Green Technology Investment: Announced vs. Unannounced Subsidy Retraction*

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Abstract

Policy uncertainty affects firms' investment decisions and the corresponding societal welfare (total surplus). One common perception is that policy uncertainty has negative welfare effects, and therefore, the regulator should be "transparent" by announcing future policy changes. We show that this is not always true. This paper investigates a firm's green technology investment decision in a dynamic setting, where it decides about the investment timing and size in the presence of technological uncertainty. Initially the regulator incentivizes the investment by subsidizing. As the cost of the green technology is expected to fall over time, at some point the subsidy is retracted. We consider two scenarios, one where the regulator announces the subsidy retraction in advance, and one where it does not do so. The subsidy retraction announcement can motivate the firm to invest too early from a welfare perspective because it wants to *catch* the subsidy. This rent-seeking behavior implies that the regulator should not always announce the subsidy retraction. We further show that a larger uncertainty about technological development encourages not to announce the subsidy retraction.

Keywords: Real options analysis; Dynamic programming; Technological development; Subsidy retraction

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1 Introduction

The share of renewable energy has increased greatly in recent years. To realize the Net Zero by 2050, the annual energy investment is expected to expand from the current USD 2 trillion to 5 trillion by 2030, and to 4.5 trillion by 2050 (Bouckaert et al., 2021). Due to the capital-intensive nature of renewable energy, various support schemes such as the feed-in policies, reimbursed investment cost subsidies, and grants, have been adopted to support high risk and early stage project developments, and to improve its competitiveness against traditional energy sources. At the same time, the steady advances in technologies, economies of scale, more efficient supply chains, and improved manufacturing capacities, have caused the renewable power generation costs to fall sharply over the years, which leads to decreasing investment costs. For instance, according to Philibert (2011), the industry of PV panels has shown a learning rate of about 19.3%, meaning that each doubling of the cumulative installed capacity has led to about 19.3% cost reduction on average over the years between 1976 and 2010. Since then, the solar power costs have continued to decrease at a rate about 15% per year.[1]

As argued by Stern (2022), "an emerging technology will be supported initially but as it moves out, or diffuses, into the productive world, or as the cost of the new technology falls, its supporting subsidy will be reduced". For example, in 2020 Norway and Sweden sealed the end of their joint green power support scheme, which effectively closed down the system at the end of 2035, 10 years earlier than originally planned[2][3]. This market based system introduced in 2012 offered energy producers a premium for the power sold to the market in the form of electricity certificates[4], targeting investments in wind turbines, hydro energy and other renewable solutions. The Norwegian energy minister Tina Bru at this time argued that "technological ... advancements had resulted in a faster and bigger build out of renewable electricity than the electricity certificates system was designed to support."

Another example is that, in 2015 China's National Development and Reform Commission announced that it would begin lowering subsidy rates. As the cost of solar PV technologies continued to decline faster than expected, even these lower subsidies still generated windfall profits for investors. Therefore, the government decided to "align subsidies with falling technology costs in a series of steps".[5] For instance, in 2018, the government announced sudden subsidy drops for solar farms and the distributed solar. Due to the subsidy cuts in three regulatory zones, which were created by the government according to their suitability for solar generations, the subsidy levels for

[1]https://cleantechnica.com/2022/06/08/just-the-facts-the-cost-of-solar-has-fallen-more-quickly-than-experts-predicted/.

[2]The system closed to new participants by the end of 2021.

[3]https://www.reuters.com/article/idUSKBN26922A/

[4]Producers of wind and hydropower received one certificate per megawatt-hour (MWh) of renewable power generated over a 15-year period. Producers could sell these certificates on the market to consumers, who were required to buy them to cover a share of their consumption.

[5]https://ucigcc.org/blog/how-solar-developed-from-the-bottom-up-in-china/

solar farms dropped from 0.90 to 0.50 CNY, from 0.95 to 0.60 CNY, and from 1.00 to 0.70 CNY per kilowatt hour, respectively. In addition, the distributed solar subsidy dropped from 0.42 to 0.32 per kilowatt hour.[6]

Over the last two decades renewable subsidy revisions have occurred frequently but have not always been anticipated upon by investors. This generated policy uncertainty for the renewable investment. An emblematic case is Spain's renewable subsidy withdrawal in 2013. As a result, "thousands of investors in renewable energy were severely damaged and hundreds of companies went bankrupt." [7]

From the regulator's perspective, the response of business to policy uncertainties is important for the effectiveness of energy policies, and therefore, policy changes should be conducted in a careful way. For instance, as suggested by Stern (2022), " policy revisions, as lessons are learned, ..., must be carried through in ways that people understand, and which can be anticipated". At the same time, Schubert and Smulders (2019) point out that uncertainty plays a major role in environmental policy. "Uncertainty not only surrounds cost and benefits per se; also the timing of costs and benefits might be uncertain". This paper investigates how important it is to announce a policy retraction from a welfare perspective in a dynamic and uncertain environment. Surprisingly enough we find that announcing a policy retraction is not always welfare improving.

In particular, we consider a model where a firm has the option to invest in a green technology. It has to decide about the timing and the size of the investment. Initially a subsidy is available. Development of the green technology is uncertain over time. But due to technological progress it is expected that investments in these technologies would become cheaper. For this reason they eventually become commercially competitive, implying that at some point in time the subsidy will be retracted. From the regulator's perspective the question is whether such a retraction should be announced or not. In the latter case the firm is exposed to policy uncertainty. We analyze and compare both cases.

The main results of our analysis are the following. First, we show that policy uncertainty in the form of unannounced subsidy retraction can generate a larger total surplus than the announced retraction because of firm's rent-seeking behavior in the latter scenario. In particular, we find that it is optimal for the firm to acquire the new technology just before the subsidy is retracted. The implication is that the firm invests too soon in a too small capacity from a welfare perspective. Second, if the technological development is more uncertain it is better for the regulator not to announce the subsidy retraction for a larger interval of subsidy rates. Third, regarding the investment strategy, a larger threat of subsidy retraction incentivizes the firm to invest earlier and in a smaller capacity. Fourth, comparing the effect of different types of subsidies on the firm's investment, we find that a feed-in-premium (FIP) subsidy positively influences the size of investment at the expense of a delay, while a reimbursed investment cost subsidy incentivizes the firm to invest early while

[6] https://www.climatechangenews.com/2018/08/15/china-solar-industry-struggles-sudden-subsidy-cuts/

[7] https://microsegur.com/en/spain-lost-four-international-arbitrations-over-cutting-renewable-energy-subsidies/.

the size is unaffected.

Due to the importance of the topic of how renewable investments are affected by policy uncertainty, a growing literature has emerged in the last two decades. Policy uncertainty has been studied regarding tax credit policy and taxation policy (Hassett and Metcalf, 1999; Eryilmaz and Homans, 2016), regime change in climate policy (Fuss et al., 2008; Blyth et al., 2007; Yang et al., 2008), and subsidy policy (Ritzenhofen and Spinler, 2016; Chronopoulos et al., 2016; Barbosa et al., 2018; Hagspiel et al., 2021; Sendstad et al., 2022). A general result is that firms delay investment to wait for favorable policy adjustment, and advance investment to avoid unfavorable policy adjustment. To the best of our knowledge, studies analyzing the effect of subsidy revisions on investment behavior have so far only focused on the effect of price or demand risk in combination with uncertain policy changes. The current work highlights the link between subsidy policy and technology diffusion, while taking into account the uncertainty in technology development. In addition, we explicitly take into account that when the technology is sufficiently developed, subsidy is no longer needed so that the regulator may consider to retract the subsidy. Another extension to the above mentioned research contributions is that we explicitly consider welfare implications.

Thus, another strand of literature that this work is related to is welfare implications of renewable investment. Barbosa et al. (2022) and Bigerna et al. (2023) consider policy design with the aim to maximize welfare. For instance, Barbosa et al. (2022) find that the firm invests later than what is socially optimal and identify the optimal subsidy levels that eliminate the inefficiency caused by late investment. Compared to Barbosa et al. (2022), Bigerna et al. (2023) considers not only the investment timing but also the capacity choice. However, neither of these two contributions take into account policy uncertainty. From this perspective, Nagy et al. (2021) is more closely related in the sense that they investigate the effects of subsidy retraction on the firm's investment decision. The difference to Nagy et al. (2021) is that we focus on the uncertainty in technological development and whether a subsidy retraction should be announced or not.

To the best of our knowledge rent-seeking has not been considered in this research area up until now. Because rent-seeking behavior generates welfare inefficiency, contributions in other research areas focus on reducing such inefficiency. Misiolek (1988), for instance, considers rent-seeking costs on the design of an efficient pollution tax and argues that the appropriate discharge tax for a monopoly firm can equal or exceed the marginal damage from its pollution. Damania (1999) compares the policy instrument of emission taxes with emission standards and finds that, firms respond to more stringent emission standards by lowering their output levels rather than raising the degree of pollution abatement because it leads to higher profits. Smulders et al. (2012) investigate the "green-paradox" that arises due to the early announcement of a carbon tax, which induces an increase in using fossil energy until the implementation date. Rittenhouse and Zaragoza-Watkins (2018) take into account the policy adjustment margin in the context of implementing new vehicle emission standard and argue that the new policy anticipation causes a sales spike just before the policy takes effect and a symmetric sales slump after implementation. None of the above mentioned papers consider uncertainty in a dynamic setting.

The structure of this paper is as follows. Section 2 develops and analyzes the model, where we focus on the reimbursed investment cost subsidy. In Section 3 we perform a welfare analysis, analyzing the total surplus in the announced and unannounced subsidy retraction scenario. Section 4 considers the feed-in-premium subsidy, and Section 5 concludes. The proofs for all propositions and corollaries can be found in the Appendix.

2 Model

We consider a risk-neutral profit maximizing monopoly firm that has the option to invest in renewable energy sources (RES). Investment costs depend on the maturity of technology development. Technological development is exposed to uncertainty, which introduces cost uncertainty to the firm's investment opportunity. We denote the firm's unit investment cost by δ_t , and assume that δ_t follows a geometric Brownian motion (GBM) process,

$$\mathrm{d}\delta_t = \mu\delta_t\mathrm{d}t + \sigma\delta_t\mathrm{d}\omega_t, \tag{1}$$

where $\mathrm{d}\omega_t$ is the increment of a Wiener process and $\sigma > 0$ is the volatility parameter. Given that technology advances over time investments become more affordable in the long term. Therefore, we assume that the trend parameter is negative, i.e., $\mu < 0$. Besides, investment costs in these technologies depend also on other factors such as raw material costs, especially on minerals and metals.[8] The development of raw material costs is typically uncertain. The second term on the right hand side of (1) models these unpredictable events.

Following the empirical evidence that the price elasticity for electricity is constant or lies in a narrow range (Lijesen, 2007; Csereklyei, 2020), we adopt the iso-elastic demand structure. The firm invests to acquire a production capacity of size K. Imposing that the firm produces up to capacity[9], the output price then equals $K^{-\gamma}$ with $\gamma \in (0, 1)$, where $-1/\gamma$ is the demand elasticity. Furthermore, the unit production cost is denoted by c. The regulator initially provides a subsidy support that covers a certain share $s \in (0, 1)$ of the firm's total investment costs, i.e., a lumpy transfer of $s\delta K$ upon the firm's investment. In Norway, for example, the state agency Enova launched in 2023 a new maritime hydrogen hub competition, with the purpose to narrow the gap between the prices of fossil fuels and the prices of hydrogen and ammonia for maritime purposes.[10]

[8]https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions/mineral-requirements-for-clean-energy-transitions

[9]Because of the influence from weather conditions, the renewable energy generation is intermittent, i.e., the production is only partly predictable and highly variable at short and medium time scales. However, it is more predictable and less variable on the long run, e.g, on yearly time scales. Given that long term investment decisions are investigated in our setup, we follow the same approach as in the literature (see e.g., Boomsma et al. (2012); Boomsma and Linnerud (2015), Dalby et al. (2018), Bigerna et al. (2019), and Bigerna et al. (2023)), and do not consider intermittency.

[10]https://www.offshore-energy.biz/fifteen-green-ship-projects-get-113-5m-in-enova-support/

Investors can receive support for up to 80 percent of their investment costs.[11]

We denote the subsidy retraction time by $\hat{t} > 0$. There are two possibilities, either the regulator announces the subsidy retraction beforehand, or it does not announce it. In the *announced subsidy retraction* (ASR) scenario the regulator initially reveals the level of investment costs, denoted by $\bar{\delta}$, at which the technology is considered advanced enough so that the subsidy is no longer necessary. This implies that $\hat{t} = \inf\{t : \delta_t \leq \bar{\delta}\}$. Given that $\delta_0 > \bar{\delta}$, and the properties of the geometric Brownian motion (Borodin and Salminen (2002, pp 628)), the expected time for δ_t to reach $\bar{\delta}$ from δ_0 equals

$$\mathbb{E}(\hat{t}) = \max\left\{0, \frac{\ln\left(\delta_0/\bar{\delta}\right)}{\sigma^2/2 - \mu}\right\}.$$

In the *unannounced subsidy retraction* (USR) scenario the regulator does not make such an announcement. This means that the firm does not know when the subsidy will be retracted. Still it takes a potential future subsidy retraction into consideration.[12] Since the firm does not have further information about the timing of the subsidy retraction, we simply assume that the probability of subsidy retraction is constant over time. To model this, we impose that the retraction follows a Poisson process with the constant rate λ, implying that the occurrence probability for a subsidy retraction in the next small time interval $\mathrm{d}t$ equals $\lambda \mathrm{d}t$. The arrival time $\hat{t}$ then follows an exponential distribution, i.e., $\mathbb{P}(\hat{t} \geq t) = \exp(-\lambda t)$, and it holds that the expected retraction time equals $\mathbb{E}(\hat{t}) = 1/\lambda$. This is in line with the literature on policy uncertainty in a real options setting, see e.g. (Dixit and Pindyck, 1994, Chapter 9).[13] Note that the parameter λ represents the retraction threat perceived by the firm.

In order to allow a fair comparison between the ASR and the USR scenario, we set the perceived retraction rate λ such that the expected retraction time in the announced and the unannounced scenario is the same from the firm's perspective. More specifically, given that $\mathbb{E}(\hat{t}) > 0$, we assume that the firm perceives λ to be equal to $\left(\sigma^2/2 - \mu\right) \times \ln^{-1}\left(\delta_0/\bar{\delta}\right)$.

In the following we first investigate the firm's optimal investment decision in the announced and the unannounced subsidy retraction scenarios, respectively. We then explore the total surplus generated by firm's investment decisions.

