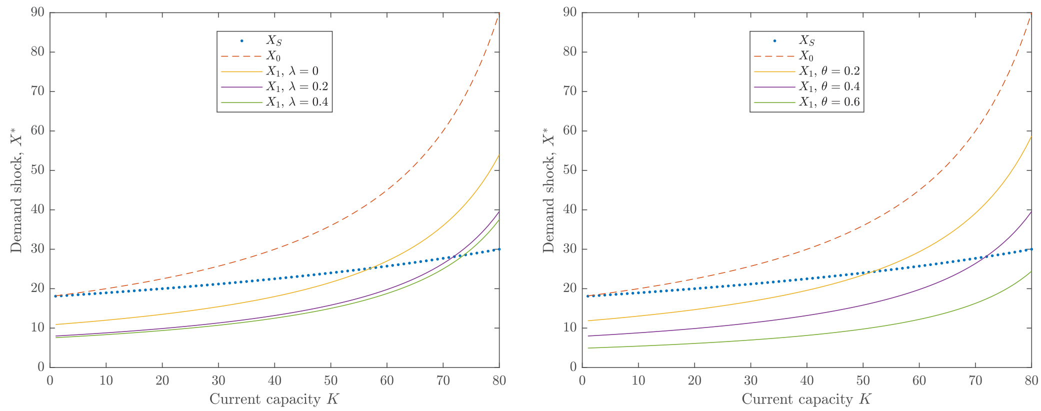
A policy maker who aims to increase a firm's capacity under a subsidy can increase the monopolist's investment by threatening to withdraw the subsidy soon. However, if the policy maker threatens to withdraw the subsidy soon but keeps the subsidy alive much longer than planned, the firm may perceive the actual subsidy withdrawal risk differently from what has been communicated by the policy maker. A future threat of withdrawing the subsidy becomes less effective, as the firm learns from experience that the subsidy will be available longer than is announced.

From the social planner's viewpoint, we observe that the sensitivity of the optimal social investment threshold, X_S, with respect to the current capacity is lower than that of the monopolist's threshold. This results from a difference in objectives between the monopolist and the social planner, as the latter includes the consumer surplus. The consumer surplus increases with capacity as long as the demand shock, X, has a positive value. Therefore, the social planner already has an incentive to install a larger aggregate capacity at lower output prices compared to the monopolist.

Comparing the monopolist's investment to the optimal social investment, we conclude that the former's threshold without a subsidy

[11] We use MATLAB R2021a for all numerical procedures as well as for the production of functional plots.

[12] Note that the monopolist's capacity is capped at $\frac{1}{2\eta}$, as the marginal revenue is non-positive for a capacity at that level or larger, meaning that no firm is willing to invest. With the parameter values in Table 1, the maximum capacity equals 100.



(a) Subsidy size $\theta = 0.4$. (b) Subsidy termination risk $\lambda = 0.2$.

Fig. 1. Investment timing as a function of the current production capacity, K, for different levels of subsidy termination risk, λ (left), and for different subsidy sizes, θ (right), compared to the optimal social decision, X_S, and firm's decision without subsidy, X_0. [General parameter values: $\mu = 0.02$, $\sigma = 0.10$, $r = 0.05$, $\eta = 0.005$, $\kappa = 300$, $dK = 1$.].

is equal to the latter's threshold when the capacity is low. A social planner interested in aligning the monopolist's investment threshold with the optimal social threshold can use a subsidy for the purpose when capacity is larger. The larger the capacity, the larger the subsidy required to align the thresholds, as can be seen from Fig. 1(a).

A policy maker may be interested in the question of whether the monopolist is more sensitive to a change in subsidy size than to one in subsidy withdrawal risk. We find that the monopolist decreases their investment threshold more from an increase in subsidy size than from an increase in subsidy withdrawal risk by the same percentage change. The effect of the former is direct, as it lowers the investment cost immediately, hence it is more effective. The effect of the latter is indirect, as the threat of subsidy withdrawal increases the probability of investment costs in the future being higher; however, it does not change the net present value (NPV) of investing today.

Next, we consider capacity growth over a longer period of time, and after subsidy withdrawal. We perform 10,000 simulations[13] to establish how the monopolist invests over time, and how this depends on subsidy withdrawal risk, subsidy size, and the time of subsidy withdrawal. Fig. 2 shows an example of two simulation runs, labeled A and B respectively, of the demand shock, X (Fig. 2(a)), and the corresponding monopolist's capacity over time (Fig. 2(b)).

Any simulation run can be broken down into three parts, although for some runs only the first two stages are reached: (1) a firm's total capacity grows while the subsidy is available; (2) the capacity stagnates after subsidy withdrawal; and (3) once the output prices reach a sufficiently high level, the capacity grows while the subsidy is unavailable. These three parts result from the monopolist's increasing the capacity sooner under a subsidy than without. The monopolist's investment threshold rises steeply at the time the subsidy is withdrawn, as its marginal cost of investment rises. Consequently, they do not invest directly after subsidy withdrawal, and delay investment until the output prices are significantly larger. In Fig. 2, simulation run A does not reach sufficiently high output prices to attract investment after subsidy withdrawal; thus, it only has the first two stages.

In Fig. 3, we show the average capacity over time of 10,000 simulations for different levels of subsidy withdrawal risk, λ. We compare the capacity growth against a baseline without a subsidy.

We observe that the monopolist's capacity under a subsidy is larger than that without a subsidy. A subsidy that is provided forever, i.e., there is no withdrawal risk, yields the most investment. In the case of a subsidy subject to withdrawal risk, the positive effect of the subsidy on the capacity is most pronounced during the lifetime of the subsidy and remains for some time after subsidy withdrawal; however, it fades after some time.

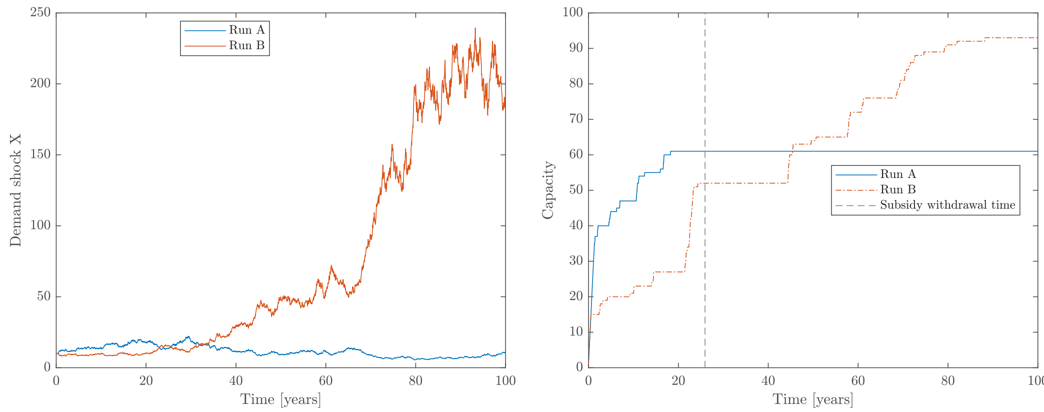
Next, we discuss the role of subsidy withdrawal risk on the monopolist's total capacity over time. The monopolist increases their capacity more during the subsidy's lifetime when the subsidy withdrawal risk is higher. As the monopolist anticipates the future withdrawal of the subsidy and the resulting increase in the investment cost, they move the investment that they would usually undertake at the mid-term (10–20 years) to the short term (less than 10 years). Consequently, the short-term capacity under a subsidy is higher when the expected life span of the subsidy is shorter. However, the threat of the subsidy being unavailable at the mid-term results in little to no expected investment at the midterm. Hence, the capacity at the mid-term under a subsidy with a longer life span is higher than that under a subsidy with a shorter life span. This effect also remains for the long term, until the time at which the effect of the subsidy has completely faded, after approximately 40 to 50 years.

We show the average capacity over time of 10,000 simulations for different subsidy sizes, θ, in Fig. 4. We again compare the capacity growth against a baseline without a subsidy.

In contrast to the effect of a lower subsidy withdrawal risk, the positive impact of a larger subsidy on investment capacity does last for long and takes longer to fade away. The monopolist increases their capacity more during the subsidy's lifetime when the subsidy is larger in size. However, the monopolist's total capacity grows at a lower rate once the subsidy is withdrawn.

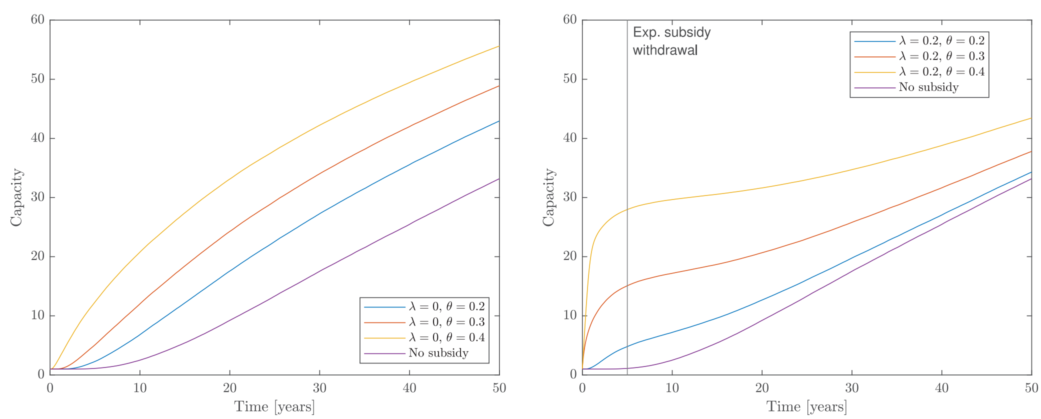
We also examine the effect of a subsidy on investment *after* its withdrawal. The monopolist does not increase their capacity for quite some time directly after the subsidy withdrawal, as shown in the example runs in Fig. 2. The larger the subsidy or the larger the likelihood of a subsidy retraction, the longer the period without investment after a subsidy withdrawal. Both a larger subsidy and a larger subsidy withdrawal risk increase the monopolist's investment during the subsidy's lifetime. Consequently, the monopolist's capacity is at a higher level at the time of the subsidy withdrawal. Once the subsidy is withdrawn, the investment costs for the monopolist rise, while the output prices

[13] The simulation of the geometric Brownian motion in (2) is performed using $X(t_i) = X(t_{i-1}) \cdot e^{(\mu - \frac{\sigma^2}{2})\cdot dt + \sigma \cdot W_i \sqrt{dt}}$ for all moments in time, t_i. W_i is a draw from the standard normal distribution, and t_i, t_{i-1} are two consecutive moments in time with step size, dt. We use antithetic variables for the simulation of the geometric Brownian motion; thus, for a simulation with draws, $W_1, W_2, \ldots$, a run with $-W_1, -W_2, \ldots$ is performed. The time of subsidy withdrawal, τ_S, is randomly regenerated via the inverse cumulative distribution function (cdf) of a Poisson jump: $\tau_S = -\frac{\log(1-Z)}{\lambda}$, where Z is a draw from the standard normal distribution. We drew 5,000 simulations of the subsidy withdrawal and used the same withdrawal time for the two runs that are linked via the use of antithetic variables.



