

How damaging are environmental policy targets in terms of welfare?*

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Abstract

International environmental agreements translate in environmental policy targets for individual countries. To reach these targets, corresponding governments must stimulate the private sector to do the right investments, for instance in renewable energy. This paper studies the effect of a subsidy on the probability of reaching the policy target and on the level of social welfare.

The subsidy in the form of a fixed price support accelerates investment and increases the investment size. As such it helps to reach a policy target in time, but also has its own welfare effects. The paper defines a new welfare measure, “the expected Welfare corresponding to the Policy Target” abbreviated by WPT, that takes all these effects into account, including the penalty that is incurred upon not reaching the policy target. Based on the WPT we determine the optimal subsidy size. We find that a policy target increases the optimal subsidy size. An international policy target can cause a tradeoff in the sense that a large investment is required to achieve the target, while at the same time such a large investment is bad for welfare.

Keywords: Investment under Uncertainty, Subsidy, Policy Target, Welfare Analysis

JEL classification: D81, E22, H23

1 Introduction

In maximizing profits or pursuing growth, private firms do not care enough about the environment. Consequently, energy producers from itself are not incentivized enough to invest in renewable energy. Instead they use fossil fuel and emit greenhouse gases to a too large extent (Eichner and Runkel, 2014). For this reason, in reaching an environmental policy target that arises from international environmental agreements, governments have to stimulate the private sector to sufficiently invest in green energy. Such a policy target is for instance set by the EU, who demands that in 2030 27% of total energy consumption should be produced

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32 by renewable energy. Moreover, according to the regulations of the EU parliament, if the member states fall
33 short in meeting their national reference points (target), they either have to take national measures to catch
34 up or to make a financial donation (EU, 2018).

35 We consider a framework where the government of a country has to deal with an environmental policy
36 target, resulting from an international environmental agreement. The target consists of investing a certain
37 amount in green energy before a certain point in time. The government employs a subsidy to stimulate
38 energy producers to undertake green energy investments. Of course, the resulting investments influence
39 social welfare and the principal aim of this paper is to investigate this effect. When the target is not
40 realized, the government incurs a certain penalty. We mainly consider a subsidy in the form of fixed price
41 support, but we check whether our results are robust in case of flexible price support or a subsidy in the
42 form of reimbursed investment cost. We take into account that the energy market is a market with uncertain
43 future demand, in which the energy producer is constantly forecasting demand and balancing the value of
44 investing now and delaying investment. To do so we employ the real options approach to determine the
45 optimal investment decision.

46 In general it holds that the difference in objective between profit and welfare maximization poses a
47 coordination problem and requires governmental regulation (Rodrik, 1992). Several policy instruments such
48 as taxation and price-cap have already been proposed in the literature and they are not exclusive to the
49 energy sector. Pennings (2000) studies taxation and investment subsidies to influence the instant investment.
50 Hassett and Metcalf (1999) consider uncertainty in the tax policy, such as the U.S. investment tax credits
51 that have been changed on many occasions since being introduced in 1964. They show that for a relatively
52 low tax rate, more tax-policy uncertainty speeds up irreversible investment because the firm inclines to invest
53 at a low tax rate. Dobbs (2004) analyzes the implementation of a price cap and finds that the first-best
54 outcome cannot be reached as the price cap has to be used to reach two goals at the same time: optimal
55 investment ex-ante and optimal post-investment pricing. Building on Dobbs (2004), Evans and Guthrie
56 (2012) show that the price cap should be lowered under scale economics where grouping investments across
57 time is cost efficient. In contrast, Willems and Zwart (2018) consider constant returns to scale where it is
58 not optimal to group investments. While assuming asymmetric information on investment costs, Willems
59 and Zwart (2018) implement an optimal mechanism where a revenue tax increases with the level of the price
60 cap.

61 Subsidy support is commonly implemented in the field of green energy. With the subsidy instrument the
62 regulator can influence the firm's investment decisions in order to meet socially optimal goals or to realize
63 the assigned policy targets. The subsidy support can take several forms such as feed-in premiums (FIP),
64 reimbursed investment costs, feed-in tariffs (FIT), tradable green certificates (TGC), and quota obligations.
65 The European Commission (2014) suggests to adopt FIP because it is a market-based approach and some
66 risk can be shared between investors and consumers.