[11] https://maritimecleantech.no/2023/12/13/new-enova-program-ammonia-and-hydrogen-for-maritime-use/

[12] In 2007 Spain implemented a number of regulatory measures to incentivize investment in renewable energy. However, the market reacted with floods of investments, which generated a tariff deficit. Due to this and the consequences of the financial crisis, Spain decided to sharply reduce subsidies from 2010 onward. These unexpected subsidy retractions led to bankruptcy of hundreds of companies and severe damage to thousands of investors in renewable energy. This resulted in several lawsuits by investors against the Spanish government. In one lawsuit the court rejected the investors' claim, stating that investors could have foreseen policy revisions and should not expect a subsidy scheme to remain unchanged throughout the life of their RE plants (Dalby et al., 2018).

[13] Following the growing concern of policy uncertainty on green investment, a growing strand of literature has taken a real options approach to study the effect of policy uncertainty on investment behavior, see e.g., Hassett and Metcalf (1999), Boomsma and Linnerud (2015), Chronopoulos et al. (2016), Nagy et al. (2021), Hagspiel et al. (2021), and more. All these contributions use a Poisson process to model policy uncertainty.

2.1 Announced subsidy retraction (ASR) scenario

At $t = 0$ the firm takes into account the announced $\bar{\delta}$ and decides about the optimal investment time τ and investment size K, i.e., it solves the following optimization problem,

$$\max_{\tau \geq 0, K \geq 0} \mathbb{E}\left(\int_{t=\tau}^{\infty} (K^{-\gamma} - c)K \exp(-rt)\mathrm{d}t - (1 - s \times \mathbb{1}_{\hat{t} \geq \tau})\delta_\tau K \exp(-r\tau)\right), \tag{2}$$

where r is the risk-free discount rate, and $(K^{-\gamma} - c)K$ is the profit flow generated by investment. If $\hat{t} \geq \tau$, then $\mathbb{1}_{\hat{t} \geq \tau} = 1$, implying that the subsidy is still in place when the firm invests, and the firm pays $(1 - s)\delta_\tau K$ for installing a renewable capacity of size K. If $\hat{t} < \tau$, then $\mathbb{1}_{\hat{t} \geq \tau} = 0$, indicating the subsidy has been retracted before the firm invests, and the firm pays investment cost of the amount $\delta_\tau K$. To solve this optimization problem, we let $V(\delta, K, s)$ denote the firm's value function upon investment for a given investment size K and subsidy rate s. From the objective function (2), we derive V as

$$V(\delta, K, s) = \left(K^{-\gamma} - c\right)K/r - \left(1 - s \times \mathbb{1}_{\delta \geq \bar{\delta}}\right)\delta K, \tag{3}$$

where the first term denotes the expected profit from investment, and the second term is the cost that occurs upon investment.

We derive the firm's investment threshold and investment size in two steps. First, we maximize $V(\delta, K, s)$ with respect to K, and derive the firm's investment size for a given δ and s. The first order condition of V with respect to K yields

$$\frac{\partial V(\delta, K, s)}{\partial K} = \frac{(1 - \gamma)K^{-\gamma} - c}{r} - \delta(1 - s \times \mathbb{1}_{\delta \geq \bar{\delta}}) = 0,$$

which implies that the discounted marginal profit stream is equal to the marginal investment cost net from the (possible) subsidy. Thus, the investment size is given by

$$K(\delta, s) = \left(\frac{1 - \gamma}{r\delta(1 - s \times \mathbb{1}_{\delta \geq \bar{\delta}}) + c}\right)^{1/\gamma}. \tag{4}$$

Second, we derive the investment threshold for a given K and s. Note that the firm holds an investment option before investment. We denote the option value as $F(\delta)$, which, according to, e.g., Dixit and Pindyck (1994, Chapter 5), satisfies the following Bellman equation,

$$rF = \mu\delta\frac{\mathrm{d}F}{\mathrm{d}\delta} + \frac{\sigma^2\delta^2}{2}\frac{\mathrm{d}^2F}{\mathrm{d}\delta^2}, \tag{5}$$

with the boundary condition $\lim_{\delta \to \infty} F(\delta) = 0$. The solution to this Bellman equation is

$$F(\delta) = A\delta^\beta, \tag{6}$$

in which A is a positive constant and can be specified once the optimal investment has been derived. The parameter β is negative because the value of the investment option is decreasing in δ, and satisfies the following quadratic equation,

$$\beta(\beta - 1)\sigma^2/2 + \mu\beta - r = 0.$$

We apply the value matching and smooth pasting conditions on the value functions before investment $F(\delta)$ and upon investment $V(\delta, K, s)$, as in (Dixit and Pindyck, 1994, Chapter 4&5). More specifically, these two conditions imply that the investment threshold should satisfy

$$F(\delta) = V(\delta, K, s) \quad \text{and} \quad \mathrm{d}F(\delta)/\mathrm{d}\delta = \partial V(\delta, K, s)/\partial \delta,$$

which lead to

$$\frac{K\left(K^{-\gamma} - c\right)}{r} = \frac{\beta - 1}{\beta}\left(1 - s \times \mathbb{1}_{\delta \geq \bar{\delta}}\right)\delta K. \tag{7}$$

Equation (7) implies that the firm invests in a way that the discounted profit stream equals the investment cost enlarged by a markup $(\beta - 1)/\beta$. Because the firm's investment is affected by the subsidy retraction and its announcement, in order to derive the optimal investment decision $\{\delta_A^*, K_A^*\}$, we distinguish the following two cases.

Let us start with the case where the reimbursed investment cost subsidy is permanently available. The firm's investment size for a given δ and s, as characterized in (4), equals

$$K^c(\delta, s) = \left(\frac{1 - \gamma}{r\delta(1 - s) + c}\right)^{1/\gamma}. \tag{8}$$

The firm's investment decision can be derived by combining (4) and (7) and solving for δ and K, which yields

$$\delta_F(s) = \frac{-c\beta\gamma}{r(1 - s)(1 + (\beta - 1)\gamma)} \geq \bar{\delta}, \tag{9}$$

$$K_F = \left(\frac{1 + (\beta - 1)\gamma}{c}\right)^{1/\gamma}, \tag{10}$$

given that $1 + (\beta - 1)\gamma > 0$. The interpretation for $\delta_F(s)$ is that it characterizes a stopping region $\delta \leq \delta_F(s)$ where it is optimal for the firm to exercise the investment option at δ because $V(\delta, K^c(\delta, s), s) \geq F(\delta)$, and a continuation region $\delta > \delta_F(s)$ where it is optimal for the firm to hold its investment option at δ because $V(\delta, K^c(\delta, s), s) < F(\delta)$. From the expressions (9) and (10), we conclude that the reimbursed investment cost subsidy makes the firm advance its investment and keep the size at the same level. Given that the firm's planning period starts at $t = 0$, it might happen that $\delta_F(s) \geq \delta_0$. In such a case, the firm is already in the stopping region at $t = 0$ and should exercise the investment option immediately and invest a capacity size $K^c(\delta_0, s)$.

The analysis above builds on the condition that $1 + (\beta - 1)\gamma > 0$. For the alternative case that $1 + (\beta - 1)\gamma \leq 0$, it is optimal for the firm to invest immediately. To show this, we state that the firm's expected discounted cash flow stream is given by

$$\left(\frac{\delta_0}{\delta}\right)^{\beta} V(\delta, K, s) = \left(\frac{\delta_0}{\delta}\right)^{\beta}\left(\frac{(K^{-\gamma} - c)K}{r} - (1 - s)\,\delta K\right), \tag{11}$$

in case that the firm invests at $\delta \leq \delta_0$ with K. Here, $(\delta_0/\delta)^{\beta}$ is a stochastic discount factor as explained in (Dixit and Pindyck, 1994, Appendix 9A). Substituting $K^c(\delta, s)$ into (11) we calculate that

$$\left(\frac{\delta_0}{\delta}\right)^{\beta} V(\delta, K^c(\delta, s), s) = \left(\frac{\delta_0}{\delta}\right)^{\beta} \frac{\gamma}{r} \left(\frac{1-\gamma}{r\delta(1-s)+c}\right)^{\frac{1-\gamma}{\gamma}}. \tag{12}$$

Taking the first order partial derivative of the expected discounted cash flow stream with respect to δ yields that

$$\frac{\partial}{\partial \delta}\left(\left(\frac{\delta_0}{\delta}\right)^{\beta} V(\delta, K^c(\delta, s), s)\right) = \left(\frac{\delta_0}{\delta}\right)^{\beta} \left(\frac{1-\gamma}{r\delta(1-s)+c}\right)^{1/\gamma} \frac{-c\beta\gamma - (1+(\beta-1)\gamma)\, r\delta(1-s)}{r\delta(1-\gamma)}. \tag{13}$$

As $\beta < 0$, it holds that this derivative is positive if $1+(\beta-1)\gamma < 0$, implying the expected discounted payoff increases in δ. Because δ_t is expected to decrease over time, it is optimal for the firm to invest immediately at δ_0. This condition $1+(\beta-1)\gamma < 0$ holds when the risk-free discount rate r is sufficiently large. Then it is understandable that the firm wants to invest immediately.

Let us now consider the second case and introduce the subsidy retraction, where we impose that the subsidy is retracted at $\bar{\delta}$. If $1+(\beta-1)\gamma < 0$ the firm always catches the subsidy because it invests immediately. Otherwise, the firm still invests at $\delta_F(s)$ as long as $\delta_F(s) \geq \bar{\delta}$ (see Claim 1 in A).

What still needs to be considered is the situation where $\delta_F(s) < \bar{\delta}$. In this situation the firm considers two alternatives: It can either invest before the retraction to *catch* the subsidy, or it can refrain from catching the subsidy by investing at a level of $\delta < \bar{\delta}$. The investment decision depends on which action results in a larger payoff. Catching the subsidy implies that the firm will invest just before the subsidy will be retracted, i.e. when δ becomes equal to $\bar{\delta}+\epsilon$ with ϵ being positive and infinitesimally small. The acquired production capacity is then equal to $\lim_{\epsilon\to 0} K^c(\bar{\delta}+\epsilon, s)$. This results in the payoff $\left(\delta_0/\bar{\delta}\right)^{\beta} V(\bar{\delta}, K^c(\bar{\delta}, s), s)$. Not catching the subsidy implies that the firm invests after subsidy retraction, then the optimal investment threshold is given by

$$\delta_n = \delta_F(0) = \frac{-c\beta\gamma}{r(1+(\beta-1)\gamma)}, \tag{14}$$

and the acquired production capacity is equal to K_F. This results in the payoff $(\delta_0/\delta_n)^{\beta} V(\delta_n, K_F, 0)$. The following proposition summarizes the analysis above and presents the optimal investment policy of the firm.

Proposition 1. *Consider the investment problem of the firm in the announced subsidy retraction scenario and the expressions*

$$\delta_F(s) = \frac{-c\beta\gamma}{r(1-s)(1+(\beta-1)\gamma)} \qquad \text{and} \qquad K_F = \left(\frac{1+(\beta-1)\gamma}{c}\right)^{1/\gamma}.$$

- *In case $1+(\beta-1)\gamma > 0$ and $\delta_F(s) < \delta_0$, the firm's optimal investment decision δ_A^* and K_A^* are such that*

  (i) If $\delta_F(s) \geq \bar{\delta}$, it is optimal for the firm to catch the subsidy by investing at $\delta_A^* = \delta_F(s)$ with $K_A^* = K_F$.

(ii) If $\delta_F(s) < \bar{\delta}$, then it is optimal for the firm to catch the subsidy when

$$\left(\frac{\delta_0}{\bar{\delta}}\right)^{\beta} V(\bar{\delta}, K^c(\bar{\delta}, s), s) \geq \left(\frac{\delta_0}{\delta_n}\right)^{\beta} V(\delta_n, K_F, 0) \tag{15}$$

by investing at $\delta_A^* = \bar{\delta}$ with $K_A^* = K^c(\bar{\delta}, s)$; Otherwise, it is optimal not to catch the subsidy by investing at $\delta_A^* = \delta_n$ with $K_A^* = K_F$.

- *In case $1 + (\beta - 1)\gamma \leq 0$ or $\delta_F(s) \geq \delta_0$, the firm's optimal investment decision is to invest at $\delta_A^* = \delta_0$ with a capacity of $K_A^* = K^c(\delta_0, s)$.*

2.2 Unannounced subsidy retraction (USR) scenario

We now consider the scenario where the regulator does not announce the subsidy retraction. As explained above the firm assumes that the subsidy will be retracted with a probability of $\lambda \mathrm{d}t$ in an infinitesimal period $\mathrm{d}t$. The value of the firm upon investment in this case equals $V(\delta, K, s)$ as before. This is because the subsidy is a lump sum transfer at the moment of investment. Policy uncertainty affects only the firm's option value before investment, i.e., $F(\delta)$, which satisfies the following Bellman equation,

$$rF = \mu\delta \frac{\mathrm{d}F}{\mathrm{d}\delta} + \frac{\sigma^2\delta^2}{2}\frac{\mathrm{d}^2 F}{\mathrm{d}\delta^2} + \lambda(A_n\delta^{\beta} - F), \tag{16}$$

with the boundary condition $\lim_{\delta\to\infty} F(\delta) = 0$. Compared with expression (5) in the ASR scenario, in equation (16) there is an extra term $\lambda(A_n\delta^{\beta} - F)$, which describes the effect of the potential subsidy retraction. More specifically, this term describes the probability of retraction in the next time instant times the change in the option value, which jumps down from $F(\delta)$ to $A_n\delta^{\beta}$. Note that, $A_n\delta^{\beta}$ denotes the option value without any subsidy support.