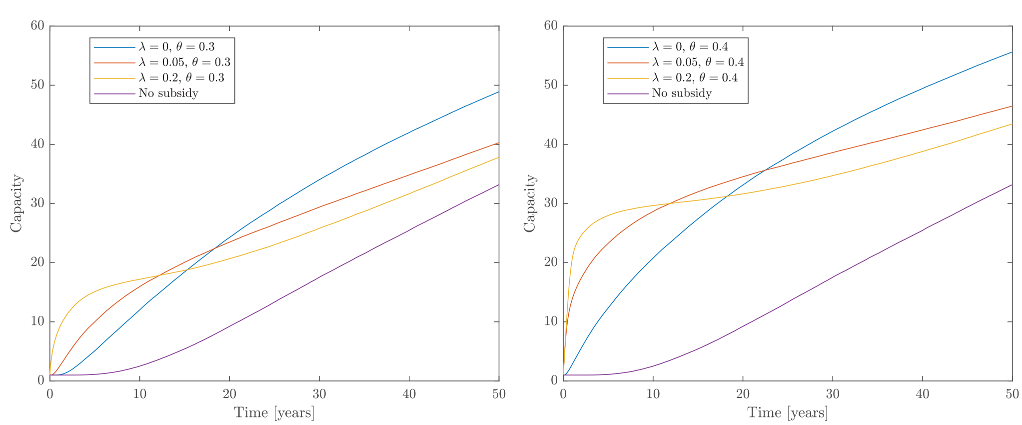
(a) Simulated demand shock X over time (b) Monopolist's capacity over time

Fig. 2. Two example runs of the simulated demand shock, X (left), and the firm's capacity (right). [General parameter values: $\mu = 0.02$, $\sigma = 0.10$, $r = 0.05$, $\eta = 0.005$, $\kappa = 300$, $dK = 1$, $x = 10$, $\lambda = 0.2$, $\theta = 0.4$.].



(a) No subsidy withdrawal risk ($\lambda = 0$). (b) Subsidy withdrawal risk $\lambda = 0.2$.

Fig. 3. Expected firm's total capacity over time for different levels of subsidy withdrawal risk. [General parameter values: $\mu = 0.02$, $\sigma = 0.10$, $r = 0.05$, $\eta = 0.005$, $dK = 1$, $x = 10$.].



(a) $\theta = 0.3$. (b) $\theta = 0.4$.

Fig. 4. Expected firm's total capacity over time for different subsidy sizes. [General parameter values: $\mu = 0.02$, $\sigma = 0.10$, $r = 0.05$, $\eta = 0.005$, $dK = 1$, $x = 10$.].

remain at approximately the same level as at the end of the subsidy's lifetime. The higher the monopolist's capacity at the time of subsidy withdrawal, the longer it takes the output prices to grow to a level that attracts investment without a subsidy.[14]

These results have several implications for the policy maker. First, a permanent subsidy is the only way to make a permanent impact on capacity, as the effects of a subsidy scheme fade away over time. Second, a policy maker aiming to reach a (long-term) capacity target must implement a subsidy that is sufficiently large to reach the target during the subsidy's lifetime. The subsidy has no contribution to reaching the goal on time otherwise, while the social planner still pays for the subsidy. If the target is not reached during the subsidy's lifetime, there will be a dry spell of investment and the target will be reached at the same time as in the scenario in which the subsidy is never implemented. Third, a policy maker who is only interested in maximizing the investment while the subsidy is in effect can do this by making the subsidy available for only a short period of time. This happens at the cost of less investment shortly after the subsidy withdrawal and results in less investment in the long run compared to a subsidy of the same size that is available longer.

4.2. Policy: Optimal subsidy and total surplus

We define the welfare optimal subsidy size as the subsidy size that maximizes the total surplus. We consider two different types of investment cost subsidies: a fixed subsidy and a flexible subsidy. With the former, we assume that the policy maker sets the subsidy size equal to a constant, and does not change this over time. In the case of a flexible subsidy, the policy maker can adjust the subsidy size for as long as the subsidy is alive. We aim to answer the following two questions: First, what is the optimal subsidy size in the case of a fixed subsidy.[15]? Second, is it possible for a policy maker to improve welfare via a flexible or fixed investment cost subsidy?

We start by answering the first question of the optimal subsidy size in the case of a fixed subsidy. We find the welfare optimal fixed subsidy size via an interval search maximizing the average total surplus over 1000 simulations. It is important to consider the time, T, at which the social planner wants to maximize the total surplus. In Fig. 5, we plot the welfare optimal fixed subsidy size as a function of the time, T, at which the social planner aims to maximize the total surplus, assuming no policy withdrawal risk (i.e., $\lambda = 0$). From this figure, we can determine how a social planner should choose their subsidy size given a certain horizon at which the total surplus should be maximized. For example, if a social planner aims to maximize the total surplus after 60 years, the optimal fixed subsidy is 60% ($\tilde{\theta}^*_{\lambda=0} = 0.6$) if the initial price is $x = 20$ and 13% ($\tilde{\theta}^*_{\lambda=0} = 0.13$) if the initial price is $x = 20$.

The welfare optimal fixed subsidy size strongly depends on the time at which the social planner maximizes the total surplus as well as the initial output price. The further into the future the social planner aims to obtain the maximum surplus, the larger the optimal subsidy. The trade-off faced by the social planner is whether it is worth incurring high costs for the investment today to accumulate more of both consumer and producer surpluses over time. A social planner with a short-term focus should not implement a subsidy as it takes time for the consumer and producer surpluses to grow and offset the high costs of investment. The optimal fixed subsidy size also increases with the initial output price. The larger the initial output price, the more valuable new investments are from a social welfare viewpoint.

Next, we examine the total surplus under different policies, comparing it with that with a no-subsidy baseline. We compare the fixed subsidy that maximizes the surplus at time T with the flexible subsidy that maximizes the surplus over an infinite time horizon, where the latter is equivalent to a social planner who maximizes total surplus, investing as discussed in Proposition 3. Fig. 6 shows the accumulated total surplus over time for different subsidy withdrawal risks when the social planner aims to maximize the total surplus after 100 years using a fixed subsidy.

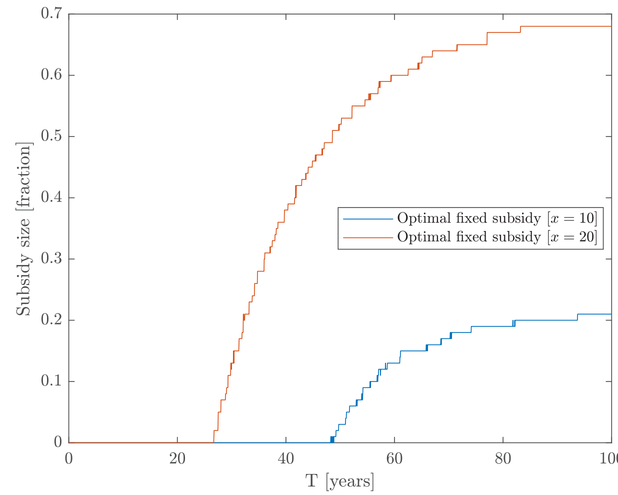


Fig. 5. Optimal fixed subsidy maximizing total surplus at different time horizons for different starting prices, x.

Straightforwardly, the flexible subsidy outperforms the fixed subsidy and the no-subsidy scenario over the long term, as the social planner can adapt the subsidy size over time. However, the fixed subsidy still yields better total welfare results than the no-subsidy baseline. The difference between the fixed-subsidy and no-subsidy scenarios is largest when there is no subsidy withdrawal risk.

In Figs. 7(a) and 7(b), we show what happens to the accumulated total surplus when the social planner aims to maximize surplus after 50 years with a fixed subsidy instead of after 100 years (as shown in Figs. 6(a) and 6(b)). [16]

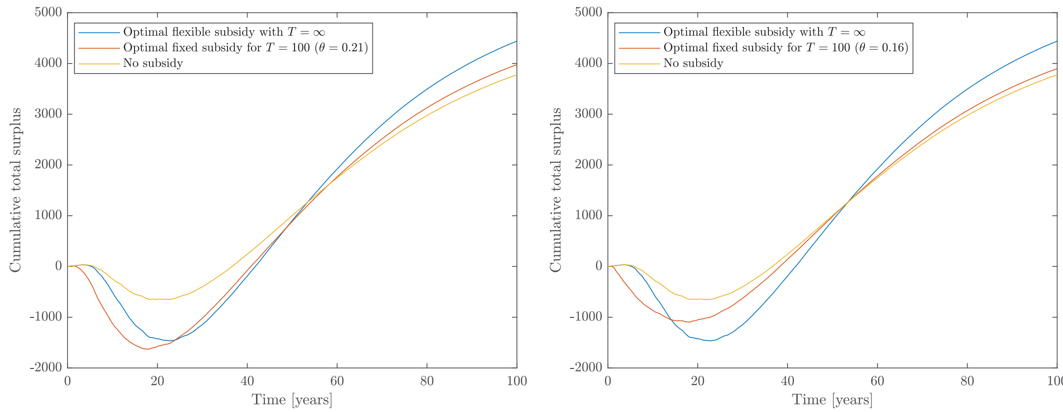
Comparing Figs. 6 and 7, we conclude that the total surplus under a fixed subsidy moves closer to the no-subsidy curve and further away from the optimal flexible subsidy when the social planner with the fixed subsidy has a more myopic mindset. The optimal subsidy is also significantly smaller when the social planner is more myopic and the subsidy is subject to subsidy withdrawal risk — similar to the scenario of no-subsidy withdrawal risk shown in Fig. 5. Interestingly, both the fixed and the flexible subsidies perform poorly in the short term compared to the no-subsidy scenario. The reason for this is that the subsidy attracts investment that leads to significant costs in the short term. These costs are only offset by the consumer surplus that is gained over a long time period. Thus, a subsidy only has value for total welfare in the long term. If the social planner aims to maximize the total surplus today, it is better *not* to implement a subsidy.