67 Our paper belongs to the research field of governmental green energy policies and their effect on the
68 investment timing decisions of private firms. Boomsma et al. (2012) take subsidy payments as a volatile
69 process. The support schemes considered include FIT, FIP, and renewable energy certificates. Boomsma
70 and Linnerud (2015) focus on the uncertainty to introduce or retract subsidy schemes and its effect on the
71 firm's investment timing. They find that the risk of subsidy termination speeds up investment. This result is
72 supported by Adkins and Paxson (2015), who provide the intuition that the firm wants to catch the subsidy
73 before it is gone. Similarly, future provision of a subsidy delays investment because the firm wants to wait
74 for the subsidy. This influence of subsidy retraction and provision is further studied by Chronopoulos et al.
75 (2016). Besides investment timing, they also consider the influence of policy uncertainty on the investment

76 capacity/size. They find that future subsidy retraction lowers the amount of installed capacity, whereas
77 future subsidy provision raises the incentive to install a larger capacity.

78 The present paper first considers the investment problem without the policy target. We find that from
79 a welfare perspective a profit maximizing firm invests too late in the right amount. Introducing a subsidy
80 in the form of a fixed price support stimulates the firm to invest earlier, which is good for welfare, but also
81 more, which is bad for welfare. Then we introduce a policy target in the form of a required investment of
82 a certain size before a certain deadline, where a penalty has to be paid upon not fulfilling the target. This
83 could introduce a tradeoff in the following form: fulfilling the target could involve a too large investment
84 being bad for welfare but on the other hand prevents paying the penalty.

85 When determining the optimal subsidy rate all these welfare effects should be taken into account. For
86 this reason we introduce a new welfare measure, “the expected Welfare corresponding to the Policy Target”
87 abbreviated by WPT. Employing the WPT we obtain that the policy target raises the optimal subsidy
88 rate, and also that the firm needs additional stimulus in the form of a higher subsidy when the economic
89 environment is more uncertain, the market trend is low, and the discount rate is high.

90 We apply our theoretical model to the Italian electricity market. We find that a fixed price support of
91 4% is optimal in order to realize the 2030 target set by the EU, which is that 30% of the energy consumption
92 comes from renewable resources.

93 As such this paper adds to the literature studying the effect of subsidies. Bigerna et al. (2019) analyzes the
94 subsidy policy that realizes the targeted investment timing and capacity, but ignores the welfare perspective.
95 Sheriff (2008) claims that politically motivated subsidies can have undesired environmental consequences,
96 and he analyzes the welfare-maximizing policy under firm’s productivity information constraints in a static
97 setting. Pineda et al. (2018) find that the FIT and FIP are more efficient than TGC in realizing a given
98 renewable investment quantity target when the power producers are risk averse. More information about
99 effects of subsidies in the renewable energy field can be found in Koltsaklis and Dagoumas (2018).

100 This paper is organized as follows. Section 2 builds the theoretical model and analyzes the profit and wel-
101 fare maximizing investment decisions. Section 3 analyzes the welfare-maximizing subsidy with and without
102 policy target constraint. Section 4 conducts an empirical analysis for the Italian electricity market. Section
103 5 carries out a comparative statics analysis with special emphasis on the implications when the policy target
104 is adjusted. Section 6 concludes.

105 2 Model

106 This section consists of three parts. First we present the model framework. We proceed by analyzing the
107 optimal investment decision from a profit maximizing perspective. Finally, we consider the same decision
108 from the point of view of the social planner.

109 2.1 Model Setup

110 Consider a framework where an energy producing firm can undertake an investment to enter the market.
111 The investment decision involves choosing the time and the size, K , of the investment, where the size is
112 the firm’s production capacity. The firm is assumed to be sufficiently large to exert market power, which
113 seems relevant in this particular market. For instance, the EU electricity industry shows a high degree of
114 concentration on national and regional scales (European Commission (2011)). We impose that the demand
115 function is iso-elastic. The reason is that, first, iso-elastic demand suits the electricity market better from the

116 perspective of demand elasticity. In particular, abundant research work has estimated the price elasticity for
 117 electricity to be a constant or lying in a narrow range, see for instance Lijesen (2007). Second, an additional
 118 advantage is that the iso-elastic demand function is linear in logs, which makes it easily tractable from an
 119 econometric point of view. It follows that the market price, p_t , is equal to

$$p_t(X_t) = X_t K^{-\gamma}, \quad (1)$$

120 where $0 < \gamma < 1$ is the inverse of demand elasticity. It is important to note that with such constant demand
 121 elasticity, it is always optimal to use all available capacity.

122 To capture the fact that the energy market is a market with uncertain future demand, the process X_t is
 123 a geometric Brownian motion (GBM) process given by

$$dX_t = \mu X_t dt + \sigma X_t d\omega_t,$$

124 in which μ is the drift rate, $d\omega_t$ is the increment of a Wiener process, and $\sigma > 0$ is the volatility parameter.