As mentioned in Section 2.1, the coefficient A_n can be specified by the firm's optimal investment decision for the case where the subsidy rate is such that $s = 0$. This corresponds to the optimal investment decision δ_n (as defined in equation (14)) and K_F (see equation (10)), and it holds that

$$A_n = \delta_n^{-\beta} V(\delta_n, K_F, 0) = \frac{\gamma}{r}\left(\frac{1 + (\beta-1)\gamma}{c}\right)^{\frac{1-\gamma}{\gamma}} \left(\frac{r(1+\gamma(\beta-1))}{-c\beta\gamma}\right)^{\beta} > 0.$$

We can further derive from (16) that $F(\delta)$ has the functional form

$$F(\delta) = A_n\delta^{\beta} + B\delta^{\beta_u}, \tag{17}$$

where B is a positive constant. By substituting $F(\delta)$ into (16), we obtain the following quadratic polynomial,

$$\beta_u(\beta_u - 1)\sigma^2/2 + \mu\beta_u - \lambda - r = 0,$$

of which β_u is the negative root and $\beta_u < \beta$ stands given that $\lambda > 0$. In case $\lambda = 0$, it holds that $\beta_u = \beta$. According to the value matching condition

$$F(\delta_U^*) = V(\delta_U^*, K(\delta_U^*, s), s), \tag{18}$$

B is given by

$$B(s) = (\delta_U^*)^{-\beta_u} V(\delta_U^*, K(\delta_U^*, s), s) - A_n(\delta_U^*)^{\beta-\beta_u}. \tag{19}$$

We proceed by analyzing the firm's investment decision in the unannounced retraction scenario as follows. For a given subsidy rate s and the investment threshold δ, the firm's investment size equals $K(\delta, s)$ as in (4). It is noteworthy that the firm does not know about $\bar{\delta}$. However, it is obvious that there are two possible outcomes: The subsidy is either available or not available upon the firm's investment. In case the subsidy is available, then within $K(\delta, s)$ it holds that $\mathbb{1}_{\delta \geq \bar{\delta}} = 1$. Otherwise, it holds that $\mathbb{1}_{\delta \geq \bar{\delta}} = 0$. In order to derive the investment threshold, we define the firm's expected payoffs at δ_0, given that it invests at δ, as

$$\Phi(\delta_0, \delta, s) = A_n\delta_0^\beta + \left(V(\delta, K(\delta, s), s) - A_n\delta^\beta\right)(\delta_0/\delta)^{\beta_u}. \tag{20}$$

$\Phi(\delta_0, \delta, s)$ represents the value of the firm in the continuation region. The first term denotes the value of the option to invest at δ_0, and the second term recognizes the fact that at the moment of investing at δ the firm exchanges the option value for the net present value of investment $V(\delta, K(\delta, s), s)$. $(\delta_0/\delta)^{\beta_u}$ in the second term is the stochastic discount factor, as explained in Section 2.1. To find the optimal δ at which to invest, we differentiate $\Phi(.)$ with respect to δ and obtain

$$\frac{\partial \Phi(\delta_0, \delta, s)}{\partial \delta} = -\frac{(\delta_0/\delta)^{\beta_u}}{\delta}\phi(\delta, s)$$

with $\phi(\delta, s)$ defined as

$$\phi(\delta, s) = A_n(\beta-\beta_u)\delta^\beta + \left(\frac{1-\gamma}{r\delta(1 - s \times \mathbb{1}_{\delta \geq \bar{\delta}}) + c}\right)^{1/\gamma} \frac{r\delta(1 - s \times \mathbb{1}_{\delta \geq \bar{\delta}})(1 + (\beta_u - 1)\gamma) + c\beta_u\gamma}{r(1-\gamma)}. \tag{21}$$

This leads to the following proposition.[14]

Proposition 2. *The firm's optimal investment threshold δ_U^* and investment size K_U^* are such that*

(i) In case the subsidy is available when the firm invests: If $\phi(\delta_0, s) \leq 0$, then $\delta_U^* = \delta_0$ and $K_U^* = K^c(\delta_0, s)$; If $\phi(\delta_0, s) > 0$, then for δ_U^* it holds that $\phi(\delta_U^*, s) = 0$ and $K_U^* = K^c(\delta_U^*, s)$.

(ii) In case the subsidy is not available when the firm invests, then $\delta_U^* = \delta_n$ and $K_U^* = K_F$.

[14]Note that we present a different derivation approach than above, to derive the investment threshold δ_U^*. We do so because this allows us to better explain the economic background for the equation $\phi(\delta_U^*, s) = 0$, which implicitly determines δ_U^*.

Proposition 2 explains what happens under the two cases in the unannounced subsidy retraction scenario. If the firm invests when the subsidy is available, the relevant investment threshold is δ_U^* such that $\phi(\delta_U^*, s) = 0$. Hence, it is implicitly defined. The corresponding investment size equals $K_U^* = K^c(\delta_U^*, s)$. However, in this unannounced subsidy retraction scenario, it can easily happen that the subsidy is suddenly retracted before the firm has actually invested. In such a case, the firm waits until δ_t reaches the threshold $\delta_U^* = \delta_n$ and then acquires a capacity size $K_U^* = K_F$.

Besides, if the subsidy is available when the firm invests, to gain some economic intuition about the implicitly defined investment threshold, we present some sensitivity analysis in the following corollary.

Corollary 1. *In case the subsidy is available when the firm invests and* $\delta_U^* < \delta_0$*,*

(i) Given that $s > 0$*, a bigger perceived retraction threat (larger* λ*) makes the firm invest earlier and less.*

(ii) A larger subsidy rate s *in the USR scenario induces the firm to invests earlier, i.e.,* $\partial\delta_U^*/\partial s > 0$.

(iii) Compared to the ASR scenario, the firm invests earlier in a smaller capacity size in the USR scenario.

Statement *(i)* in Corollary 1 shows that a larger perceived retraction threat by the firm results in the firm investing earlier and less. The intuition is as follows: A stronger retraction threat incentivizes the firm to invest earlier because at every point in time there is a larger probability that the subsidy is retracted. An earlier investment induces a smaller investment size.

Statement *(ii)* in Corollary 1 characterizes the effect of the subsidy rate on firm's investment timing decision. i.e., a larger subsidy rate advances the firm's investment. This is the same as the ASR scenario in Section 2.1, which is due to that a larger subsidy rate makes investing cheaper for the firm. As a result, the firm invests at a point in time when the technology is less developed and more expensive. However, different than the ASR scenario, where the subsidy does not influence the firm's investment size when $\delta_F(s) \geq \bar{\delta}$, the effect of the subsidy rate on the investment size in the USR scenario is less straightforward (see the proof of Corollary 1 (ii) in A). More specifically, it is possible that a larger subsidy rate induces a larger (or smaller) investment size. This can be explained by the two effects of subsidy rate s on $K_U^* = K^c(\delta_U^*, s)$: one positive direct effect and one negative indirect effect through δ_U^*, i.e.,

$$\frac{\mathrm{d}K^c(\delta_U^*, s)}{\mathrm{d}s} = \frac{\partial K^c}{\partial s} + \frac{\partial K^c}{\partial \delta_U^*}\frac{\partial \delta_U^*}{\partial s}. \tag{22}$$

On the one hand, a larger subsidy rate motivates the firm to invest more because investment becomes cheaper. On the other hand, a larger subsidy rate incentivizes the firm to invest earlier due to the retraction threat, which affects the investment size negatively. In the ASR scenario the two effects cancel out and yield a constant investment size if the firm invests before subsidy retraction. However, in the USR scenario either effect can become the dominant.

Statement *(iii)* suggests that the firm invests earlier and less for a given subsidy rate s in the USR than in the ASR scenario. This is due to the fact that, apart from the technological uncertainty, there is also subsidy retraction uncertainty in the USR scenario. More uncertainty implies that the firm has a larger option value, and a larger value incentivizes the firm to invest earlier at a larger δ_t in the USR scenario. Correspondingly, the firm invests with a smaller capacity size when investing earlier.

2.3 Welfare (total surplus)

In this section we study the welfare implications of the firm's investment behavior in different scenarios. To do so, we denote $TS(\delta, K, s)$ as the total surplus when the firm invests at δ with a capacity of size K under the subsidy rate s,

$$TS(\delta, K, s) = PS(\delta, K, s) + CS(\delta, K) - (1 + \eta)C(\delta, K, s). \tag{23}$$

Note that $PS(.)$ represents the producer surplus, which is given by the value of the firm $V(.)$ defined in equation (3). $CS(\delta, K)$ refers to the expected consumer surplus, and $C(\delta, K, s)$ denotes the expected subsidy cost. Following the literature (see, e.g., Alizamir et al. (2016)), we assume there is an economic distortion generated by implementing the subsidy policy. To capture the inefficiency in policy frictions, we introduce a deadweight loss parameter $\eta > 0$.

We first take a look at the expected consumer surplus upon the firm's investment, which equals

$$CS(\delta, K) = \mathbb{E}\left(\int_0^{\infty} \exp(-rt) \times \left(\int_{K^{-\gamma}}^{\infty} p^{-1/\gamma} \mathrm{d}p\right) \mathrm{d}t\right) = \frac{\gamma K^{1-\gamma}}{r(1-\gamma)}, \tag{24}$$

in which the integral with respect to p calculates the instantaneous consumer surplus at time t after investment. In addition, because the subsidy is a lump-sum transfer of $s\delta K$ upon the firm's investment, the subsidy cost can be calculated as

$$C(\delta, K, s) = s\delta K \times \mathbb{1}_{\delta \geq \bar{\delta}}.$$

Equation (23) can be rewritten as

$$TS(\delta, K, s) = \frac{K^{1-\gamma} - (1-\gamma)cK}{r(1-\gamma)} - (1 - s\eta \times \mathbb{1}_{\delta \geq \bar{\delta}})\delta K.$$

The subsidy rate s and the subsidy retraction threshold $\bar{\delta}$ affect the total surplus through the firm's investment decision. To get more insight about how the total surplus is affected in the ASR and the USR scenario, we derive the socially optimal investment threshold δ_W and size K_W. In particular, δ_W and K_W maximize the discounted expected total surplus $(\delta_0/\delta)^{\beta} TS(\delta, K, 0)$ and are summarized in the following proposition.

Proposition 3. *In case* $1 + (\beta - 1)\gamma > 0$*, the socially optimal investment decision is given by*

$$\delta_W = \frac{-c\beta\gamma}{r(1 + (\beta - 1)\gamma)} < \delta_0 \quad \text{and} \quad K_W = \left(\frac{1 + (\beta - 1)\gamma}{c(1 - \gamma)}\right)^{1/\gamma}.$$

Otherwise, the socially optimal investment decision is given by $\delta_W = \delta_0$ *and* $K_W = (c + r\delta_0)^{-1/\gamma}$*.*

Proposition 3 implies that $\delta_W = \delta_F(0) < \delta_F(s)$ and $K_W > K_F$, i.e., the socially optimal investment happens relatively late with a larger size than the subsidized investment. Note that the social planner has an incentive to investment more because it takes into account the consumer surplus. Investing more means it is more expensive and for this reason it is inclined to reduce the unit investment cost.

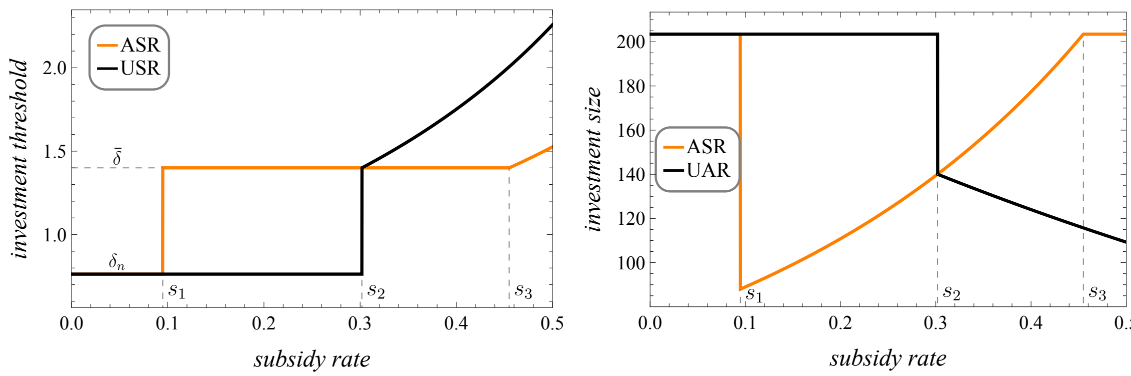
3 Results

The following presents the results in three sections. In Section 3.1 we determine the investment decisions in the announced and unannounced subsidy retraction scenario as a function of subsidy rate. Section 3.2 develops the welfare implications. A comparative static analysis is provided in Section 3.3.

3.1 The investment decisions in the ASR and the USR scenario

Figure 1 depicts the optimal investment decisions, where δ_0 is sufficiently large and $1+(\beta-1)\gamma > 0$ holds such that it is not optimal for the firm to invest immediately in both the ASR (orange line), see Proposition 2, and the USR (black line) scenario, see Proposition 2. For our baseline we specify parameter values that are in reasonable ranges as in the literature such as Dixit and Pindyck (1994). Later on in Section 3.3, we study the sensitivity of our results with respect to changes in each specific parameter value.

The orange (black) solid curves in Figure 1 represent the optimal investment decisions (investment threshold and size) for the (un)announced scenario. Consider first the announced subsidy retraction scenario. When the subsidy is not present or small, the firm does not care about receiving the subsidy. In this case, it invests late at the small threshold δ_n in a relatively large capacity. In the other extreme case where the subsidy is relatively large, the subsidized unit investment cost for the firm is that low that it is optimal to invest relatively soon, which takes place at the threshold $\delta_F(s) > \bar{\delta}$. As derived in Proposition 2, the corresponding capacity size is constant. For the intermediate level of subsidies, the firm invests just before the subsidy is retracted, i.e., at $\bar{\delta}$. In this region, the acquired capacity is increasing with the subsidy rate. This is because a larger s makes investment cheaper given that the firm invests at $\bar{\delta}$. The subsidy level s_1 is the lowest subsidy level where the firm decides to catch the subsidy. This implies that s_1 makes the expression (15) hold



(a) (b)

Figure 1: Illustration of the optimal investment decisions in the announced (ASR) and the unannounced (USR) subsidy retraction scenario. The used parameter values are $r = 0.1$, $\mu = -0.08$, $\sigma = 0.1$, $\gamma = 0.2$, $c = 0.2$, $\bar{\delta} = 1.4$, $\lambda = 0.067$, $\eta = 0$, and $\delta_0 = 5$.

with equality. Then it follows that

$$s_1 = 1 + \frac{c}{r\bar{\delta}}\left(1 - \frac{(1-\gamma)\left(\delta_n/\bar{\delta}\right)^{\beta\gamma/(1-\gamma)}}{1+(\beta-1)\gamma}\right). \tag{25}$$

At the subsidy level s_3, the threshold level $\delta_F(s)$ meets the retraction threshold $\bar{\delta}$. From the equality $\delta_F(s) = \bar{\delta}$, it follows that

$$s_3 = 1 + \frac{c\beta\gamma}{r\bar{\delta}(1+(\beta-1)\gamma)}. \tag{26}$$

Let us now consider the unannounced subsidy retraction scenario. Figure 1a depicts that in the USR scenario, a large subsidy rate $s \geq s_2$ leads to the firm investing early enough such that the subsidy is available upon investment. However, the lower the subsidy rate is, the less eager the firm is to receive the subsidy. Hence, the investment threshold decreases when the subsidy rate becomes smaller, as stated in (ii) of Corollary 1, and the corresponding capacity size increases, i.e., $\mathrm{d}K^c(.)/\mathrm{d}s < 0$ as in equation (22). This suggests that the negative effect of the subsidy rate s on K_U^* dominates the positive effect. At the subsidy level s_2, the investment threshold δ_U^* meets $\bar{\delta}$, implying that the firm does not receive the subsidy anymore. Therefore, for lower levels of s the firm waits with investing until the no-subsidy threshold δ_n is reached. It follows that s_2 is implicitly defined by the equality $\phi(\bar{\delta}, s_2) = 0$ in expression (21).