Surprisingly, the optimal fixed subsidy is larger under a subsidy withdrawal risk, $\lambda = 0.2$, than under no-subsidy withdrawal risk, ($\lambda = 0$). This results from the relatively short-time focus of the social planner in combination with the subsidy being available forever when $\lambda = 0$. Therefore, the firm has little incentive to invest now, while the social planner wants to see investment relatively soon. It means that attracting investment now via the subsidy is rather costly, while the cost cannot be earned back in 50 years. However, the subsidy withdrawal risk of $\lambda = 0.2$ provides the firm with a natural incentive

[14] A detailed analysis of the distribution of the times of the first investment after a subsidy withdrawal is show in Appendix C.

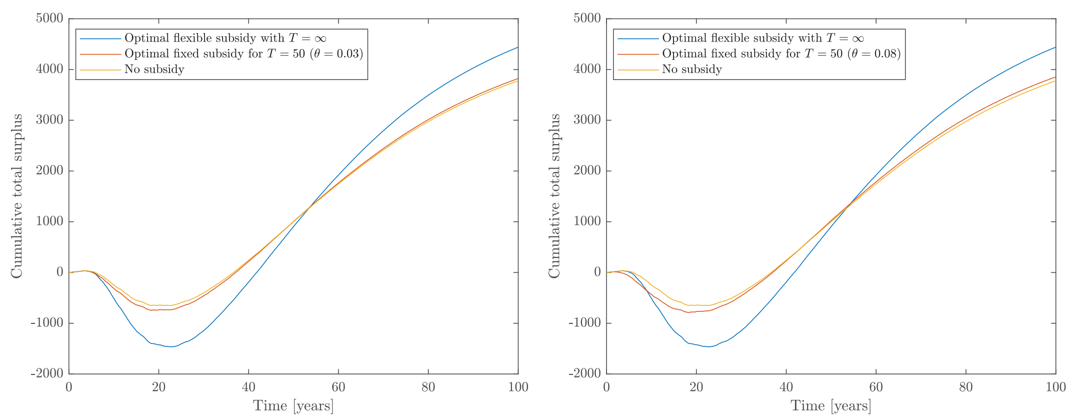
[15] Note that when the subsidy is flexible, the welfare optimal subsidy size is given by Proposition 4 We provide a numerical example in Appendix D.

[16] In Appendix E, we perform the same analysis as in Figs. 6 and 7 with an initial demand intercept $x = 20$ instead of $x = 10$.



(a) $\lambda = 0$. (b) $\lambda = 0.2$.

Fig. 6. Cumulative total surplus over time for different levels of subsidy termination risk, λ, with a social planner maximizing total surplus at $T = 100$. [General parameter values: $\mu = 0.02$, $\sigma = 0.10$, $r = 0.05$, $\eta = 0.005$, $\kappa = 300$, $dK = 1$, $x = 10$.].



(a) $\lambda = 0$, $T = 50$. (b) $\lambda = 0.2$, $T = 50$.

Fig. 7. Cumulative total surplus over time for different levels of subsidy termination risk, λ, with a social planner who maximizes total surplus at $T = 50$. [General parameter values: $\mu = 0.02$, $\sigma = 0.10$, $r = 0.05$, $\eta = 0.005$, $\kappa = 300$, $dK = 1$, $x = 10$.].

to invest relatively early, even when the subsidy is small. This means that the social planner requires less subsidy to attract investment now, leading to a higher surplus at $T = 50$.

5. Conclusion and policy implications

This study examines the effect of an investment cost subsidy subject to withdrawal risk on a monopolist's series of infinitesimal investments. The social planner aims to increase capacity or maximize welfare, and does so by implementing a subsidy. The size of the subsidy is decided upon by the social planner and is assumed to be either variable or fixed throughout the entire lifetime of the subsidy. The timing of the subsidy termination is assumed to be random, with a known probability distribution. The monopolist determines when to invest. The investment is irreversible and incremental. We examine both the problem of the profit-maximizing firm and that of the social planner who aims to maximize welfare.

Examining the firm's problem, we find that a firm invests sooner when the likelihood of subsidy withdrawal or the subsidy size is larger. Compared to a scenario in which no subsidy is implemented, the monopolist is having a ball and invests more during the lifetime of the subsidy. This result starkly contrasts with the investment of a monopolist that instead has a one-time (lumpy) investment. Once the subsidy is withdrawn, the monopolist stops with investment until the prices have grown sufficiently to attract investment without a subsidy. This means that a policy maker can use a subsidy to attract investment in the short term; however, this effect of the subsidy tapers off over time. Furthermore, for a subsidy to be effective in letting the industry's capacity reach a capacity target faster than an industry without subsidy, the subsidy must be sufficiently large such that the target is reached during the subsidy's lifetime. If the target is not reached during the subsidy's lifetime, the target will be reached at the same time as in the scenario in which a subsidy is never implemented, meaning that the subsidy has no contribution to reaching the goal on time.

Considering the social planner's problem of welfare maximization, we find that both flexible and fixed subsidies increase total welfare in the long run if optimally set. When a firm accounts for the risk of a subsidy being withdrawn in the future, the policy maker can use a flexible subsidy as a tool to perfectly align the monopolist's investment with the optimal social investment. The optimal flexible subsidy size increases with the monopolist's capacity and decreases with subsidy withdrawal risk. Although the social planner can use a flexible or fixed subsidy to increase welfare in the long run, the total surplus in the short term under a subsidy is generally lower than that without a subsidy. Investment is very costly, while it takes time to accumulate consumer and producer surpluses to offset the investment cost. This also leads to welfare in the midterm being lower for the welfare optimal flexible subsidy with a long-term horizon than for the welfare optimal fixed subsidy with a mid-term horizon. The optimal fixed subsidy is extremely sensitive to the social planner's time horizon.

Its size decreases if a social planner is more myopic. A social planner with long-term goals should implement a large subsidy, and this policy is most effective if the subsidy withdrawal risk is low. Generally, the optimal fixed subsidy size decreases with the subsidy retraction risk. The exception is when prices are low, in which case an increase in subsidy retraction risk can lead to an increase in the optimal fixed subsidy.

For future research, it may be interesting to study the role of competition. Huisman and Kort (2015) examine a duopoly in which two firms each can do a lumpy investment, and find that the market leader invests sooner than a monopolist due to the competition. A similar effect can be expected in the presence of a subsidy subject to withdrawal risk: a firm subject to competition and subsidy withdrawal risk may invest sooner than a monopolist subject to subsidy withdrawal risk alone. This effect is most likely amplified if one assumes the social planner is subject to a budget constraint and may withdraw the subsidy when the budget for the subsidy is depleted.

Furthermore, one may want to include technological developments as well as multiple policy interventions to examine long-term policy impact. In our study, we focused on the long-term impact of a single policy. However, to do a forecast of the future and explore whether long-term policy targets will be reached, one needs to understand how technologies will develop over time, and how policy interventions on the mid-term can steer the market for the long-term.

CRediT authorship contribution statement

Roel L.G. Nagy: Conceptualization, Methodology, Software, Validation, Formal analysis, Writing – original draft, Writing – review & editing, Visualization. **Stein-Erik Fleten:** Conceptualization, Methodology, Writing – review & editing, Supervision, Funding acquisition. **Lars H. Sendstad:** Conceptualization, Methodology, Writing – review & editing.

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.

Data availability

No data was used for the research described in the article.

Acknowledgments

This study was supported by the Research Council of Norway [grant numbers 268093, 296205]. Furthermore, the authors are grateful for the helpful and insightful comments from Verena Hagspiel and participants of the 24th Annual International Real Options Conference (September 2021) and NTNU Business School Conference (October 2020).

Appendix A. Miscellaneous derivations

A.1. Derivation and discussion of the monopolist's objective

Let $\Delta P_i(X)$ be the price change from increasing the capacity for the ith time, i.e., $\Delta P_i(X) = P(X\cdot, K_i) - P(X\cdot, K_{i-1})$. The objective can be rewritten as follows:

$$V = \sup_{\tau_1,\tau_2,\ldots} \mathbb{E}\left[\sum_{i=0}^{\infty} \int_{\tau_i}^{\tau_{i+1}} P(X, K_i)\cdot K_i \cdot e^{-rt} dt - \sum_{i=1}^{\infty} (1-\theta\cdot \mathbb{1}_{\xi(\tau_i)})\kappa \cdot dK \cdot e^{-r\tau_i} \,\middle|\, X(\tau_i), \xi(\tau_i) \right] \tag{A.1}$$

$$= \sup_{\tau_1,\tau_2,\ldots} \mathbb{E}\left[\int_0^\infty P(X,k)\cdot k \cdot e^{-rt} dt + \sum_{i=1}^{\infty} \int_{\tau_i}^{\infty} \left(\Delta P_i(X)\cdot K_{i-1} + P(X,K_i)\cdot dK \right) \cdot e^{-rt} dt - \sum_{i=1}^{\infty} (1-\theta\cdot \mathbb{1}_{\xi(\tau_i)})\kappa\cdot dK\cdot e^{-r\tau_i} \,\middle|\, X(0)=x, \xi(0)=1 \right] \tag{A.2}$$

$$= \mathbb{E}\left[\int_0^\infty P(X,k)\cdot k\cdot e^{-rt} dt \,\middle|\, X(0)=x,\xi(0)=1 \right] + \sum_{i=1}^\infty \sup_{\tau_i} \left\{ \mathbb{E}\left[\int_{\tau_i}^\infty \left(\Delta P_i(X)\cdot K_{i-1} + P(X,K_i)\cdot dK \right)\cdot e^{-rt} dt - (1-\theta\cdot \mathbb{1}_{\xi(\tau_i)})\kappa\cdot dK\cdot e^{-r\tau_i} \,\middle|\, X(0)=x,\xi(0)=1 \right] \right\}. \tag{A.3}$$

Eq. (A.3) shows that when capacity is increased, there are only three relevant factors (which are within the sup-operator of Eq. (A.3)):

(a) the additional revenue from the capacity expansion, captured by the term, $P(X(t), K_i)\cdot dK$;
(b) the price change decreasing the marginal revenue of every unit of the current capacity, captured by the term, $\Delta P_i(X(t))\cdot K_{i-1}$; and
(c) the investment cost of expanding the capacity, dependent on the availability of the subsidy and captured by the term, $(1-\theta\cdot \mathbb{1}_{\xi(\tau_i)})\kappa\cdot dK$.