Finally we compare the investment decisions in the ASR and the USR scenario. When the subsidy rate is $s < s_2$, the firm invests so late that the subsidy is already retracted before the investment time in the USR scenario. Because the firm does not know $\bar{\delta}$, it cannot secure receiving the subsidy by investing sufficiently early. Thus, the subsidy is unavailable upon investment and the firm invests at δ_n with K_F. This is different in the ASR scenario, where a subsidy rate $s_1 \leq s < s_2$

is still attractive enough for the firm to invest at $\bar{\delta}$ to catch the subsidy. As a result, the firm in the ASR scenario invests earlier and less than in the USR scenario, i.e., the orange line is above the the black line in Figure 1a, but below in Figure 1b. However, at a subsidy rate $s < s_1$ it is no longer attractive for the firm in the ASR scenario to catch the subsidy. There the firm just invests at δ_n with K_F after the subsidy retraction, which is the same as in the USR scenario. Therefore, the orange and the black lines overlap for $s < s_1$ in Figure 1.

3.2 Welfare implications

Based on the investment decisions discussed in the previous section, we analyze the corresponding producer surplus, the consumer surplus, the subsidy cost, and the total surplus. They are depicted in Figure 2, where the orange line represents the ASR scenario and the black line the USR scenario. All welfare levels are discounted to δ_0 by the discount term $(\delta_0/\delta)^\beta$ for the convenience of comparison.

The results in Figure 2a show that policy uncertainty in the form of unknown subsidy retraction timing almost always leads to a smaller producer surplus, i.e., the orange line is almost always above the black line and otherwise equal. This is because there is more information about the subsidy retraction in the ASR scenario, and such information is valuable to the firm. The difference in the value of the producer surplus between the ASR and USR scenario represents the value of knowing the exact time of the subsidy retraction.

Figure 2b illustrates the discounted consumer surplus in the ASR and the USR scenario. The relationship shown in 2b is qualitatively similar to that depicted in 2a. Note that the consumer surplus depends on both the timing from which the consumption starts (the investment threshold), and the amount of consumption (the investment size). Thus, later investment has a negative effect, whereas a larger investment has a positive effect on the consumer surplus. For $s_1 < s < s_2$ the firm invests earlier in less capacity in the ASR scenario compared to the USR scenario. The results in Figure 2b show that the consumer surplus is larger in the ASR scenario, implying that the timing effect dominates the size effect. For $s > s_2$ the firm invests later in more capacity in the ASR scenario. In Figure 2b we see that this leads to a higher consumer surplus. So here the size effect dominates.

Figure 2c depicts the influence of the subsidy rate s on the discounted expected subsidy cost from the social planners perspective. This depends on both the investment timing and the size. Investing earlier implies that the technology is less developed and therefore, the unit investment cost is higher (timing effect). However, investing earlier usually induces to smaller investment. Investing less implies a smaller overall investment cost (size effect). For a relatively small subsidy rate $s < s_1$, the firm invests as in the no-subsidy scenario. Therefore, there are no subsidy costs, i.e., the orange and the black lines are both equal to zero. When $s_1 \leq s < s_2$, the firm in the USR scenario invests after the subsidy retraction, which results in no subsidy costs for the social planner. In the ASR scenario the firm invests at the retraction threshold $\bar{\delta}$. Here it catches the subsidy. So there are positive subsidy costs. When the subsidy is relatively large, i.e. $s \geq s_2$, the

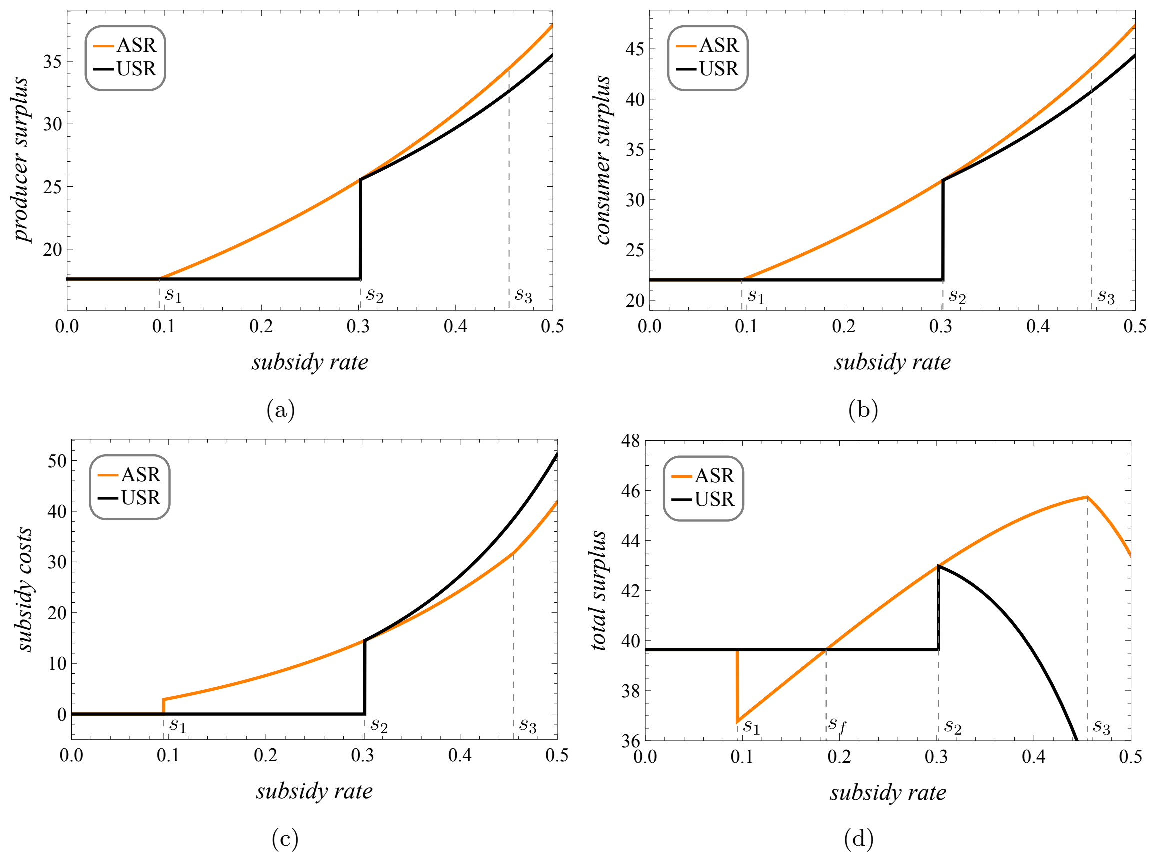


Figure 2: Illustration of the producer, the consumer, and the total surpluses in the announced (ASR) and the unannounced (USR) subsidy retraction scenario. The used parameter values are $r = 0.1$, $\mu = -0.08$, $\sigma = 0.1$, $\gamma = 0.2$, $c = 0.2$, $\bar{\delta} = 1.4$, $\lambda = 0.067$, $\eta = 0$, and $\delta_0 = 5$.

firm invests earlier and less in the USR than in the ASR scenario, and in both scenarios the firm catches the subsidy. Figure 2c shows that the timing effect dominates the size effect, in the sense that the subsidy costs are larger in the USR scenario.

Figure 2d shows the total surplus under the ASR and the USR scenario. Let us start with the extreme subsidy cases. In case the subsidy is that small that $s < s_1$, the firm is not subsidized upon investment in both scenarios. Consequently, the total surplus is the same. In case the subsidy is large, i.e., $s \geq s_2$, the firm's investment happens when the subsidy is still available in both scenarios. Figures 2a, 2b, and 2c show that the producer and the consumer surpluses are larger, but the subsidy cost is smaller in the ASR compared to the USR scenario. Thus, the ASR yields a larger total surplus than the USR scenario, i.e., the orange line is above the black line in Figure 2d.

Now let us consider the intermediate region, i.e. $s_1 \leq s < s_2$. In the ASR scenario, the producer and the consumer surplus are higher than in the USR scenario, but in the USR scenario there are no subsidy costs. By looking at the orange and the black lines in Figure 2d, we see that they intersect at a certain subsidy level that we denote as s_f. For $s \geq s_f$, the total surplus in the ASR scenario is larger than the USR scenario. There the excess sum of the producer and the consumer surplus for the ASR scenario compared to the USR scenario more than outweighs the subsidy costs in the ASR scenario. However, when $s_1 \leq s < s_f$ the opposite result holds, i.e. the subsidy does not generate an excess surplus that outweighs the corresponding subsidy costs. This means that from the social planner's perspective not announcing the subsidy in fact generates a larger welfare than announcing the subsidy. It follows that right at s_f the social planner is indifferent between announcing and not announcing the subsidy retraction, i.e., $(\delta_0/\bar{\delta})^\beta TS(\bar{\delta}, K_F(\bar{\delta}, s_f), s_f) = (\delta_0/\delta_n)^\beta TS(\delta_n, K_F, 0)$, which is equivalent to s_f satisfying

$$\frac{r\bar{\delta}s_f - \gamma(2-\gamma)(c + r\bar{\delta})}{\gamma(2-\gamma)(1-\gamma)} \left(\frac{1-\gamma}{c + r\bar{\delta}(1-s_f)}\right)^{\frac{1}{\gamma}} + \left(\frac{1 + (\beta - 1)\gamma}{c}\right)^{\frac{1-\gamma}{\gamma}} \left(\frac{\bar{\delta}}{\delta_n}\right)^\beta = 0. \tag{27}$$

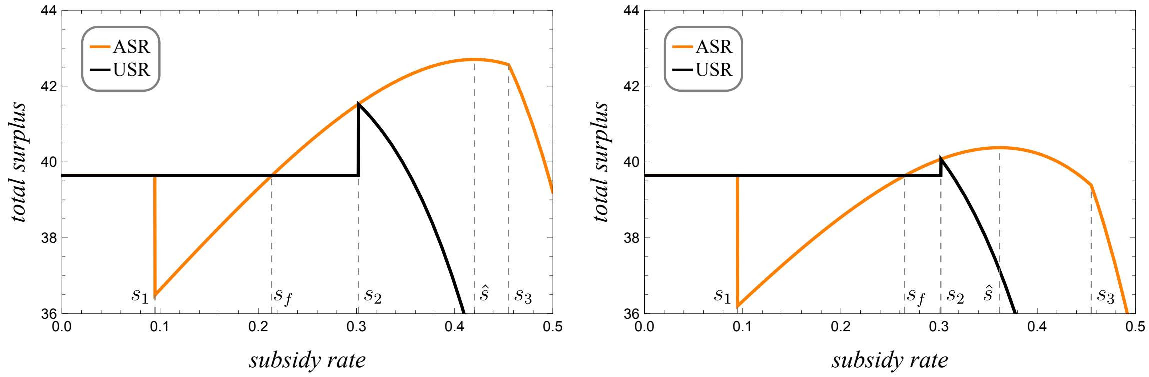
This is due to a "rent-seeking" behavior by the firm in the ASR scenario. In fact, the firm invests at a too high technology cost from a social planner's perspective. It does so because it wants to secure the subsidy. This implies that the firm invests relatively early when the technology is not well developed, which means that the subsidy costs for the social planner are high. Note that the society as a whole incurs the full cost implied by the large δ.

The firm's "rent-seeking" behavior implies that in the ASR scenario the firm wants to catch the subsidy by investing early at $\bar{\delta}$, which inevitably leads to an inefficiently small investment size $K^c(\bar{\delta}, s)$. In fact, the "firm catching the subsidy" can be considered as the firm "manipulating the social environment". This is good for the firm because it increases the producer surplus, i.e., "growing one's existing wealth", but bad for the social welfare in such a way that it leads to a total surplus smaller than that under policy uncertainty, and thus creates a "negative effect on the rest of society". In this sense, Stern's argument (Stern, 2022) that "policy revisions must be carried through such that it can be anticipated", fails because market participants go for "rent-seeking" behavior. To avoid this the regulator better leaves the subsidy retraction unannounced when the subsidy rate falls in this interval $[s_1, s_f)$, so that the firm has no incentive to "manipulate the social environment".

3.3 Comparative statics analysis

In the previous section we present the result that it is sometimes better not to announce a subsidy retraction because this could lead to a loss in welfare, based on a specific parameter set. The aim of this section is to show that this result holds for a wide range of parameter sets.

We first concentrate on the inefficiency parameter η, which we take as 0 in the previous section. Figure 3 shows that our result that not announcing the retraction leads to a larger total surplus is robust for different values of the inefficiency parameter η. In particular, by comparing Figure 3



(a) $\eta = 0.1$ (b) $\eta = 0.2$

Figure 3: Illustration of the total surplus in the announced (ASR) and the unannounced (USR) subsidy retraction scenario. The used parameter values are $r = 0.1$, $\mu = -0.08$, $\sigma = 0.1$, $\gamma = 0.2$, $c = 0.2$, $\bar{\delta} = 1.4$, $\lambda = 0.067$, and $\delta_0 = 5$.

with Figure 2d, we see that a larger inefficiency parameter η enlarges the interval $[s_1, s_f)$. On the one hand, a larger η does not affect s_1, where the firm is indifferent between taking the subsidy or investing without subsidy in the ASR scenario, because η does not influence the strategy of the firm. On the other hand, a larger η implies a larger efficiency loss, which decreases the total surplus when the firm catches the subsidy. As a result, the orange line shifts downwards, which moves the intersection point s_f to the right.

The conclusion of the previous section is that for a subsidy rate in the region $[s_1, s_f)$ not announcing the subsidy retraction is welfare improving compared to announcing the retraction. We now study the effect of different parameter values on the existence of this region. In particular, we compare three subsidy levels in our analysis, namely s_1, s_f, and s_2. This is because according to our baseline in the previous section, the USR scenario could generate a larger total surplus for a given rate $s \in [s_1, s_2)$, where s_1 is the lowest subsidy that makes the firm take the subsidy in the ASR scenario, and s_2 is the largest rate where the firm invests without subsidy in the USR scenario. There might exist a subsidy rate $s_f \in [s_1, s_2]$ such that the discounted total surpluses are the same in the ASR and the USR scenario. In particular, a subsidy rate $s \in [s_1, \min\{s_f, s_2\})$ would lead to a larger total surplus in the USR than in the ASR scenario. This interval is denoted by the shaded orange areas in Figure 4.

Starting out from our baseline case in Figure 4 we consider the effect of unilateral parameter deviations. This means that we change one of the parameter values but keep the others at the same level. Looking at Figure 4 we conclude that the result that not announcing the retraction is better than announcing the retraction prevails in many cases.

Thus, the policy implication here is that, the regulator should not announce the subsidy re-

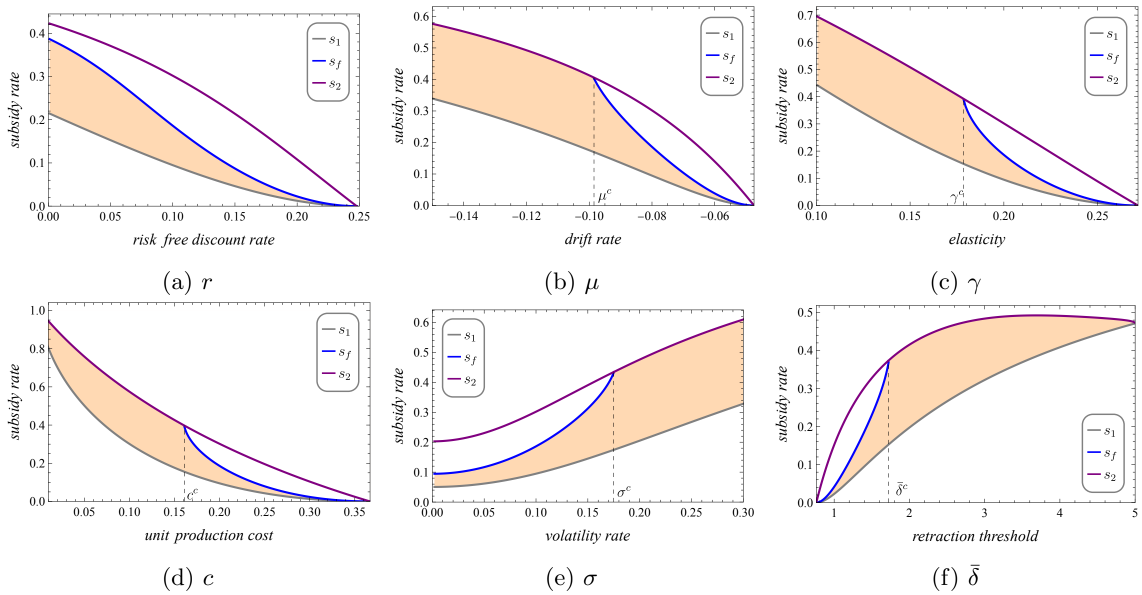


Figure 4: Robustness check that the unannounced retraction (USR) generates a larger total surplus than the announced retraction (ASR). The used parameter values are $r = 0.1$, $\mu = -0.08$, $\sigma = 0.1$, $\gamma = 0.2$, $c = 0.2$, $\bar{\delta} = 1.4$, $\lambda = 0.067$, $\eta = 0$, and $\delta_0 = 5$.

traction for a larger range of subsidy support levels, when the risk free rate is low, the average development of technology is fast, the demand elasticity is high, the unit production cost is not too high, and/or the retraction threshold level is at intermediate level.

We now consider the effect of the uncertainty in technology development, as depicted in Figure 4e, on the total surplus of not announcing vs. announcing the subsidy retraction. The figure shows that as σ becomes larger, not announcing the retraction is optimal for a larger range of subsidy levels. The driving force behind this result is that, as the standard real option literature advocates (see e.g., Dixit and Pindyck (1994)), uncertainty generates a value of waiting with investment. Comparing the investment strategy of the firm in the announced and the unannounced scenario learns that the firm invests later in the unannounced scenario because in the announced scenario the firm invests early to catch the subsidy. Under a sufficiently high level of σ there is a significant value of waiting so that a later investment is preferable. From the welfare perspective, it is also welfare-improving to invest later with a larger capacity size for higher levels of uncertainty. Therefore, the optimal strategy in the unannounced scenario results in a higher total surplus compared to the announced subsidy scenario, along the whole interval $[s_1, s_2)$ for a sufficiently large σ.

4 Feed-in-premium (FIP) subsidy

We have shown so far that the unannounced subsidy retraction could yield a larger total surplus than the announced retraction due to the firm's rent-seeking behavior, especially under the subsidy scheme of the reimbursed investment cost, i.e., a lumpy subsidy. In this section we show that this result also holds for the feed-in-premium (FIP) subsidy, which takes the form of a continuous payoff flow to the firm. Note that FIP has been widely adopted by regulators to incentivize renewable investment because it is market approach oriented and allows some market risk to be shared between investors and consumers (EU, 2014). Within the EU, for instance, 14 countries have implemented the FIP subsidy as of 2019 (CEER, 2021).

The subsidy in the FIP scheme is a fixed add-on to the market price, i.e., $p+s$. We assume that the subsidy rate is smaller than the unit production cost such that $s < c$.[15] Besides, we take the policy change in the form of subsidy retraction as a non-retroactive one, implying that the subsidy retraction does not affect the payoff of the already installed investment. Thus, as long as the firm invests a capacity K before δ_t reaches $\bar{\delta}$, it receives a perpetual subsidy flow of sK. This section focuses on the firm's optimal investment decisions in the ASR and the USR scenarios, and the corresponding welfare implications. Detailed derivations of the investment decision can be found in B.

In the ASR scenario, the retraction threshold $\bar{\delta}$ is announced at $t = 0$. Given that the firm invests at δ with capacity K, analogous to expression (3), the firm value upon investment at δ can be written as

$$V^p(\delta, K, s) = (K^{-\gamma} - c + s)K/r - \delta K, \tag{28}$$

where the term sK/r represents the discounted subsidy stream for the firm in case $\delta \geq \bar{\delta}$. Alternatively, the firm receives no subsidy in case $\delta < \bar{\delta}$, and the corresponding value upon investment equals $V^p(\delta, K, 0)$. Equation (28) implies the firm's investment size for a given δ equals

$$K^p(\delta, s) = \left(\frac{1-\gamma}{r\delta + c - s}\right)^{1/\gamma}. \tag{29}$$

Similar as for the reimbursed investment cost subsidy, the firm takes advantage of the announced $\bar{\delta}$ when investing to maximize the discounted expected payoff $(\delta_0/\delta)^\beta V^p(\cdot)$. The optimal investment decision $\{\delta_A^*, K_A^*\}$ can be summarized in the following proposition. Proofs for the propositions and the corollary in this section can be found in B.

Proposition 4. *Consider the investment problem of the firm in the announced FIP subsidy retraction scenario.*

- *In case* $1 + (\beta - 1)\gamma \leq 0$*, the optimal investment decision is* $\delta_A^* = \delta_0$ *and* $K_A^* = K^p(\delta_0, s)$*.*

[15] The economic intuition for this assumption is that the subsidy for every unit of output is not enough to cover the production cost. Thus, firm's payoff after investment does not always increase with the installed capacity size.

- *In case* $1+(\beta-1)\gamma>0$, *define*

$$\delta_F^p(s)=\frac{-(c-s)\beta\gamma}{r(1+(\beta-1)\gamma)} \quad \text{and} \quad K_F^p(s)=\left(\frac{1+(\beta-1)\gamma}{c-s}\right)^{1/\gamma}.$$

The optimal investment decision is such that,

  (i) If $\bar{\delta}\leq\delta_F^p(s)<\delta_0$, *then* $\delta_A^*=\delta_F^p(s)$ *and* $K_A^*=K_F^p(s)$.

  (ii) If $\delta_F^p(s)<\bar{\delta}\leq\delta_F^p(0)$, *then* $\delta_A^*=\bar{\delta}$ *and* $K_A^*=K^p(\bar{\delta},s)$.

  (iii) If $\delta_F^p(s)<\delta_F^p(0)<\bar{\delta}$, *then* $\delta_A^*=\bar{\delta}$ *and* $K_A^*=K^p(\bar{\delta},s)$ *if*

$$\left(\frac{\delta_0}{\bar{\delta}}\right)V^p(\bar{\delta},K^p(\bar{\delta},s),s)\geq\left(\frac{\delta_0}{\delta_n}\right)V^p(\delta_n,K_F,0); \tag{30}$$

  Otherwise, $\delta_A^*=\delta_n$ *and* $K_A^*=K_F$.

Proposition 4 shows that the effect of an FIP subsidy is that the investment threshold $\delta_F^p(s)$ decreases with the subsidy rate s, whereas the investment size $K_F^p(s)$ is increasing in s. In other words, implementing an FIP subsidy makes the firm investing later and more. Note that this is different from the effect of a reimbursed investment cost subsidy, where we concluded from expressions (9) and (10) that this subsidy advances the investment while it keeps the size at the same level.

When the regulator does not announce the subsidy retraction in advance, similar as for the reimbursed investment cost subsidy, the investment threshold is implicitly determined. Following the same steps as for the investment cost model, we arrive at the following proposition.

Proposition 5. *Define* $\phi^p(\delta,s)$ *such that*

$$\phi^p(\delta,s)=\frac{(\beta-\beta_u)\gamma cK_F}{r(1+(\beta-1)\gamma)}\left(\frac{\delta}{\delta_n}\right)^{\beta}+\frac{r\delta+\gamma(c-s)}{1-\gamma}\frac{\beta_uK^p(\delta,s)}{r}+(1-\beta_u)\delta K^p(\delta,s). \tag{31}$$

The firm's investment threshold δ_U^* *and investment size* K_U^* *are such that*

(i) In case the subsidy is available when the firm invests: If $\phi^p(\delta_0,s)\leq 0$, *then* $\delta_U^*=\delta_0$ *and* $K_U^*=K^p(\delta_0,s)$*; If* $\phi^p(\delta_0,s)>0$, *then for* δ_U^* *it holds that* $\phi^p(\delta_U^*,s)=0$ *and* $K_U^*=K^p(\delta_U^*,s)$.

(ii) In case the subsidy is not available when the firm invests, then $\delta_U^*=\delta_n$ *and* $K_U^*=K_F$.

We compare the firm's investment decision in the ASR (orange line) and the USR (black line) scenario in Figure 5. Figure 5a shows that in the ASR scenario, when the subsidy rate is relatively small, i.e., $s<s_4$, the firm does not take the subsidy because the discounted expected payoff without the subsidy is larger than with the subsidy, i.e., (30) does not hold. This implies that a small subsidy rate is not attractive enough for the firm to advance investment to catch the subsidy. Thus, the corresponding investment size equals K_F, as shown in Figure 5b. Alternatively, when

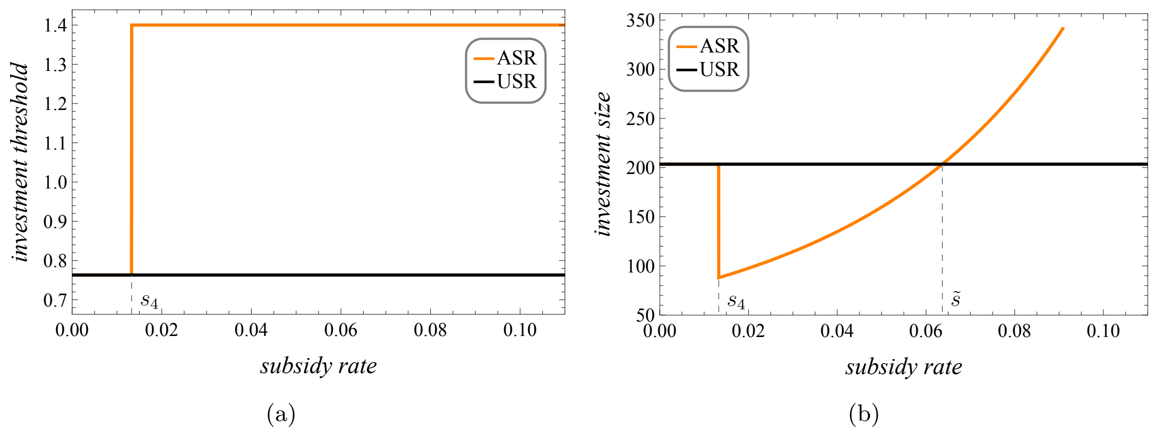


Figure 5: Illustration of the optimal investment decisions in the announced (ASR) and the unannounced (USR) scenario under the feed-in-premium subsidy. The used parameter values are $r = 0.1$, $\mu = -0.08$, $\sigma = 0.1$, $\gamma = 0.2$, $c = 0.2$, $\bar{\delta} = 1.4$, $\lambda = 0.067$, and $\delta_0 = 5$.

the rate is relatively large, i.e., $s \geq s_4$, the firm catches the subsidy and invests at $\bar{\delta}$ because the discounted expected payoff with the subsidy is larger than without the subsidy in this case, i.e., (30) holds. The corresponding investment size $K^p(\bar{\delta}, s)$ increases with s for $s \geq s_4$, as illustrated in Figure 5b.

As for the investment decision in the USR scenario, Figure 5 shows that the investment threshold and the size are equal to δ_n and K_F, respectively. This is because for the given parameter values, (31) yields an investment threshold δ_U^* that is smaller than the retraction threshold $\bar{\delta}$. This implies that the policy uncertainty makes the firm invest too late, meaning that the subsidy is already retracted at the investment time. We now present the sensitivity results concerning the effect of the perceived subsidy retraction rate on the investment strategy in the following corollary.

Corollary 2. *In case the subsidy is available upon the firm's investment and* $\delta_U^* < \delta_0$ *it holds that:*

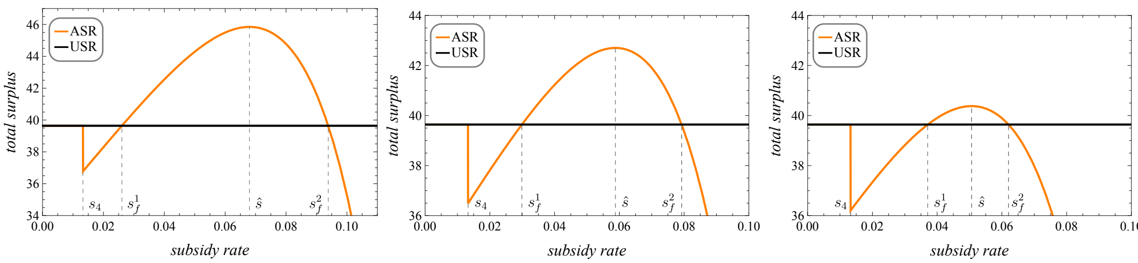
- *A bigger perceived retraction threat (larger* λ*) makes the firm invest earlier and in a smaller capacity.*
- *Compared to the ASR scenario, the firm invests earlier in a smaller capacity size in the USR scenario.*

We now compare the total surplus in both the ASR and the USR scenario. Note that the expression for the discounted consumer surplus upon the firm's investment is given by expression (24). Because the consumer surplus is influenced only by the timing and size of the firm's investment, not by the the Hence, $CS(\delta, K)$ under the price subsidy is the same as under the reimbursed investment cost subsidy. However, the subsidy cost under the FIP subsidy is different than for the reimbursed investment cost subsidy. For the FIP subsidy it equals

$$C^p(\delta, K, s) = (sK/r) \times \mathbb{1}_{\delta<\bar{\delta}}.$$

Correspondingly, the total surplus upon the firm's investment, when taking into account the welfare loss due to inefficiency captured by the parameter η, equals

$$TS^p(\delta, K, s) = V^p(\delta, K, s) + CS(\delta, K) - (1 + \eta)C^p(\delta, K, s).$$



(a) $\eta = 0$ (b) $\eta = 0.1$ (c) $\eta = 0.2$

Figure 6: Illustration of the total surplus and the influence of the policy inefficiency under the feed-in-premium subsidy. The used parameter values are $r = 0.1$, $\mu = -0.08$, $\sigma = 0.1$, $\gamma = 0.2$, $c = 0.2$, $\bar{\delta} = 1.4$, $\lambda = 0.067$, and $\delta_0 = 5$.