As long as the costs explained in factors (b) and (c) together outweigh the benefits from (a), it is optimal for the monopolist to delay increasing its capacity.

A.2. Derivation and discussion of the social planner's objective

The consumer surplus is calculated by taking the expectation and integral over the instantaneous consumer surplus (ICS) (see, e.g., Huisman and Kort (2015)). The instantaneous consumer surplus is given by

$$ICS(X,K) = \int_{P(X,K)}^{X} D(P) dP \tag{A.4}$$

$$= \frac{1}{2}\eta X K^2, \tag{A.5}$$

where $D(P)$ is the demand function, i.e., the inverse of (1). The consumer surplus can be derived as follows:

$$CS(X,K) = \mathbb{E}\left[\sum_{i=1}^{\infty} \int_{\tau_{i-1}}^{\tau_i} \frac{1}{2}\eta X(t)\cdot K_{i-1}^2 \cdot e^{-rt} dt \,\middle|\, X(0)=x \right] \tag{A.6}$$

$$= \mathbb{E}\left[\sum_{i=1}^{\infty} \int_{\tau_{i-1}}^{\tau_i} \frac{1}{2}\eta X(t)\cdot \left(k^2 + 2k(i-1)dK + (i-1)^2 dK^2 \right) \cdot e^{-rt} dt \,\middle|\, X(0)=x \right] \tag{A.7}$$

$$= \mathbb{E}\left[\int_0^\infty \tfrac{1}{2}\eta X(t)\cdot k^2\cdot e^{-rt} dt \,\middle|\, X(0)=x \right] + \mathbb{E}\left[\sum_{i=1}^{\infty} \int_{\tau_{i-1}}^{\tau_i} \frac{1}{2}\eta X(t)\cdot \left(2k(i-1) + (i-1)^2 dK \right) dK\cdot e^{-rt} dt \,\middle|\, X(0)=x \right] \tag{A.8}$$

$$= \mathbb{E}\left[\int_0^\infty \tfrac{1}{2}\eta X(t)\cdot k^2\cdot e^{-rt} dt \,\middle|\, X(0)=x \right] + \sum_{i=1}^{\infty} \mathbb{E}\left[\int_{\tau_{i-1}}^{\infty} \frac{1}{2}\eta X(t)\cdot \left(2k + (2i-1)dK \right) dK\cdot e^{-rt} dt \,\middle|\, X(0)=x \right]. \tag{A.9}$$

The producer surplus under any demand function is derived in Appendix A.1. The producer surplus under the demand function given by (1) is given by

$$\sup_{\tau_1,\tau_2,\dots} PS(X,K) = \mathbb{E}\left[\int_0^\infty X(t)\cdot(1-\eta k)\cdot k\cdot e^{-rt}dt \,\middle|\, X(0)=x\right] + \sum_{i=1}^{\infty}\sup_{\tau_i}\left\{ \mathbb{E}\left[\int_{\tau_i}^{\infty}\left(-\eta X(t)\cdot dK\cdot K_{i-1} + X(t)\cdot(1-\eta K_i)\cdot dK\right)\cdot e^{-rt}dt - \kappa\cdot dK\cdot e^{-r\tau_i}\,\middle|\, X(0)=x\right]\right\}. \tag{A.10}$$

Then, we add the expressions for the consumer surplus and the producer surplus to find the total surplus:

$$TS(X,K) = \mathbb{E}\left[\int_0^\infty X(t)\cdot\left(1-\frac{1}{2}\eta k\right)\cdot k\cdot e^{-rt}dt\,\middle|\, X(0)=x\right] + \sum_{i=1}^{\infty}\mathbb{E}\left[\int_{\tau_i}^{\infty}\left(X(t)\cdot(1-\eta K_i)+\eta X(t)\cdot dK\right)\cdot dK\cdot e^{-rt}dt - \kappa\cdot dK\cdot e^{-r\tau_i}\,\middle|\, X(\tau_{i-1})\right]. \tag{A.11}$$

In Eq. (A.11), the term in the first line, $X(t)\cdot(1-\frac{1}{2}\eta k)\cdot k$, captures the total surplus if capacity remains at capacity $K = k$ forever. When increasing the capacity, there are three elements (all in the second line of Eq. (A.11)) that change the total surplus:

(i) the producer obtains an additional profit from the additional unit of capacity, dK, that is sold against the price, $X(t)\cdot(1-\eta K_i)$;
(ii) the consumer surplus increases as supply increases, while the producer's marginal revenue for their current production decreases as supply increases. The increase in consumer surplus dominates the negative effect on the producer surplus. Both effects are captured in the term, $\eta X(t)\cdot dK^2$;
(iii) when the producer increases their capacity, they pay the investment cost, $\kappa\cdot dK$.

A social planner maximizing total surplus will increase their capacity when the effects in (i) and (ii) jointly outweigh the investment cost of increasing the capacity in (iii). Compared to the profit-maximizing monopolist's considerations outlined in the discussion of Eq. (A.3), effects (i) and (iii) for the social planner are the same as (a) and (c) for the producer. The social planner and the monopolist have different optimal decisions due to the difference in the effect of the increase of supply discussed in (ii) and (b), respectively. For a firm, increasing the supply has a negative effect on the value of the current production (i.e., production at the level before the capacity increase) as it decreases the output price. For the social planner, the negative effect is offset by an increase in consumer surplus.

A.3. Derivation of the optimal subsidy without subsidy withdrawal risk

Solving the monopolist's optimal investment threshold for a subsidy of size θ without any withdrawal risk, ($\lambda = 0$), yields

$$X_1|_{\lambda=0}(K) = \frac{\beta_{01}}{\beta_{01}-1}\cdot\frac{(r-\mu)(1-\theta)\kappa}{1-2\eta K}. \tag{A.12}$$

The social planner's optimal investment threshold for maximizing total surplus is given by

$$X_S(K) = \frac{\beta_{01}}{\beta_{01}-1}\cdot\frac{(r-\mu)\kappa}{1-\eta K}. \tag{A.13}$$

Solving $X_1|_{\lambda=0}(K) = X_S(K)$ for θ yields the stated expression.

Alternatively, one can derive the stated expression by substituting $\lambda = 0$ into (14), using the fact that $\beta_{11} = \beta_{01}$ when $\lambda = 0$.

Appendix B. Proofs of propositions and corollaries

B.1. Proof of Proposition 1

Using Itô calculus and the Bellman equation, it follows that

$$\frac{1}{2}\sigma^2X^2\cdot\frac{d^2V_0(X,K)}{dX^2} + \mu X\cdot\frac{dV_0(X,K)}{dX} - rV_0(X,K) = 0 \tag{B.1}$$

should hold for the value of the option to expand capacity without the subsidy for the current value, X, of the demand shock process and K for the capacity. In this ordinary differential equation (ODE), r is the discount rate. The solution to this ODE is given by

$$V_0(X,K) = A_{01}(K)\cdot X^{\beta_{01}} + \frac{X(1-\eta K)K}{r-\mu}, \tag{B.2}$$

where $A_{01}(K)$ is a positive expression to be determined. The marginal revenue of the option with respect to capacity is given by

$$\frac{dV_0(X,K)}{dK} = \frac{dA_{01}(K)}{dK}\cdot X^{\beta_{01}} + \frac{X(1-2\eta K)}{r-\mu}. \tag{B.3}$$

We follow the approach by Dixit and Pindyck (1994) and apply the value matching and smooth pasting conditions to the objective (B.3) to derive the optimal investment threshold. The value matching condition tells us that when the monopolist decides to expand, their marginal revenue equals marginal costs. The smooth pasting guarantees that the expression we value match is smooth with respect to the timing threshold, X. The value matching and smooth pasting conditions for the investment threshold without subsidy are given by

$$\frac{dA_{01}(K)}{dK}\cdot\left(X_0^i\right)^{\beta_{01}} + \frac{X_0^i(1-2\eta K_i)}{r-\mu} = \kappa, \tag{B.4}$$

$$\beta_{01}\cdot\frac{dA_{01}(K)}{dK}\cdot\left(X_0^i\right)^{\beta_{01}-1} + \frac{1-2\eta K_i}{r-\mu} = 0. \tag{B.5}$$

Dixit and Pindyck (1994) solve this system of equations and conclude that the optimal investment threshold without subsidy is given by

$$X_0^i(K_i) = \frac{\beta_{01}}{\beta_{01}-1}\cdot\frac{(r-\mu)\kappa}{1-2\eta K_i}. \tag{B.6}$$

The expression $A_{01}(K)$ has to satisfy

$$\frac{dA_{01}(K_i)}{dK} = -\left(\frac{\beta_{01}-1}{\kappa}\right)^{\beta_{01}-1}\cdot\left(\frac{1-2\eta K_i}{\beta_{01}(r-\mu)}\right)^{\beta_{01}}. \tag{B.7}$$

By integration,[17], we obtain

$$A_{01}(K_i) = \left(\frac{\beta_{01}-1}{\kappa}\right)^{\beta_{01}-1}\cdot\frac{1-2\eta K_i}{2\eta(\beta_{01}+1)}\cdot\left(\frac{1-2\eta K_i}{\beta_{01}(r-\mu)}\right)^{\beta_{01}} \tag{B.8}$$

$$= \frac{\kappa(1-2\eta K_i)}{2\eta(\beta_{01}-1)(\beta_{01}+1)}\cdot\left(\frac{(\beta_{01}-1)(1-2\eta K_i)}{\beta_{01}\kappa(r-\mu)}\right)^{\beta_{01}}. \tag{B.9}$$

B.2. Proof of Proposition 2

We apply Ito's lemma and use the Bellman equation to derive the value of the option to expand capacity under a subsidy. The equation is given by

$$\frac{1}{2}\sigma^2X^2\cdot\frac{d^2V_1(X,K)}{dX^2} + \mu X\cdot\frac{dV_1(X,K)}{dX} - rV_1(X,K) + \lim_{dt\to 0}\mathbb{P}[\text{Subsidy withdrawal occurs in time interval } dt]\cdot\frac{1}{dt}\cdot(V_0(X,K)-V_1(X,K)) = 0. \tag{B.10}$$

In this case, we also have to account for the risk of policy withdrawal. We obtain

$$\frac{1}{2}\sigma^2X^2\cdot\frac{d^2V_1(X,K)}{dX^2} + \mu X\cdot\frac{dV_1(X,K)}{dX} - rV_1(X,K) + \lambda(V_0(X,K)-V_1(X,K)) = 0. \tag{B.11}$$

[17] Following Dixit and Pindyck (1994, p. 365–366) we set the integration constant to be equal to zero.

The solution to (B.11) is given by

$$V_1(X,K) = A_{11}(K)\cdot X^{\beta_{11}} + A_{01}(K)\cdot X^{\beta_{01}} + \frac{X(1-\eta K)K}{r-\mu}, \tag{B.12}$$

where $A_{11}(K)$ is a positive expression to be determined.

Similar to the case without a subsidy, the optimal investment threshold follows from solving the system comprising the value matching and smooth pasting conditions. We thus obtain the following two equations:

$$\frac{dA_{11}(K)}{dK}\cdot(X_1^i)^{\beta_{11}} + \frac{dA_{01}(K_i)}{dK}\cdot(X_1^i)^{\beta_{01}} + \frac{X_1^i(1-2\eta K_i)}{r-\mu} = (1-\theta)\kappa, \tag{B.13}$$

$$\beta_{11}\cdot\frac{dA_{11}(K)}{dK}\cdot(X_1^i)^{\beta_{11}-1} + \beta_{01}\cdot\frac{dA_{01}(K_i)}{dK}\cdot(X_1^i)^{\beta_{01}-1} + \frac{1-2\eta K_i}{r-\mu} = 0. \tag{B.14}$$

Combining these two equations results in an implicit equation for our investment threshold, X_1^i:

$$\frac{\beta_{11}-\beta_{01}}{\beta_{11}}\cdot\frac{dA_{01}(K_i)}{dK}\cdot(X_1^i)^{\beta_{01}} + \frac{\beta_{11}-1}{\beta_{11}}\cdot\frac{X_1^i(1-2\eta K_i)}{r-\mu} - (1-\theta)\kappa = 0. \tag{B.15}$$

B.3. Proof of Corollary 1

We refer to the implicit Eq. (11) as $f(X_1)$:

$$f(X_1) \equiv \frac{\beta_{11}-\beta_{01}}{\beta_{11}}\cdot\frac{dA_{01}(K)}{dK}\cdot X_1^{\beta_{01}} + \frac{\beta_{11}-1}{\beta_{11}}\cdot\frac{X_1(1-2\eta K)}{r-\mu} - (1-\theta)\kappa = 0. \tag{B.16}$$

By total differentiation, we derive the following:

$$0 = \frac{df}{d\lambda} = \frac{\partial f}{\partial\lambda} + \frac{\partial f}{\partial X}\cdot\frac{\partial X}{\partial\lambda} \iff \frac{\partial X}{\partial\lambda} = -\frac{(\frac{\partial f}{\partial\lambda})}{(\frac{\partial f}{\partial X})}. \tag{B.17}$$

We show that $\frac{df}{d\lambda} < 0$ by showing that both $\frac{\partial f}{\partial\lambda} > 0$ and $\frac{\partial f}{\partial X} > 0$. First, we prove $\frac{\partial f}{\partial\lambda} > 0$. By directly differentiating (B.16) with respect to λ, we derive the following:

$$\frac{\partial f}{\partial\lambda} = \frac{1}{\beta_{11}^2}\cdot\frac{d\beta_{11}}{d\lambda}\cdot\left(\beta_{01}\cdot\frac{dA_{01}(K)}{dK}\cdot X_1^{\beta_{01}} + \frac{X_1(1-2\eta K)}{r-\mu}\right) \tag{B.18}$$

$$= -\frac{1}{\beta_{11}}\cdot\frac{d\beta_{11}}{d\lambda}\cdot\frac{dA_{11}(K)}{dK}\cdot X_1^{\beta_{11}}, \tag{B.19}$$

where $\frac{d\beta_{11}}{d\lambda} = \frac{1}{\sigma(\beta_{11}-1)+\mu} > 0$. $\frac{\partial f}{\partial\lambda} > 0$ follows from $\frac{dA_{11}(K)}{dK} < 0$.

Second, it remains to be proven that $\frac{\partial f}{\partial X} > 0$ for any λ. The expression for $\frac{\partial f}{\partial X}$ is given by

$$\frac{\partial f}{\partial X} = \frac{\beta_{11}-\beta_{01}}{\beta_{11}}\cdot\frac{dA_{01}(K)}{dK}\cdot\beta_{01}\cdot X_1^{\beta_{01}-1} + \frac{\beta_{11}-1}{\beta_{11}}\cdot\frac{1-2\eta K}{r-\mu}, \tag{B.20}$$

where $\frac{dA_{01}(K)}{dK} = -\left(\frac{\beta_{01}-1}{\kappa}\right)^{\beta_{01}-1}\cdot\left(\frac{1-2\eta K}{\beta_{01}(r-\mu)}\right)^{\beta_{01}} < 0$. We rewrite the condition, $\frac{\partial f}{\partial X} > 0$, using the expressions for $\frac{\partial f}{\partial X}$ and $\frac{dA_{01}(K)}{dK}$ to

$$(\beta_{11}-\beta_{01})\cdot\left(\frac{\beta_{01}-1}{\beta_{01}}\cdot\frac{1-2\eta K}{\kappa(r-\mu)}\cdot X_1\right)^{\beta_{01}-1} < \beta_{11}-1. \tag{B.21}$$

By recognizing the expression for the investment threshold without a subsidy, X_0, on the left hand side, we can rewrite this as

$$(\beta_{11}-\beta_{01})\cdot\left(\frac{X_1}{X_0}\right)^{\beta_{01}-1} < \beta_{11}-1. \tag{B.22}$$

Note that this expression holds for $\lambda = 0$, as then $\beta_{11} = \beta_{01} > 1$ and $X_1 = (1-\theta)X_0 < X_0$. Therefore, $\frac{\partial f}{\partial\lambda} < 0$ at $\lambda = 0$. For $\lambda > 0$ (hence $\beta_{11} > \beta_{01}$), we can rewrite the condition to

$$\left(\frac{X_1}{X_0}\right)^{\beta_{01}-1} < \frac{\beta_{11}-1}{\beta_{11}-\beta_{01}}. \tag{B.23}$$

This condition always holds for positive λ as then, both $\left(\frac{X_1}{X_0}\right)^{\beta_{01}-1} < 1$, while $\frac{\beta_{11}-1}{\beta_{11}-\beta_{01}} > 1$. To see $\left(\frac{X_1}{X_0}\right)^{\beta_{01}-1} < 1$, note that at $\lambda = 0$, we have $X_1 < X_0$ and $\frac{df}{d\lambda} < 0$. Therefore, at some small positive λ, we see that X_1 is lower, hence $X_1 < X_0$ still holds and condition (B.23) holds, leading to $\frac{df}{d\lambda} < 0$ at that positive value of λ.

B.4. Proof of Corollary 2

Similarly to the proof of Corollary 1 (Appendix B.3), the derivative of the optimal investment threshold with respect to subsidy size, θ, can be written as

$$\frac{\partial X}{\partial\theta} = -\frac{(\frac{\partial f}{\partial\theta})}{(\frac{\partial f}{\partial X})}. \tag{B.24}$$

We directly derive $\frac{\partial f}{\partial\theta}$ by differentiation of the implicit Eq. (B.16):

$$\frac{\partial f}{\partial\theta} = \kappa. \tag{B.25}$$

Therefore,

$$\frac{\partial X}{\partial\theta} = -\frac{\kappa}{(\frac{\partial f}{\partial X})}, \tag{B.26}$$

and

$$\frac{\partial X}{\partial\theta} < 0 \iff \frac{\partial f}{\partial X} > 0. \tag{B.27}$$

Proving $\frac{\partial f}{\partial X} > 0$ for any θ can be done in the same way as proving $\frac{\partial f}{\partial X} > 0$ for any λ; see the second half of the proof of Corollary 1 in Appendix B.3.

B.5. Proof of Proposition 3

Repeating the steps in the proof of Proposition 1 (Appendix B.1), it follows that the value of the social planner's option satisfies the following ODE:

$$\frac{1}{2}\sigma^2X^2\cdot\frac{d^2V_S(X,K)}{dX^2} + \mu X\cdot\frac{dV_S(X,K)}{dX} - rV_S(X,K) = 0 \tag{B.28}$$

The marginal added surplus of the option with respect to capacity is given by

$$\frac{dV_S(X,K)}{dK} = \frac{dA_S(K)}{dK}\cdot X^{\beta_{01}} + \frac{X(1-\eta K)}{r-\mu}, \tag{B.29}$$

in which V_S is the value of the social planner's option, and $A_S(K)$ is some positive function.

We apply the value matching and smooth pasting conditions to the objective (B.29) to derive the optimal social investment threshold. The value matching and smooth pasting conditions for the optimal social investment threshold (denoted by X_S^i) are given by

$$\frac{dA_S(K_i)}{dK}\cdot(X_S^i)^{\beta_{01}} + \frac{X_S^i(1-\eta K_i)}{r-\mu} = \kappa, \tag{B.30}$$

$$\beta_{01}\cdot\frac{dA_S(K_i)}{dK}\cdot(X_S^i)^{\beta_{01}-1} + \frac{1-\eta K_i}{r-\mu} = 0. \tag{B.31}$$

We find that the optimal investment threshold without a subsidy is given by

$$X_S^i(K_i) = \frac{\beta_{01}}{\beta_{01}-1}\cdot\frac{(r-\mu)\kappa}{1-\eta K_i}. \tag{B.32}$$

The expression, $A_S(K)$, has to satisfy the following:

$$\frac{dA_S(K_i)}{dK} = -\left(\frac{\beta_{01}-1}{\kappa}\right)^{\beta_{01}-1}\cdot\left(\frac{1-\eta K_i}{\beta_{01}(r-\mu)}\right)^{\beta_{01}}. \tag{B.33}$$

As before, we integrate to obtain

$$A_S(K_i) = \left(\frac{\beta_{01}-1}{\kappa}\right)^{\beta_{01}-1}\cdot\frac{1-\eta K_i}{\eta(\beta_{01}+1)}\cdot\left(\frac{1-\eta K_i}{\beta_{01}(r-\mu)}\right)^{\beta_{01}} \tag{B.34}$$

Table C.2
The percentage of simulations in which no investment occurred after (before) a subsidy withdrawal.