Figure 6 illustrates how different levels of policy inefficiency affect the total surplus generated by the investment decisions characterized in Proposition 4 and 5. The figure confirms that our rent-seeking result for the reimbursed investment cost subsidy carries over to the FIP subsidy. In particular, in the region $s_4 \leq s < s_f^1$ the firm invests too early and in a too small capacity just in order to catch the subsidy by investing at $\bar{\delta}$ in the ASR scenario. However, in addition we find another rent-seeking region for relatively high subsidy rate, i.e. $s \geq s_f^2$. There the firm in the ASR scenario also invests at $\bar{\delta}$ but then acquires a far too large capacity size, which induces a too large subsidy costs for the social planner. As for the previous subsidy the rent-seeking regions are increasing in the size of the policy inefficiency parameter.

5 Conclusion

In the last two decades, subsidies have contributed to the diffusion and development of renewable technologies. In some cases the cost of using these technologies has already fallen to such an extent that they have become commercially competitive. The implication is that subsidies are not needed anymore and they should be retracted at some point. The common perception is that this should happen in such a way that firms can anticipate the subsidy retraction. Our paper analyzes the welfare implications of whether a subsidy retraction should be announced or not. We find that in the announced case, rent-seeking behavior can occur such that from a welfare perspective it is actually better not to announce the subsidy retraction beforehand.

From the policymaker's perspective, two recommendations can be formulated based on our results. First, when considering whether a subsidy retraction should be announced or not, a regulator should carefully evaluate the extent to which the firms in this industry would go for rent-seeking behavior and how costly this would be for the society. Second, concerning the subsidy type we advise the regulator to choose the reimbursed investment cost subsidy when the investment speed is essential. However, when investment size is important, we advise the regulator to implement a feed-in-premium subsidy scheme.

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Appendix

A Proofs for the reimbursed investment cost subsidy

In the main text we characterize that the firm can decide whether to *catch* the subsidy in case the subsidy rate s makes it invest after the subsidy retraction, i.e., $\delta_F(s) < \bar{\delta}$. We denote this case as that the firm does not *receive* the subsidy. In the alternative case where the subsidy rate s makes the firm invest before the subsidy retraction, i.e., $\delta_F(s) \geq \bar{\delta}$, we denote it as that the firm *receives* the subsidy. In the latter case, we have the following claim.

Claim 1. *The firm should always catch the subsidy when the firm receives it.*

Proof. The firm receives the subsidy in two situations. The first situation is $1 + (\beta - 1)\gamma \leq 0$, and the firm catches the subsidy by investing at δ_0. The second situation is $1+(\beta-1)\gamma > 0$, where there are two possible cases where the firm receives the subsidy. The first possible case is $\bar{\delta} \leq \delta_F(s) < \delta_0$, and the firm catches the subsidy by investing at $\delta_F(s)$. The second possible case is $\delta_F(s) \geq \delta_0 > \bar{\delta}$, then the firm catches the subsidy by investing at δ_0. We show in the following analysis that under both situations the firm gets a larger payoff when catching the subsidy.

In the first situation, the firm could catch the subsidy by investing at δ_0. Its corresponding payoff is

$$V(\delta_0, K^c(\delta_0, s), s) = \frac{\gamma}{r}\left(\frac{1-\gamma}{r\delta_0(1-s)+c}\right)^{\frac{1-\gamma}{\gamma}}. \tag{32}$$

Besides, it apparently holds that

$$V(\delta_0, K^c(\delta_0, s), s) > V(\delta_0, K^c(\delta_0, 0), 0).$$

In case the firm does *not* want to catch the subsidy, it would wait until the subsidy has been retracted and the corresponding expected payoff equals $(\delta_0/\delta)^\beta V(\delta, K^c(\delta, 0), 0)$ when investing at δ. Given that $1 + (\beta - 1)\gamma \leq 0$ and $\beta < 0$, it holds that

$$\frac{\partial}{\partial\delta}\left(\left(\frac{\delta_0}{\delta}\right)^\beta V(\delta, K^c(\delta, 0), 0)\right) = \left(\frac{\delta_0}{\delta}\right)^\beta \left(\frac{1-\gamma}{r\delta+c}\right)^{1/\gamma} \frac{-c\beta\gamma - (1+(\beta-1)\gamma)\, r\delta}{r\delta(1-\gamma)} > 0. \tag{33}$$

It implies that the firm should invest at $\bar{\delta}-\epsilon$ with a positive and infinitely small ϵ when *not* catching the subsidy. Then the corresponding discounted payoff equals

$$\lim_{\epsilon\to 0}\left(\frac{\delta_0}{\bar{\delta}-\epsilon}\right)^\beta V(\bar{\delta}-\epsilon, K^c(\bar{\delta}-\epsilon, 0), 0) = \left(\frac{\delta_0}{\bar{\delta}}\right)^\beta \frac{\gamma}{r}\left(\frac{1-\gamma}{c+r\bar{\delta}}\right)^{\frac{1-\gamma}{\gamma}}. \tag{34}$$

Given that $\bar{\delta} < \delta_0$ and $K^c(\delta_0, 0) = K_F$, the following equation holds according to (33) ,

$$\lim_{\epsilon\to 0}\left(\frac{\delta_0}{\bar{\delta}-\epsilon}\right)^\beta V(\bar{\delta}-\epsilon, K^c(\bar{\delta}-\epsilon, 0), 0) < V(\delta_0, K_F, 0) < V(\delta_0, K^c(\delta_0, s), s), \tag{35}$$

which implies that it is optimal to catch the subsidy and invests at δ_0 with $K^c(\delta_0, s)$ when $1+(\beta-1)\gamma \leq 0$.

For the first possible case in the second situation, where $1+(\beta-1)\gamma > 0$ and $\bar{\delta} \leq \delta_F(s) < \delta_0$, the firm would invest at $\delta_F(s)$ with K_F to catch the subsidy. Such an investment decision yields a discounted payoff that equals

$$\left(\frac{\delta_0}{\delta_F(s)}\right)^\beta V(\delta_F(s), K_F, s) = \left(\frac{\delta_0}{\delta_F(s)}\right)^\beta \frac{\gamma}{r}\left(\frac{1+(\beta-1)\gamma}{c}\right)^{\frac{1-\gamma}{\gamma}}.$$

In case the firm does *not* want to catch the subsidy, its investment decision depends on the comparison between $\bar{\delta}$ and δ_n. If $\delta_n < \bar{\delta}$, the firm would invest at δ_n with K_F when not catching the subsidy, and the corresponding discounted payoff equals

$$\left(\frac{\delta_0}{\delta_n}\right)^\beta V(\delta_n, K_F, 0) = \left(\frac{\delta_0}{\delta_n}\right)^\beta \frac{\gamma}{r}\left(\frac{1+(\beta-1)\gamma}{c}\right)^{\frac{1-\gamma}{\gamma}}.$$

Because $\beta < 0$ and $\delta_F(s) > \delta_n$ for $s > 0$, it holds that

$$\left(\frac{\delta_0}{\delta_F(s)}\right)^\beta V(\delta_F(s), K_F, s) > \left(\frac{\delta_0}{\delta_n}\right)^\beta V(\delta_n, K_F, 0).$$

If $\delta_n \geq \bar{\delta}$, then not catching the subsidy implies the firm actively avoids the subsidy, which we will show cannot be optimal. Suppose the firm avoids the subsidy by investing at δ such that $\delta_n \geq \bar{\delta} > \delta$, the corresponding discounted payoff is $(\delta_0/\delta)^\beta V(\delta, K^c(\delta, 0), 0)$ as stated above in the first situation, which yields the same first order partial derivative as (33). Note that this partial derivative is now non-negative because $\delta_n \geq \delta$ and $1+(\beta-1)\gamma > 0$. Thus, the firm should invests at $\bar{\delta}-\epsilon$ when it avoids the subsidy, which leads to the same payoff as (34). Overall, if $\delta_n \geq \bar{\delta}$ the following inequality holds,

$$\lim_{\epsilon\to 0}\left(\frac{\delta_0}{\bar{\delta}-\epsilon}\right)^\beta V(\bar{\delta}-\epsilon, K^c(\bar{\delta}-\epsilon, 0), 0) \leq \left(\frac{\delta_0}{\delta_n}\right)^\beta V(\delta_n, K_F, 0) < \left(\frac{\delta_0}{\delta_F(s)}\right)^\beta V(\delta_F(s), K_F, s). \quad (36)$$

Therefore, the firm is better off by investing at $\delta_F(s)$ with K_F to catch the subsidy in the first possible case when both $1+(\beta-1)\gamma > 0$ and $\bar{\delta} \leq \delta_F(s) < \delta_0$ hold.

For the second possible case in the second situation, where $1+(\beta-1)\gamma > 0$ and $\delta_F(s) \geq \delta_0 > \bar{\delta}$, the firm invests at δ_0 when catching the subsidy. This yields a payoff given by (32). In case the firm does not catch the subsidy, the firm would invest at $\bar{\delta}-\epsilon$ if $\delta_n > \bar{\delta}$ according to the similar argument as in the first possible case above and the inequality (36) still holds. However, the firm would invest at δ_n in case $\delta_n \leq \bar{\delta} < \delta_0 < \delta_F(s)$, then the following inequality holds,

$$\begin{aligned}\left(\frac{\delta_0}{\delta_n}\right)^\beta V(\delta_n, K_F, 0) = \left(\frac{\delta_0}{\delta_n}\right)^\beta \frac{\gamma}{r}\left(\frac{1+(\beta-1)\gamma}{c}\right)^{\frac{1-\gamma}{\gamma}} &\leq \frac{\gamma}{r}\left(\frac{1+(\beta-1)\gamma}{c}\right)^{\frac{1-\gamma}{\gamma}} \\ &< \frac{\gamma}{r}\left(\frac{1-\gamma}{r\delta_0(1-s)+c}\right)^{\frac{1-\gamma}{\gamma}} = V(\delta_0, K^c(\delta_0, s), s),\end{aligned}$$

where the second inequality follows from

$$\frac{1-\gamma}{r\delta_0(1-s)+c} > \frac{1-\gamma}{r(1-s)\delta_F(s)+c} = \frac{1+(\beta-1)\gamma}{c}.$$

Thus, catching the subsidy yields a larger payoff also in the second possible cases of the second situation. □

Proof of Proposition 1

Proof. The analysis in Section 2.1 illustrates the derivation of the optimal investment strategy in the permanent subsidy scenario. When there is announced subsidy retraction, the derivation of the firm's optimal investment strategy is similar as in the permanent scenario. In particular, because the reimbursed investment cost subsidy is a lumpy transfer that occurs only at the moment of the firm's investment, the optimal investment decision can be distinguished into two cases: either the firm catches the subsidy, or the firm does not catch the subsidy.

In case the subsidy makes the firm invest before the subsidy retraction, i.e., the firm "receives" the subsidy, the firm finds itself in a similar situation as in the permanent subsidy scenario. The announced subsidy retraction does not affect the firm's investment strategy. From the permanent subsidy scenario, we know that the firm invests at $\delta_A^* = \delta_0$ with $K_A^* = K^c(\delta_0, s)$ if either $1+(\beta-1)\gamma \leq 0$ or both $1+(\beta-1)\gamma > 0$ and $\delta_F(s) \geq \delta_0 > \bar{\delta}$ hold. The firm invests at $\delta_A^* = \delta_F(s)$ with $K_A^* = K_F$ if both $1+(\beta-1)\gamma > 0$ and $\bar{\delta} \leq \delta_F(s) \leq \delta_0$ hold.

However, if the subsidy rate does not make the firm invest before the subsidy retraction, i.e., the firm does not "receive" the subsidy, which happens when both $\delta_F(s) < \bar{\delta}$ and $1+(\beta-1)\gamma > 0$ hold. In such a case the firm in the announced subsidy retraction scenario invests differently than in the permanent subsidy scenario. In particular, the firm has two strategies: It either catches the subsidy or it does not catch. When catching the subsidy, the discounted expected payoff upon investment is the same as characterized in expression (12), whose first order partial derivative with respect to δ is given in (13). Because (13) is positive for $\delta < \delta_F(s)$ and negative for $\delta > \delta_F(s)$, given that $\bar{\delta} > \delta_F(s)$ and δ_t is expected to decrease over time, investing at $\bar{\delta}$ generates the largest payoff for the firm when catching the subsidy. The corresponding investment size is $K^c(\bar{\delta}, s)$. When the firm does not catch the subsidy, then it generates a discounted payoff upon investment that equals $(\delta_0/\delta)^\beta V(\delta, K^c(\delta, 0), 0)$. According to the first order partial derivative specified in expression (13) with $s = 0$, it is optimal for the firm to invest at δ_n, which is smaller than $\delta_F(s)$, and $\bar{\delta}$ as well. Correspondingly, the firm invests with a capacity size K_F. Overall, the firm compares two payoff levels, $(\delta_0/\bar{\delta})^\beta V(\bar{\delta}, K^c(\bar{\delta}, s), s)$ for investing at $\bar{\delta}$ and $(\delta_0/\delta_n)^\beta V(\delta_n, K_F, 0)$ for investing at δ_n, and chooses the larger one.

□

Proof of Proposition 2

Proof. As stated in the main text above Proposition 2, there are two steps when deriving the firm's optimal investment decision in the USR scenario. In the second step, we determine for a given investment size K the corresponding investment threshold by maximizing the firm's option value in the continuation region. This is not a typical real options method as in Dixit and Pindyck (1994). However, we show that our approach generates the same investment threshold. More specifically, in case the subsidy is available upon the firm's investment, i.e., $\mathbb{1}_{\delta \geq \bar{\delta}} = 1$, employing the value matching and smooth pasting conditions for the option value before investment, $F(\delta) = A_n \delta^{\beta} + B\delta^{\beta_u}$, and for the firm value upon investment, $V(\delta, K^c(\delta, s), s)$, leads to that the investment threshold δ should satisfy the following implicit equation

$$A_n(\beta - \beta_u)\delta^{\beta} + \left(\frac{1-\gamma}{c + r\delta(1-s)}\right)^{\frac{1}{\gamma}} \frac{c\beta_u\gamma + r\delta(1-s)\big(1 + (\beta_u - 1)\gamma\big)}{r(1-\gamma)} = 0,$$

which is equivalent to $\phi(\delta, s) = 0$ when $\mathbb{1}_{\delta \geq \bar{\delta}} = 1$. Thus, it yields the same result as our approach. Recall from the main text that the first order derivative of $\Phi(\delta_0, \delta, s)$ with respect to δ equals $-\phi(\delta, s)\delta_0^{\beta_u}/\delta^{\beta_u+1}$. Given that δ_t is expected to decrease over time, the firm is in the stopping region at $t = 0$ if $\phi(\delta_0, s) \leq 0$, i.e., $\partial\Phi(\delta_0, \delta, s)/\partial\delta|_{\delta=\delta_0} \geq 0$. Then the optimal investment threshold is $\delta_U^* = \delta_0$. The firm is in the continuation region at $t = 0$ if $\phi(\delta_0, s) > 0$, i.e., $\partial\Phi(\delta_0, \delta, s)/\partial\delta|_{\delta} < 0$. Correspondingly, the firm waits to invest until δ_t reaches δ_U^* that makes $\phi(\delta_U^*, s) = 0$. The corresponding optimal investment size is $K_U^* = K^c(\delta_U^*, s)$.

If the subsidy is not available upon investment, it holds that $\mathbb{1}_{\delta \geq \bar{\delta}} = 0$ in (4). Then it is equivalent that the firm invests with a capacity size $K^c(\delta, 0)$ at a given δ. In particular, according to the expression of $\Phi(\delta, s)$, the firm exchanges the option value for a net present value of $V(\delta, K^c(\delta, 0), 0)$. In particular, $V(\delta, K^c(\delta, 0), 0)$ is the firm value upon investment without subsidy support. Correspondingly,

$$\phi(\delta, 0) = \left(\delta + \frac{\gamma(r\delta + c)}{r(1-\gamma)}\left(\beta_u + (\beta - \beta_u)\left(\frac{r\delta(1 + (\beta - 1)\gamma)}{-c\beta\gamma}\right)^{\beta}\right)\right)\left(\frac{1-\gamma}{r\delta + c}\right)^{1/\gamma} = 0,$$

which yields the optimal investment threshold $\delta_U^* = \delta_n$, and the firm invests a capacity size $K_U^* = K^c(\delta_n, 0) = K_F$. □

Proof of Corollary 1

Proof. Given that the subsidy is available upon the firm's investment and $\delta_U^* < \delta_0$, it holds according to the proposition 2 that δ_U^* is such that $\phi(\delta_U^*, s) = 0$. We prove the three statements in Corollary 1 one by one.

(*i*) As stated in the main text, the perceived subsidy retraction threat λ influences only β_u, i.e., $\partial\beta_u/\partial\lambda < 0$. In order to analyze the effect of λ on the firm's investment decision δ_U^* and K_U^*, we just need to focus on how the changes in β_u affect δ_U^* and K_U^*. In particular, we argue that $\partial\delta_U^*/\partial\beta_u < 0$ holds by the graphic illustration of Figure 7. Note that for a given subsidy rate s and δ, the value upon investment is $V(\delta, K^c(\delta, s), s)$, which is independent of β_u and is represented by the black line in 7. The value before investment (option value) is just the discounted expected payoff $\Phi(\delta_0, \delta, s)$, which is affected by β_u. Suppose $\beta_u^o < \beta_u^n$, which corresponds to $\lambda^o > \lambda^n$. Then for a given δ, the option value $\Phi(\delta_0, \delta, s|\beta_u = \beta_u^n)$ (blue line in 7) should be above $\Phi(\delta_0, \delta, s|\beta_u = \beta_u^o)$ (red line in 7), because a lower λ implies a smaller policy uncertainty and thus a larger option value. According to the value matching and the smooth pasting condition at the optimal investment threshold, the two option value curves intersect tangentially with the same value-upon-investment curve $V(\delta, K^c(\delta, s), s)$, i.e., the black line. Therefore, a smaller β_u corresponds to a larger investment threshold δ_U^*, i.e., ${\delta_U^*}^o > {\delta_U^*}^n$ as illustrated in Figure 7. As a result, we can conclude that $\partial\delta_U^*/\partial\lambda > 0$. Correspondingly, the optimal investment size $K_U^* = K^c(\delta_U^*, s)$ decreases with δ_U^*. Thus, it can be concluded that $\partial K_U^*/\partial\lambda < 0$.

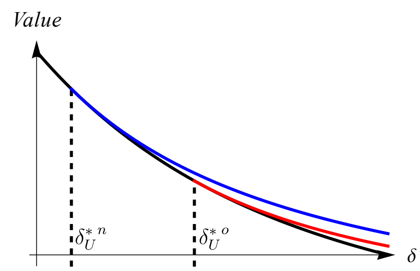

Figure 7: Graphic illustration for $\partial\delta_U^*/\partial\beta_u < 0$

(ii) To get insight on how the subsidy rate s affects the optimal investment decision δ_U^* and K_U^*, we first take a look at δ_U^* and show that $\partial\delta_U^*/\partial s > 0$. By taking the first order partial derivative on both sides of the equation $\phi(\delta_U^*, s) = 0$ with respect to s, we get that

$$A_n\beta(\beta-\beta_u){\delta_U^*}^{\beta-1}\frac{\partial\delta_U^*}{\partial s} + \frac{1+(\beta_u-1)\gamma}{1-\gamma}\left(\frac{1-\gamma}{c+r\delta_U^*(1-s)}\right)^{1/\gamma}\frac{\partial\delta_U^*}{\partial s}$$
$$+\frac{c\beta_u\gamma + r\delta_U^*(1+(\beta_u-1)\gamma)}{\gamma(1-\gamma)(c+r\delta_U^*(1-s))}\left(\frac{1-\gamma}{c+r\delta_U^*(1-s)}\right)^{1/\gamma}\left(\delta_U^* - (1-s)\frac{\partial\delta_U^*}{\partial s}\right) = 0.$$

From $\phi(\delta_U^*, s) = 0$ we can conclude that

$$A_n{\delta_U^*}^\beta = \frac{-c\beta_u\gamma - r\delta_U^*\big(1+(\beta_u-1)\gamma\big)}{r(\beta-\beta_u)(1-\gamma)}\left(\frac{1-\gamma}{c+r\delta_U^*(1-s)}\right)^{1/\gamma}. \tag{37}$$

Then the equation above can be further rewritten as

$$\left(\frac{1-\gamma}{c+r\delta_U^*(1-s)}\right)^{1/\gamma}\left(-\frac{c\beta\beta_u\gamma+r\delta_U^*(\beta-1)(1+(\beta_u-1)\gamma))}{r\delta_U^*(1-\gamma)}\frac{\partial\delta_U^*}{\partial s}\right.$$
$$\left.+\frac{c\beta_u\gamma+r\delta_U^*(1+(\beta_u-1)\gamma)}{\gamma(1-\gamma)(c+r\delta_U^*(1-s))}\left(\delta_U^*-(1-s)\frac{\partial\delta_U^*}{\partial s}\right)\right)=0. \tag{38}$$

It implies that

$$\frac{\partial\delta_U^*}{\partial s}=\frac{r{\delta_U^*}^2(c\beta_u\gamma+r\delta_U^*(1+(\beta_u-1)\gamma))}{\Delta},$$

with

$$\Delta = c^2\beta\beta_u\gamma^2+r^2{\delta_U^*}^2(1-s)\big(1+(\beta-1)\gamma\big)\big(1+(\beta_u-1)\gamma\big)$$
$$-c\gamma r\delta_U^*\big(1-\gamma-\beta_u(1-\gamma-s)-\beta(1-\gamma)+(2-s)\gamma\beta_u\big).$$

Note that $A_n{\delta_U^*}^\beta>0$ and $\beta_u<\beta<0$, (37) implies that the numerator is negative. In order to determine the sign of $\partial\delta_U^*/\partial s$, we have to check the sign for the denominator Δ. Because the expression for Δ is complicated, we are going to show the sign of Δ in an indirect way. In particular, we resort to the statement (i) that $\partial\delta_U^*/\partial\beta_u<0$.

For a given s, taking the first order derivative with respect to β_u on both sides of $\phi(\delta_U^*,s)=0$ leads to that

$$A_n\beta(\beta-\beta_u){\delta_U^*}^{\beta-1}\frac{\partial\delta_U^*}{\partial\beta_u}+\frac{c\gamma+r\delta_U^*\gamma+r\big(1+(\beta_u-1)\gamma\big)}{r(1-\gamma)}\frac{\partial\delta_U^*}{\partial\beta_u}\left(\frac{1-\gamma}{c+r\delta_U^*(1-s)}\right)^{1/\gamma}$$
$$-A_n{\delta_U^*}^{\beta_u}-\frac{(1-s)\big(c\beta_u\gamma+r\delta_U^*\big(1+(\beta_u-1)\gamma\big)\big)}{\gamma\big(c+r\delta_U^*(1-s)\big)(1-\gamma)}\left(\frac{1-\gamma}{c+r\delta_U^*(1-s)}\right)^{1/\gamma}\frac{\partial\delta_U^*}{\partial\beta_u}$$
$$=\frac{1}{r(1-\gamma)}\left(\frac{c\beta\gamma+r\delta_U^*(1+(\beta-1)\gamma)}{\beta-\beta_u}+\frac{-\Delta}{r\delta(c+r\delta_U^*(1-s))}\frac{\partial\delta_U^*}{\partial\beta_u}\right)\left(\frac{1-\gamma}{c+r\delta_U^*(1-s)}\right)^{1/\gamma}$$
$$=0. \tag{39}$$

Because $\partial\delta_U^*/\partial\beta_u<0$ and $\beta_u<\beta$, it can be concluded that $\delta_U^*>\delta_F(s)$, with $\delta_F(s)$ corresponding to δ_U^* under $\beta_u=\beta$. Given that $\delta_F(s)$ increases with s, it holds that $\delta_F(s)>\delta_n=\frac{-c\beta\gamma}{r(1+(\beta-1)\gamma)}$. Therefore, it can be concluded that $\delta_U^*>\frac{-c\beta\gamma}{r(1+(\beta-1)\gamma)}$ and it further holds that $c\beta\gamma+r\delta_U^*(1+(\beta-1)\gamma)>0$ because $1+(\beta-1)\gamma>0$. Overall, we get that for terms in the big bracket in (39), it holds that

$$\frac{c\beta\gamma+r\delta_U^*(1+(\beta-1)\gamma)}{\beta-\beta_u}>0 \quad\text{and}\quad \frac{\partial\delta_U^*}{\partial\beta_u}<0,$$

which suggest that (39) is only possible if $\Delta<0$. In the end, we reach the conclusion that $\partial\delta_U^*/\partial s>0$.

Regarding the effect of the subsidy rate s on the optimal investment threshold $K_U^* = K^c(\delta_U^*, s)$, we take the first order partial derivative of $K^c(\delta_U^*, s)$ with respect to s, which yields that

$$\frac{\partial K^c(\delta_U^*, s)}{\partial s} = \frac{r}{\gamma(1-\gamma)} \left(\frac{1-\gamma}{c + r\delta_U^*(1-s)} \right)^{\frac{1+\gamma}{\gamma}} \left(\delta_U^* - (1-s)\frac{\partial \delta_U^*}{\partial s} \right).$$

Thus, the sign of $\partial K_U^*/\partial s$ depends on the sign for $\delta_U^* - (1-s)\partial\delta_U^*/\partial s$. Note that these two terms are also present in equation (38). In particular, in the expression (38) we already know that

$$\frac{\partial \delta_U^*}{\partial s} > 0 \quad \text{and} \quad \frac{c\beta_u\gamma + r\delta_U^*(1 + (\beta_u - 1)\gamma)}{\gamma(1-\gamma)(c + r\delta_U^*(1-s))} < 0.$$

Therefore, in case $c\beta\beta_u\gamma + r\delta_U^*(\beta-1)(1+(\beta_u-1)\gamma) \geq 0$, then it holds that $\delta_U^* - (1-s)\partial\delta_U^*/\partial s \leq 0$, i.e., $\partial K_U^*/\partial s \leq 0$. Alternatively, in case $c\beta\beta_u\gamma + r\delta_U^*(\beta-1)(1+(\beta_u-1)\gamma) < 0$, then it holds that $\delta_U^* - (1-s)\partial\delta_U^*/\partial s > 0$, i.e., $\partial K_U^*/\partial s > 0$.

(*iii*) In order to prove this statement, we would like to show that $\delta_F(s)$, the investment threshold in the announced scenario, lies in the stopping region of the firm's investment decision in the unannounced scenario, i.e., $\phi(\delta_F(s), s) < 0$. It can be derived that

$$\phi(\delta_F(s), s) = -\frac{\gamma(\beta - \beta_u)}{r} \left(1 - \left(\frac{1}{1-s} \right)^{\beta} \right) \left(\frac{1 + (\beta-1)\gamma}{c} \right)^{\frac{1-\gamma}{\gamma}} < 0.$$

For a given subsidy rate s, the optimal investment decision in the unannounced retraction scenario is δ_U^*, which is larger than δ_A^* where $\lambda = 0$ according to the statement (i), and $K_U^* = K^c(\delta_U^*, s)$. The fact that $\delta_U^* > \delta_A^*$ and $K^c(\delta, s)$ decreases with δ implies that $K_U^* < K_A^*$.

□

Proof of Proposition 3

Proof. In our setup, the socially optimal investment decision maximizes the discounted expected total surplus that equals

$$\left(\frac{\delta_0}{\delta} \right)^{\beta} TS(\delta, K, 0) = \left(\frac{\delta_0}{\delta} \right)^{\beta} \left(\frac{K}{r} \left(\frac{K^{-\gamma}}{1-\gamma} - c \right) - \delta K \right).$$

The social investment size for a given δ maximizes terms in the second bracket and is given by $K(\delta) = (c + r\delta)^{-1/\gamma}$. The value matching and smooth pasting conditions would yield the social investment threshold for a given size K as

$$\delta(K) = \frac{-\beta\left(K^{-\gamma} - c(1-\gamma)\right)}{r(1-\beta)(1-\gamma)}.$$

Combining and solving $\delta(K)$ and $K(\delta)$ leads to the socially optimal investment decision δ_W and K_W as in Proposition 3. □

B Feed-in-premium (FIP) subsidy

Proof of Proposition 4

Proof. We prove the statements in Proposition 4 case by case. First, as has been mentioned in the main text, the firm value upon investment is $V^p(\delta, K, s)$ and the corresponding investment size is $K^p(\delta, s)$, if the firm invests before the subsidy retraction. Suppose the firm value before investment is $F^p(\delta)$, then $F^p(\delta)$ also satisfies the Bellman equation (5) and has the functional form of $F^p(\delta) = A_a^p \delta^\beta$ with A_a^p as a positive constant. Applying the value matching and smooth pasting conditions at the investment threshold δ^p, i.e.,

$$F^p(\delta^p) = V^p(\delta^p, K, s) \quad \text{and} \quad \mathrm{d}F^p(\delta^p)/\mathrm{d}\delta = \partial V^p(\delta^p, K, s)/\partial\delta,$$

we can derive for a given investment size K and a subsidy rate s that

$$\delta^p(K, s) = \frac{\beta\,(K^{-\gamma} + s - c)}{r(\beta - 1)} \quad \text{or} \quad \frac{K\,(K^{-\gamma} + s - c)}{r} = \frac{(\beta - 1)\delta^p(K, s)K}{\beta}.$$

So the firm invests such that the discounted revenue stream equals the investment cost marked up by $(\beta - 1)/\beta$. Combing $K^p(\delta, s)$ and $\delta^p(K, s)$ leads to the investment decision for a given subsidy rate s as

$$\delta_F^p(s) = \frac{-(c - s)\beta\gamma}{r(1 + (\beta - 1)\gamma)} \quad \text{and} \quad K_F^p(s) = \left(\frac{1 + (\beta - 1)\gamma}{c - s}\right)^{1/\gamma},$$

where it holds that $1 + (\beta - 1)\gamma > 0$. Note that $\mathrm{d}\delta_F^p(s)/\mathrm{d}s < 0$ and $\mathrm{d}K_F^p(s)/\mathrm{d}s > 0$, implying that the firm invests later and more for a larger subsidy rate s. This is different than the reimbursed investment cost subsidy, where a larger subsidy rate makes the firm invest earlier and keep the investment capacity at the same level. However, in case $s = 0$, we still get that $\delta_n = \delta_F^p(0)$ and $K_F = K_F^p(0)$.