	$\theta = 0.2$	$\theta = 0.3$	$\theta = 0.4$
$\lambda = 0.05$	14.81 (44.72)	18.73 (20.77)	25.01 (0.28)
$\lambda = 0.1$	10.91 (53.97)	14.38 (15.42)	20.13 (0.50)
$\lambda = 0.2$	9.65 (60.19)	12.85 (2.26)	18.33 (0.82)

$$= \frac{\kappa(1-\eta K_i)}{\eta(\beta_{01}-1)(\beta_{01}+1)} \cdot \left(\frac{(\beta_{01}-1)(1-\eta K_i)}{\beta_{01}\kappa(r-\mu)}\right)^{\beta_{01}}. \tag{B.35}$$

B.6. Proof of Proposition 4

Solving the monopolist's optimal investment threshold for a given subsidy of size θ and any level of withdrawal risk follows from the implicit Eq. (11). Substituting the social planner's optimal investment threshold for maximizing total surplus, defined in (13), into (11) and solving for θ yields

$$\theta^*_\lambda(K) = 1 - \frac{1}{\kappa} \cdot \left(\frac{\beta_{11}-\beta_{01}}{\beta_{11}} \cdot \frac{dA_{01}(K)}{dK} \cdot X_S^{\beta_{01}} + \frac{\beta_{11}-1}{\beta_{11}} \cdot \frac{X_S(1-2\eta K)}{r-\mu}\right). \tag{B.36}$$

Plugging in the optimal social investment threshold, X_S, yields

$$\theta^*_\lambda(K) = 1 - \frac{1}{\beta_{11}(\beta_{01}-1)} \cdot \left[\beta_{01}(\beta_{11}-1) \cdot \frac{1-2\eta K}{1-\eta K} - (\beta_{11}-\beta_{01}) \cdot \left(\frac{1-2\eta K}{1-\eta K}\right)^{\beta_{01}}\right]. \tag{B.37}$$

B.7. Proof of Corollary 3

Taking the derivative with respect to K of the optimal subsidy size, $\theta^*(K)$, defined in (14) yields

$$\frac{d\theta^*}{dK} = \frac{\beta_{01}}{\beta_{11}} \cdot \frac{\beta_{11}-1}{\beta_{01}-1} \cdot \frac{\eta}{(1-\eta K)^2} \cdot \left[1 - \frac{\beta_{11}-\beta_{01}}{\beta_{11}-1} \cdot \left(\frac{1-2\eta K}{1-\eta K}\right)^{\beta_{01}-1}\right]. \tag{B.38}$$

As $\beta_{11} > \beta_{01} > 1$ and $\left(\frac{1-2\eta K}{1-\eta K}\right)^{\beta_{01}-1} \in (0,1]$, we have that $\frac{d\theta^*}{dK} > 0$.

B.8. Proof of Corollary 4

Taking the derivative with respect to λ of the optimal subsidy size, $\theta^*(K)$, defined in (14) yields

$$\frac{d\theta^*}{d\lambda} = \frac{d\beta_{11}}{d\lambda} \cdot \frac{\beta_{01}}{\beta_{01}-1} \cdot \frac{1}{\beta_{11}^2} \cdot \frac{1-2\eta K}{1-\eta K} \cdot \left[\left(\frac{1-2\eta K}{1-\eta K}\right)^{\beta_{01}-1} - 1\right]. \tag{B.39}$$

As $\frac{d\beta_{11}}{d\lambda} = \frac{1}{\sigma(\beta_{11}-1)+\mu} > 0$ and $\left(\frac{1-2\eta K}{1-\eta K}\right)^{\beta_{01}-1} \in (0,1]$, we have that $\frac{d\theta^*}{d\lambda} \leq 0$.

Appendix C. Statistics on capacity growth after subsidy withdrawal

In Fig. 8, we show the histograms of the number of years it takes the monopolist to increase their capacity for the first time after the subsidy has been withdrawn.

Table C.2 shows both the percentage of simulations that yield no investment after a subsidy withdrawal and the percentage of simulations in which no investment occurs during the subsidy's lifetime. We simulate a total period of 100 years. When the subsidy is small, i.e., $\theta = 0.2$, less than 15% of the simulations always result in no investment after a subsidy retraction. However, when the subsidy is large, i.e., $\theta = 0.4$, approximately 18% to 25% of the simulations yield no investment after a subsidy withdrawal.

We observe that the larger the subsidy, the more likely that investment occurs during the subsidy's lifetime. However, the likelihood of no investment after subsidy withdrawal also increases with subsidy size. The likelihood of no investment after a subsidy withdrawal also increases with subsidy withdrawal risk.

The effect of the likelihood of a subsidy withdrawal has a non-monotonic effect on investment during a subsidy's lifetime due to two opposing effects. First, the firm's incentive to invest now increases when the likelihood of a subsidy withdrawal is larger. However, the time during which the firm can invest under a subsidy has also become shorter. When the subsidy is small, the likelihood of no investment during the subsidy's lifetime increases with the subsidy withdrawal rate, λ. The reward for the firm from investing during the subsidy's lifetime is small and the second effect dominates the first. The likelihood of no investment during the subsidy's lifetime decreases with subsidy withdrawal risk when the subsidy is large. The first effect dominates the second, as the reward for the firm from investing during the subsidy's lifetime is large.

Appendix D. Welfare optimal flexible study

The optimal subsidy size when the subsidy size is flexible is given by Proposition 4. In this appendix, we provide a numerical example and show that our results for the subsidy size are consistent with Corollaries 3 and 4. Furthermore, we break down the total surplus from the simulations of the welfare optimal flexible subsidy.

D.1. Welfare optimal flexible study size

The optimal subsidy size that maximizes total surplus as a function of the firm's capacity, K, θ^*_λ, for different levels of subsidy withdrawal risk, λ, is plotted in Fig. 9.

We observe that the optimal subsidy size increases in the monopolist's capacity, which is consistent with Corollary 3. The gap between the monopolist's and social planner's optimal investment thresholds is larger when the current capacity is large. On the one hand, the monopolist has less incentive to increase their capacity when the current capacity is already large, due to one additional unit of capacity yielding a low marginal revenue. On the other hand, a social planner's optimal threshold is somewhat invariant to the current capacity level (see X_S in Fig. 1). A larger subsidy is required to close this gap.

The optimal subsidy size decreases with subsidy withdrawal risk, in line with Corollary 4. The gap between the social planner's optimal threshold and the monopolist's decreases when the likelihood of subsidy withdrawal increases. The monopolist increases their capacity sooner under the pressure of losing the subsidy in the future. Despite the fact that the policy maker's and monopolist's thresholds are better aligned under a larger subsidy withdrawal, this does not per se mean the policy maker's long-term targets are reached faster. Due to the larger subsidy withdrawal risk, the subsidy is also very likely to be withdrawn sooner, meaning that the encouraging effect of the subsidy are also in effect for a shorter period of time.

D.2. Statistics on consumer and producer surpluses

This Appendix breaks down the total surplus from welfare optimal flexible subsidies using simulations, identical to the simulations outlined in Section 3.1.

In Fig. 10, the total surplus under the decisions by the monopolist without a subsidy is shown on the left, while the total surplus under the optimal flexible subsidy is shown on the right. The total surplus is broken down into producer and consumer surpluses in both figures. Under the welfare optimal flexible subsidy, the consumer surplus is larger than under the firm's decisions, while the producer surplus is approximately zero. When the monopolist makes the decision, they maximize producer surplus, and the consumer surplus is much smaller

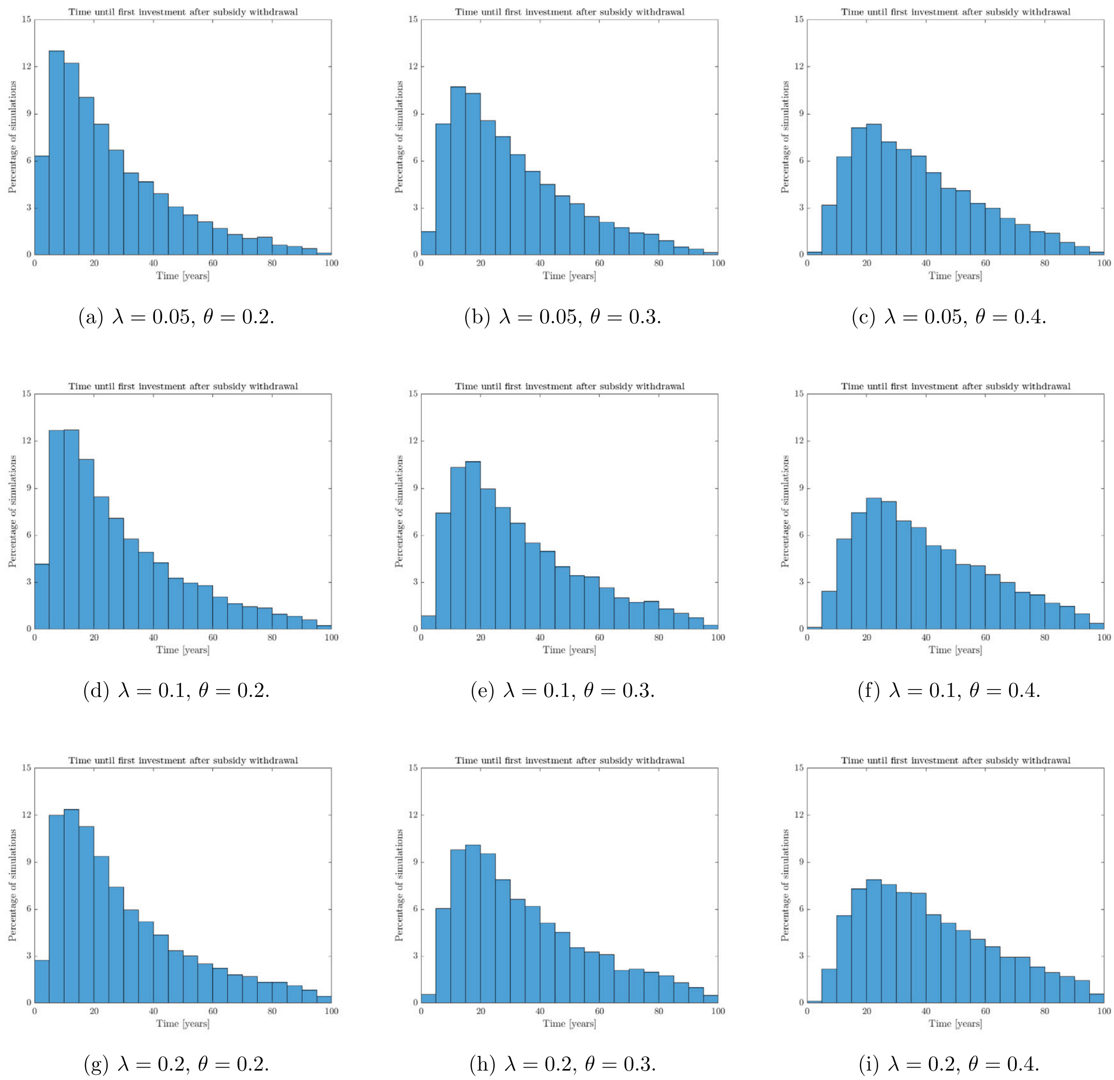


Fig. 8. Histograms of the time until the first investment after a subsidy withdrawal for different levels of subsidy termination risk, λ, and subsidy size, θ. [General parameter values: $\mu = 0.02$, $\sigma = 0.10$, $r = 0.05$, $\eta = 0.005$, $\kappa = 300$, $dK = 1$, $x = 10$.].

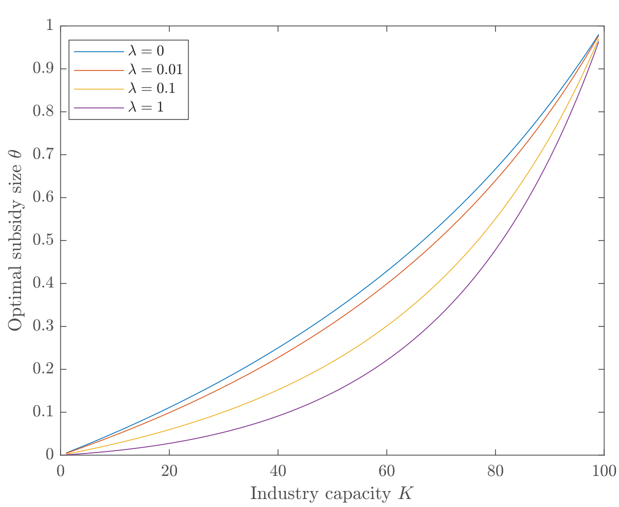


Fig. 9. Optimal subsidy size, θ, as a function of the firm's total capacity for different subsidy retraction risk, λ. [General parameter values: $\mu = 0.02$, $\sigma = 0.10$, $r = 0.05$, $\eta = 0.005$, $\kappa = 300$, $dK = 1$, $x = 10$].

than the producer surplus; the firm increases capacity at a lower rate than the social planner to keep output prices higher than desirable from an optimal social viewpoint.

The consumer and producer surplus under the decisions by the monopolist for an optimal subsidy is shown in Fig. 11(b), and the gain in total surplus compared to the no-subsidy case is shown in Fig. 11(a), both for a subsidy withdrawal risk $\lambda = 0.2$. In most of the simulations, the total surplus increases due to a subsidy. The firm invests sooner under a subsidy, hence the consumer surplus increases compared to the case of no-subsidy. The subsidy also increases the producer surplus; however, the increase in producer surplus is mainly financed from the subsidy, hence the social planner's subsidy payouts increase at approximately the same rate. As the firm invests sooner under a subsidy, the consumer surplus increases compared to the no-subsidy scenario.

However, note too that the subsidy is not successful in increasing the total surplus in all simulations. In some of the simulations, the total surplus decreases due to the subsidy while in many no changes to the total surplus occur. As the subsidy causes the firm to increase capacity sooner, there are cases in which the prices decline quickly after the firm has increased capacity. This may lead to significant losses to the already-installed units of capacity, leading to a negative producer surplus. It also keeps out new investors, causing the monopolist's capacity to be low, hence the consumer surplus is also low.

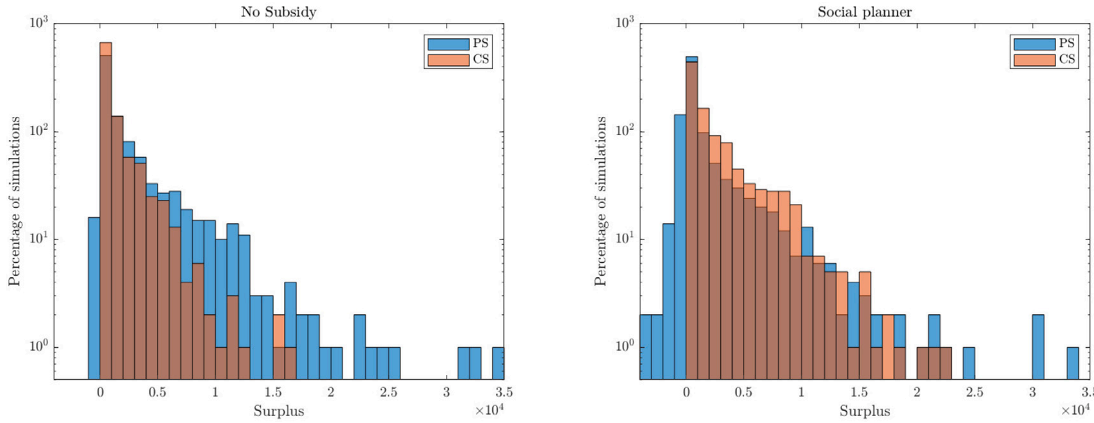


Fig. 10. Distribution of producer and consumer surpluses in the simulations when investment decisions are made by the monopolist without a subsidy (left) and by the social planner (right). [General parameter values: $\mu = 0.01$, $\sigma = 0.05$, $r = 0.03$, $\eta = 0.01$, $\kappa = 300$, $dK = 1$, $x = 10$.].

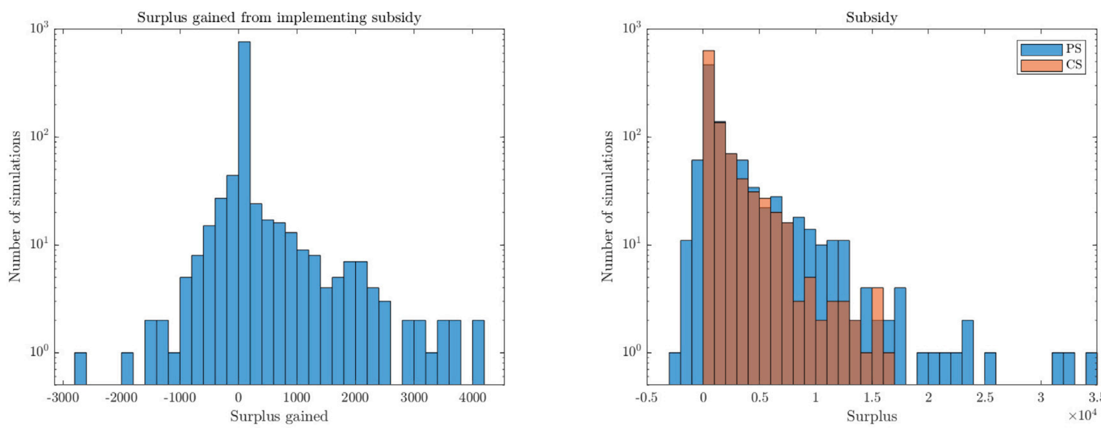
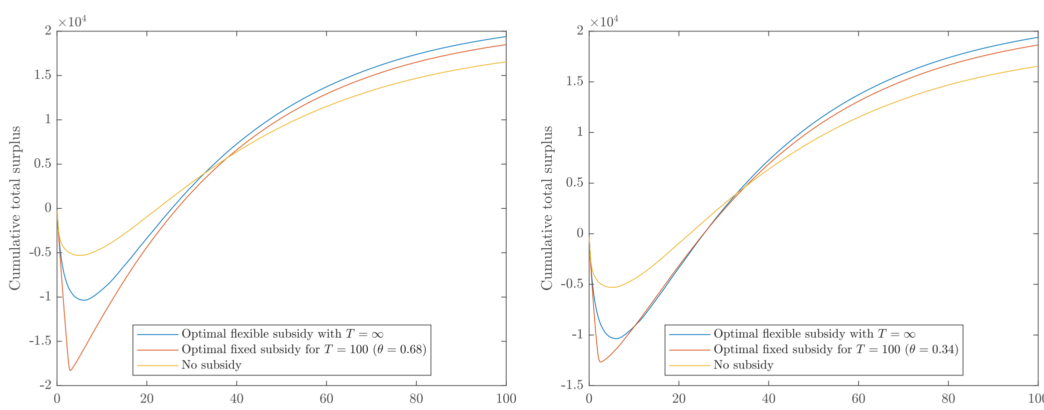


Fig. 11. The gain in total surplus compared to the case when the monopolist not subsidized (left) and the producer and consumer surplus in the simulations by a subsidized monopolist (right), with $\lambda = 0.2$ and $\theta = \theta^*_\lambda$. [General parameter values: $\mu = 0.02$, $\sigma = 0.10$, $r = 0.05$, $\eta = 0.01$, $\kappa = 300$, $dK = 1$, $x = 10$.].



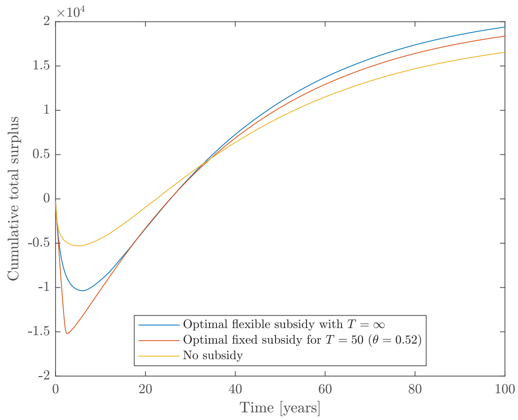
(a) $\lambda = 0$.   (b) $\lambda = 0.2$.

Fig. 12. Cumulative total surplus over time for different levels of subsidy termination risk, λ, with a social planner maximizing total surplus at $T = 100$. [General parameter values: $\mu = 0.02$, $\sigma = 0.10$, $r = 0.05$, $\eta = 0.005$, $\kappa = 300$, $dK = 1$, $x = 20$.].