- In case $1 + (\beta - 1)\gamma \leq 0$, the discounted expected value function for the firm equals

$$\left(\frac{\delta_0}{\delta}\right)^\beta V^p(\delta, K^p(\delta, s), s) = \left(\frac{\delta_0}{\delta}\right)^\beta \times \frac{(r\delta + c - s)\gamma K^p(\delta, s)}{r - r\gamma}. \tag{40}$$

  Taking the first order derivative of (40) with respect to δ yields that

$$\left(\frac{\delta_0}{\delta}\right)^\beta \frac{K^p(\delta, s)}{r\delta(1 - \gamma)}\Big((s - c)\gamma\beta - r\delta(1 + (\beta - 1)\gamma)\Big). \tag{41}$$

  Because $s < c$ and $\beta < 0$, it holds that (41) is positive if $1 + (\beta - 1)\gamma \leq 0$, implying that the firm's discounted expected payoff increases with δ. Because δ_t is expected to decrease overtime, it is thus optimal for the firm to invest immediately at δ_0 with a size $K^p(\delta_0, s)$.

- In case $1+(\beta-1)\gamma>0$, similar as for the reimbursed investment cost subsidy, we distinguish the situations where the firm receives and and where the firm catches the subsidy. In particular, the firm receives the subsidy for $\delta_F^p(s)\geq\bar{\delta}$, and for the FIP subsidy we also show that the firm is better off catching the subsidy when it receives the subsidy.

  (*i*) Note that under the price subsidy, the firm invests later and more for a larger subsidy rate s. Thus, it holds that $\delta_F^p(s)<\delta_n$. In case the firm receives the subsidy, then it holds that $\bar{\delta}\leq\delta_F^p(s)$, and the firm's discounted expected payoff equals

  $$\left(\frac{\delta_0}{\delta_F^p(s)}\right)^\beta\frac{\gamma}{r}\left(\frac{1+(\beta-1)\gamma}{c-s}\right)^{\frac{1-\gamma}{\gamma}}.$$

  In case the firm avoids the subsidy, then the firm would invest at $\bar{\delta}-\epsilon$ with ϵ as an infinitely small and positive number. This is because as δ decreases, the discounted expected payoff first increases for $\delta>\delta_n$ and then decreases for $\delta<\delta_n$. Given that $\bar{\delta}\leq\delta_F^p(s)<\delta_n$, the discounted expected payoff reaches its maximum when the firm, trying to avoid the subsidy, invest at $\bar{\delta}-\epsilon$ with a size $K^p(\bar{\delta}-\epsilon,0)$. According to (40), the corresponding discounted expected payoff equals

  $$\lim_{\epsilon\to0}\left(\frac{\delta_0}{\bar{\delta}-\epsilon}\right)^\beta V^p(\bar{\delta}-\epsilon,K^p(\bar{\delta}-\epsilon,0),0)=\lim_{\epsilon\to0}\left(\frac{\delta_0}{\bar{\delta}-\epsilon}\right)^\beta\frac{\gamma}{r}\left(\frac{1-\gamma}{r(\bar{\delta}-\epsilon)+c}\right)^{\frac{1-\gamma}{\gamma}}$$
  $$=\left(\frac{\delta_0}{\bar{\delta}}\right)^\beta\frac{\gamma}{r}\left(\frac{1-\gamma}{r\bar{\delta}+c}\right)^{\frac{1-\gamma}{\gamma}}<\left(\frac{\delta_0}{\delta_n}\right)^\beta\frac{\gamma}{r}\left(\frac{1+(\beta-1)\gamma}{c}\right)^{\frac{1-\gamma}{\gamma}}=\left(\frac{\delta_0}{\delta_n}\right)^\beta V^p(\delta_n,K_F,0).$$

  Furthermore, it can be calculated that

  $$\frac{\mathrm{d}}{\mathrm{d}s}\left(\left(\frac{\delta_0}{\delta_F^p(s)}\right)^\beta V^p(\delta_F^p(s),K_F^p(s),s)\right)=\left(\frac{\delta_0}{\delta_F^p(s)}\right)^\beta\frac{K_F^p(s)}{r}>0.$$

  Thus, it holds for $s>0$ that

  $$\left(\frac{\delta_0}{\delta_F^p(s)}\right)^\beta V^p(\delta_F^p(s),K_F^p(s),s)>\left(\frac{\delta_0}{\delta_F^p(0)}\right)^\beta V^p(\delta_F^p(0),K_F^p(0),0)=\left(\frac{\delta_0}{\delta_n}\right)^\beta V^p(\delta_n,K_F,0).$$

  Therefore, we can conclude that the firm has a larger payoff when it takes the subsidy rather than avoiding it in case $\delta_F^p(s)\geq\bar{\delta}$.

  (*ii*) In the following analysis, we focus on the situation where the firm does not receive the subsidy, i.e., $\delta_F^p(s)<\bar{\delta}$. Note that when $1+(\beta-1)\gamma>0$, (41) is negative for $\delta>\delta_F^p(s)$. We illustrate the discounted expected payoff in Figure 8 and show that, as δ decreases from δ_0, the discounted expected payoff first increases and then decreases with δ. Therefore, if the firm catches the subsidy, it should invest at $\bar{\delta}$ with a size $K^p(\bar{\delta},s)$. If the firm does not catch the subsidy, then there are two possibilities.

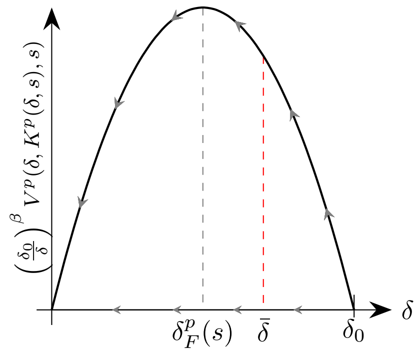

Figure 8: Illustration for the discounted expected payoff as a function of δ when $1 + (\beta - 1)\gamma > 0$.

When $\delta_F^p(s) < \bar{\delta} \leq \delta_n$, the firm would invest at $\bar{\delta} - \epsilon$ with a capacity size $K^p(\bar{\delta} - \epsilon, 0)$, where ϵ is positive and infinitely small. The corresponding discounted payoff equals

$$\lim_{\epsilon \to 0} \left(\frac{\delta_0}{\bar{\delta} - \epsilon}\right)^\beta V^p(\bar{\delta} - \epsilon, K^p(\bar{\delta} - \epsilon, 0), 0) = \lim_{\epsilon \to 0} \left(\frac{\delta_0}{\bar{\delta} - \epsilon}\right)^\beta \frac{\gamma}{r} \left(\frac{1 - \gamma}{r(\bar{\delta} - \epsilon) + c}\right)^{\frac{1-\gamma}{\gamma}}$$

$$= \left(\frac{\delta_0}{\bar{\delta}}\right)^\beta \frac{\gamma}{r} \left(\frac{1 - \gamma}{r\bar{\delta} + c}\right)^{\frac{1-\gamma}{\gamma}} < \left(\frac{\delta_0}{\bar{\delta}}\right)^\beta \frac{\gamma}{r} \left(\frac{1 - \gamma}{r\bar{\delta} + c - s}\right)^{\frac{1-\gamma}{\gamma}} = \left(\frac{\delta_0}{\bar{\delta}}\right)^\beta V^p(\bar{\delta}, K^p(\bar{\delta}, s), s),$$

implying that the firm is better off when catching the subsidy.

When $\delta_F^p(s) < \delta_n < \bar{\delta}$, the firm invests at δ_n if it does not catch the subsidy. The corresponding discounted expected payoff is $(\delta_0/\delta_n)^\beta V^p(\delta_n, K_F, 0)$. Thus, the firm should catch the subsidy by investing at $\bar{\delta}$ with $K^p(\bar{\delta}, s)$ when

$$\left(\frac{\delta_0}{\bar{\delta}}\right)^\beta V^p(\bar{\delta}, K^p(\bar{\delta}, s), s) \geq \left(\frac{\delta_0}{\delta_n}\right)^\beta V^p(\delta_n, K_F, 0).$$

Otherwise, the firm would wait for the subsidy to be retracted and invests at δ_n with K_F.

□

Proof of Proposition 5

Proof. Similar as the reimbursed investment cost subsidy, we assume the option value before investment is denoted by $F^p(\delta)$. Then F^p satisfies the Bellman equation as specified in (16) and have the functional form of $A_n\delta^\beta + B^p\delta^{\beta_u}$. Because $A_n\delta^\beta$ denotes the option value without any subsidy support, this term is the same as in the reimbursed investment cost subsidy. B^p is a positive constant. If we still denote the optimal investment decision in the USR scenario as $\{\delta_U^*, K_U^*\}$, then according to

$$F(\delta_U^*) = V^p(\delta_U^*, K^p(\delta_U^*, s), s),$$

it can be calcualted that

$$B^p(s) = \delta_U^{*\,-\beta_u} V^p(\delta_U^*, K^p(\delta_U^*, s), s) - A_n \delta_U^{*\,\beta-\beta_u}.$$

There are still two scenarios depending on whether the subsidy is available upon firm's investment.

(i) The subsidy is available when the firm invests. In this scenario, we define the firm's expected payoffs at δ_0, given that it invests at δ, as

$$\Phi^p(\delta_0, \delta, s) = A_n \delta_0^\beta + \left(V^p(\delta, K^p(\delta, s), s) - A_n \delta^\beta\right) (\delta_0/\delta)^{\beta_u}.$$

Taking the first order partial derivative of $\Phi^p(\delta_0, \delta, s)$ with respect to δ leads to

$$\frac{\partial \Phi(\delta_0, \delta, s)}{\partial \delta} = -\frac{(\delta_0/\delta)^{\beta_u}}{\delta} \phi^p(\delta, s).$$

Thus, it can be concluded that in case $\phi^p(\delta, s) > 0$, i.e., $\partial \Phi^p/\partial \delta < 0$, then the firm is in the continuation region. This is because δ_t decreases overtime, investing later at a smaller δ would generate a larger Φ^p. Therefore, if $\phi^p(\delta_0, s) > 0$, the optimal investment threshold δ_U^* makes it hold that $\phi^p(\delta_U^*, s) = 0$ and $K_U^* = K^p(\delta_U^*, s)$. Analogously, the firm is in the stopping region in case $\phi^p(\delta, s) \leq 0$, i.e., $\partial \Phi^p/\partial \delta \geq 0$. Correspondingly, if $\phi^p(\delta_0, s) \leq 0$, it holds that $\delta_U^* = \delta_0$ and $K_U^* = K^p(\delta_0, s)$.

(ii) The subsidy is not available when the firm invests. In this case, the firm value upon investment is $V^p(\delta, K, 0)$, which yields the investment size for a given δ and $s = 0$ as $K^p(\delta, 0)$. By similar procedures as for the case above, we get that the firm's investment threshold δ_U^* should satisfy $\phi^p(\delta_U^*, 0) = 0$, which yields that $\delta_U^* = \delta_n$. The firm's corresponding investment size is $K_U^* = K^p(\delta_n, 0) = K_F$.

□

Proof of Corollary 2

Proof. Same as the reimbursed investment cost subsidy, the perceived retraction rate λ affects the firm's investment decision δ_U^* only through β_u. Therefore, to prove the statements in Corollary 2, we can apply similar arguments as in the proof of Corollary 1.

(i) We use the same arguments as in the proof of the statement (i) in the "*Proof of Corollary 1*" to show $\partial \delta_U^*/\partial \lambda > 0$. For a given subsidy rate s and the same δ, a larger perceived retraction rate λ implies a smaller β_u and a lower option value $\Phi^p(\delta_0, \delta, s)$. A lower option value curve intersects tangentially with the value upon investment $V^p(\delta, K^p(\delta, s), s)$ at a larger investment threshold δ_U^*, as illustrated in Figure 7. Therefore, it can be concluded that $\partial \delta_U^*/\partial \lambda > 0$. Because $K^p(\delta, s)$ decreases with δ, it can be conclude that $\partial K_U^*/\partial \lambda > 0$.

(ii) To compare the investment decisions between the ASR and the USR scenario, we adopt the similar approach as in the "*Proof of Corollary 1*" for the statement (iii). Recall that the optimal investment threshold δ_U^* makes it hold that $\phi^p(\delta_U^*, s) = 0$. Besides, $\phi(\delta, s) < 0$ suggests that δ is in the stopping region, implying $\delta < \delta_U^*$. It can be calculated that

$$\begin{aligned}\phi^p(\delta_F^p(s), s) &= \frac{(c-s)(\beta-\beta_u)\gamma}{r(1+(\beta-1)\gamma)}\left(\left(\frac{c}{c-s}\right)^{1-\beta}\left(\frac{1+(\beta-1)\gamma}{c}\right)^{1/\gamma}-\left(\frac{1+(\beta-1)\gamma}{c-s}\right)^{1/\gamma}\right)\\ &< \frac{(c-s)(\beta-\beta_u)\gamma}{r(1+(\beta-1)\gamma)}\left(\frac{1+(\beta-1)\gamma}{c}\right)^{1/\gamma}\left(\left(\frac{c}{c-s}\right)^{1-\beta}-1\right) < 0.\end{aligned}$$

Thus, it holds that $\delta_A^* = \delta_F^p(s) < \delta_U^*$, i.e., the firm invests earlier in the USR scenario. Correspondingly, we have that $K^p(\delta_A^*, s) > K^p(\delta_U^*, s)$, i.e., $K_A^* > K_U^*$, and the firm invests less in the USR scenario.

□