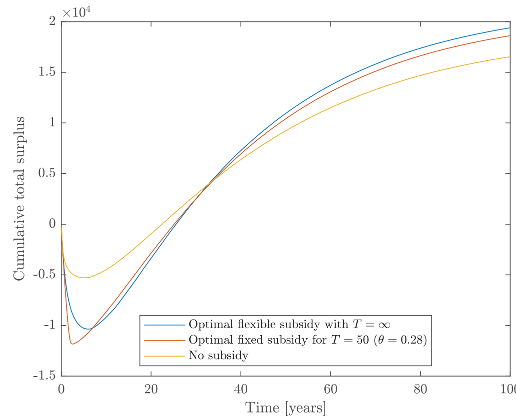
Appendix E. Sensitivity analysis for total surplus and initial demand shock x

In this Appendix, we assume $x = 20$ instead of $x = 10$, and examine the total surplus over time in figures, similar to Figs. 6 and 7. The total surplus in all the scenarios has increased due to the higher prices. The trajectories of the no-subsidy and the optimal flexible subsidy cases are approximately identical to their counterparts in Figs. 6 and 7. In this Appendix, we mainly focus on the effects for the optimal fixed subsidy.

In Fig. 12, we plot the cumulative total surplus over time in three different scenarios - no subsidy, optimal fixed subsidy maximizing surplus at $T = 100$, and the optimal flexible subsidy. The optimal fixed subsidy is significantly larger compared to their counterparts in



(a) $\lambda = 0$.



(b) $\lambda = 0.2$.

Fig. 13. Cumulative total surplus over time for different levels of subsidy termination risk, λ, with a social planner maximizing total surplus at $T = 50$. [General parameter values: $\mu = 0.02$, $\sigma = 0.10$, $r = 0.05$, $\eta = 0.005$, $\kappa = 300$, $dK = 1$, $x = 20$.].

Figs. 6 and 7 due to a higher initial demand intercept, x. The optimal subsidy increases as the value of investment from a social perspective (i.e., the consumer surplus) increases significantly with the higher prices. Considering the role of the time horizon, T, we still see that the optimal subsidy decreases the more myopic a policy maker is. The argument remains the same: A more myopic social planner does not care about the surplus accounted for over a very long time period, but is more affected by the high investment costs incurred early.

The main difference is the role of the subsidy withdrawal, λ, for the social planner with time horizon $T = 50$ in Fig. 13 compared to Fig. 7. In Fig. 13, the optimal subsidy when $\lambda = 0.2$ is smaller than when $\lambda = 0$, while with the lower output price in Fig. 7, it is the other way around. In both cases, the increase in subsidy withdrawal risk leads to a small decrease in total surplus after both 50 and 100 years.

Appendix F. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.enpol.2022.113309.

References

Azevedo, A., Pereira, P.J., Rodrigues, A., 2021. Optimal timing and capacity choice with taxes and subsidies under uncertainty. Omega 102, 102312.

Bar-Ilan, A., Strange, W.C., 1999. The timing and intensity of investment. J. Macroecon. 21 (1), 57–77.

Barbosa, D., Carvalho, V.M., Pereira, P.J., 2016. Public stimulus for private investment: An extended real options model. Econ. Model. 52, 742–748.

Boomsma, T.K., Linnerud, K., 2015. Market and policy risk under different renewable electricity support schemes. European J. Oper. Res. 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.

Bunn, D.W., Muñoz, J.I., 2016. Supporting the externality of intermittency in policies for renewable energy. Energy Policy 88, 594–602.

Bush, G.W., 2003. State of the Union Address. https://georgewbush-whitehouse.archives.gov/news/releases/2003/02/20030206-2.html (Online; Accessed 04 May 2022).

Center for American Progress, 2020. The trump administration is stifling renewable energy on public lands and waters.

Chronopoulos, M., Hagspiel, V., Fleten, S.-E., 2016. Stepwise green investment under policy uncertainty. Energy J. 37 (4), 87–108.

CORDIS Europa, 2004. Hydrogen is the way forward, says Prodi. https://cordis.europa.eu/article/id/21474-hydrogen-is-the-way-forward-says-prodi (Online; Accessed 04 May 2022).

Danielova, A., Sarkar, S., 2011. The effect of leverage on the tax-cut versus investment-subsidy argument. Rev. Financial Econ. 20 (4), 123–129.

Dixit, A.K., Pindyck, R.S., 1994. Investment under Uncertainty. Princeton University Press.

European Commission, 2020. A hydrogen strategy for a climate-neutral Europe. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0301 (Online; Accessed 04 May 2022).

Feil, J.-H., Musshoff, O., Balmann, A., 2013. Policy impact analysis in competitive agricultural markets: a real options approach. Eur. Rev. Agricu. Econ. 40 (4), 633–658.

Fernandes, B., Cunha, J., Ferreira, P., 2011. The use of real options approach in energy sector investments. Renew. Sustain. Energy Rev. 15 (9), 4491–4497.

Forbes, 2020. As trump dismisses renewables, energy sector doubles down.

Gan, L., Eskeland, G.S., Kolshus, H.H., 2007. Green electricity market development: Lessons from Europe and the US. Energy Policy 35 (1), 144–155.

Ganhammar, K., 2021. The effect of regulatory uncertainty in green certificate markets: Evidence from the Swedish-Norwegian market. Energy Policy 158, 112583.

García-Álvarez, M.T., Cabeza-García, L., Soares, I., 2018. Assessment of energy policies to promote photovoltaic generation in the European union. Energy 151, 864–874.

Gerlagh, R., Kverndokk, S., Rosendahl, K.E., 2009. Optimal timing of climate change policy: Interaction between carbon taxes and innovation externalities. Environ. Res. Econ. 43 (3), 369–390.

Gryglewicz, S., Hartman-Glaser, B., 2020. Investment timing and incentive costs. Rev. Financ. Stud. 33 (1), 309–357.

Hassett, K.A., Metcalf, G.E., 1999. Investment with uncertain tax policy: Does random tax policy discourage investment. Econ. J. 109 (457), 372–393.

He, H., Pindyck, R.S., 1992. Investments in flexible production capacity. J. Econom. Dynam. Control 16, 575–599.

Hu, J., Chen, H., Zhou, P., Guo, P., 2022. Optimal subsidy level for waste-to-energy investment considering flexibility and uncertainty. Energy Econ. 108, 105894.

Huisman, K.J., Kort, P.M., 2015. Strategic capacity investment under uncertainty. Rand J. Econ. 46 (2), 376–408.

IRENA, IEA, REN21, 2018. Renewable Energy Policies in a Time of Transition. IRENA, OECD/IEA and REN21.

Karthikeyan, S.P., Raglend, I.J., Kothari, D., 2013. A review on market power in deregulated electricity market. Electr. Power Energy Syst. 48, 139–147.

Keen, S., 2020. The appallingly bad neoclassical economics of climate change. Globalizations 1–29.

Kozlova, M., 2017. Real option valuation in renewable energy literature: Research focus, trends and design. Renew. Sustain. Energy Rev. 80, 180–196.

Kydland, F.E., Prescott, E.C., 1977. Rules rather than discretion: The inconsistency of optimal plans. J. Polit. Econ. 85 (3), 473–492.

Liski, M., Vehviläinen, I., 2020. Gone with the wind? An empirical analysis of the equilibrium impact of renewable energy. J. Assoc. Environ. Res. Econ. 7 (5), 873–900.

Muñoz, J.I., Bunn, D.W., 2013. Investment risk and return under renewable decarbonization of a power market. Clim. Policy 13 (sup01), 87–105.

Musshoff, O., Hirschauer, N., 2008. Adoption of organic farming in Germany and Austria: an integrative dynamic investment perspective. Agric. Econ. 39 (1), 135–145.

Nagy, R.L.G., Hagspiel, V., Kort, P.M., 2021. Green capacity investment under subsidy withdrawal risk. Energy Econ. 98.

Nordhaus, W.D., 2007. A Review of the Stern Review on the Economics of Climate Change. J. Econ. Lit. 45 (3), 686–702. http://dx.doi.org/10.1257/jel.45.3.686.

Panteghini, P.M., 2005. Asymmetric taxation under incremental and sequential investment. J. Public Econ. Theory 7 (5), 761–779.

Pennings, E., 2000. Taxes and stimuli of investment under uncertainty. Eur. Econ. Rev. 44, 383–391.

Pindyck, R.S., 1988. Irreversible investment, capacity choice, and the value of the firm. Amer. Econ. Rev. 78, 969–985.

REN21, 2022. Renewables 2022 global status report.

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.

Rocha Armada, M.J., Pereira, P.J., Rodrigues, A., 2012. Optimal subsidies and guarantees in public–private partnerships. Eur. J. Finance 18 (5), 469–495.

Rossi, M., Festa, G., Gunardi, A., 2019. The Evolution of Public-Private Partnerships in a Comparison between Europe and Italy: Some Perspectives for the Energy Sector. Int. J. Energy Econ. Policy 9 (3), 403–413.

Sarkar, S., 2012. Attracting private investment: Tax reduction, investment subsidy, or both? Econ. Model. 29 (5), 1780–1785.

Stern, N., 2006. Stern Review: The Economics of Climate Change. Cambridge University Press.

Stern, N., 2018. Public economics as if time matters: Climate change and the dynamics of policy. J. Public Econ. 162, 4–17.

Stern, N., Stiglitz, J.E., Taylor, C., 2022. The economics of immense risk, urgent action and radical change: towards new approaches to the economics of climate change. J. Econ. Methodol..

Stokes, L.C., 2015. Power Politics: Renewable Energy Policy Change in US States (Ph.D. thesis). Massachusetts Institute of Technology.

Stokes, L.C., Warshaw, C., 2017. Renewable energy policy design and framing influence public support in the United States. Nat. Energy 2.

The Economist, 2012. Agricultural subsidies.

The Economist, 2013. Blown away.

The Economist, 2018. Donald trump hopes to save america's failing coal-fired power plants.

The Economist, 2019. Some farmers are especially good at milking European taxpayers.

The Economist, 2020. British farmers fret about losing their protection and their subsidies.

The New York Times, 2019. We fact-checked president trump's Dubious claims on the Perils of wind power.

Tsiodra, M., Chronopoulos, M., 2021. A bi-level model for optimal capacity investment and subsidy design under risk aversion and uncertainty. J. Oper. Res. Soc. 1–13.

Van Benthem, A., Kramer, G., Ramer, R., 2006. An options approach to investment in a hydrogen infrastructure. Energy Policy 34 (17), 2949–2963.

Yu, C.-F., Chang, T.-C., Fan, C.-P., 2007. FDI timing: Entry cost subsidy versus tax rate reduction. Econ. Model. 24 (2), 262–271.