125 The firm is assumed to be risk neutral and discounts against rate r . We also assume $r > \mu$, as otherwise
 126 it would always be optimal for the firm to delay the investment (Dixit and Pindyck (1994)). The investment
 127 costs take the form $\delta_0 + \delta_1 K$ with $\delta_0 \geq 0$ and $\delta_1 > 0$.

128 2.2 Profit-maximizing investment decision

129 To obtain the investment decision that maximizes the expected profit stream, the firm has to solve the
 130 following optimization problem:

$$F(X) = \max_{K \geq 0, T \geq 0} \mathbb{E} \left(\int_{t=T}^{\infty} X_t K^{1-\gamma} \exp(-rt) dt - (\delta_0 + \delta_1 K) \exp(-rT) \mid X_0 = X \right),$$

131 where $F(X)$ is the value of the firm's option to invest, and T is the moment of investment.

132 The optimal investment decision involves finding the optimal size and the optimal timing. For a given
 133 value of X , we derive the optimal value of the investment size $K_F(X)$ by solving

$$\max_{K \geq 0} \mathbb{E} \left(\int_{t=0}^{\infty} X_t K^{1-\gamma} e^{-rt} dt - \delta_0 - \delta_1 K \mid X_0 = X \right) = \max_{K \geq 0} \left(\frac{X K^{1-\gamma}}{r - \mu} - \delta_0 - \delta_1 K \right). \quad (2)$$

134 This gives

$$K_F(X) = \left(\frac{X(1-\gamma)}{(r-\mu)\delta_1} \right)^{1/\gamma}. \quad (3)$$

135 Second, we consider the optimal investment timing. To do so we determine the investment threshold X_F
 136 at which it holds that the firm is indifferent between investing and not investing. In the scenario where
 137 $X_0 < X_F$ it is optimal for the firm to invest when the process X reaches X_F for the first time. Otherwise, it
 138 is optimal to invest immediately. Following the standard real options analysis (Dixit and Pindyck (1994)),
 139 we obtain that for $X \leq X_F$ the value of the option to invest can be expressed as

$$F(X) = AX^\beta,$$

140 where A is a positive constant and β is the positive root of the quadratic polynomial

$$\frac{1}{2}\sigma^2\beta^2 + \left(\mu - \frac{1}{2}\sigma^2\right)\beta - r = 0. \quad (4)$$

141 In what follows we impose that

$$\beta\gamma > 1,$$

142 because if this expression does not hold, the firm will postpone investment as the risk adjusted discount rate
143 will be negative (see also Dixit and Pindyck (1994)).

When the firm invests, we denote the value of the investment project by $V(X, K)$. The following value matching and smooth pasting conditions can then be employed to determine the optimal investment threshold X_F for a given capacity size K :

$$\begin{aligned} F(X_F) &= V(X_F, K), \\ \frac{\partial F(X)}{\partial X} \Big|_{X=X_F} &= \frac{\partial V(X, K)}{\partial X} \Big|_{X=X_F}. \end{aligned}$$

144 This yields

$$X_F(K) = \frac{\beta(r - \mu)(\delta_0 + \delta_1 K)}{(\beta - 1)K^{1-\gamma}} \quad (5)$$

145 Based on (3) and (5) we can develop the following proposition.

Proposition 1 *The optimal investment threshold X_F^* and the corresponding optimal capacity level K_F^* are given by*

$$\begin{aligned} X_F^* &= \frac{r - \mu}{1 - \gamma} \delta_1 \left(\frac{\delta_0 \beta (1 - \gamma)}{\delta_1 (\beta \gamma - 1)} \right)^\gamma, \\ K_F^* &\equiv K_F(X^*) = \frac{\delta_0 \beta (1 - \gamma)}{\delta_1 (\beta \gamma - 1)}. \end{aligned}$$

146 Note that if at time $t = 0$ it already holds that $X_0 \geq X_F^*$, then the firm invests immediately at X_0 to
147 attract a capacity of size $K_F(X_0)$.

148 2.3 Welfare-maximizing investment decision

149 The regulator maximizes total social surplus consisting of the sum of producer and consumer surplus. The
150 instantaneous consumer surplus $cs(X_t, K)$ is equal to

$$\int_p^\infty \left(\frac{X_t}{p} \right)^{1/\gamma} dp = \frac{\gamma X_t^{1/\gamma}}{1 - \gamma} p^{\frac{\gamma-1}{\gamma}} \Big|_{X_t K^{-\gamma}}^\infty = \frac{\gamma X_t}{1 - \gamma} K^{1-\gamma}.$$

151 Given $X_0 = X$ at time 0 and capacity level K , the total expected consumer surplus $CS(X, K)$ is equal to

$$CS(X, K) = \mathbb{E} \left[\int_{t=0}^\infty \frac{e^{-rt} \gamma X_t K^{1-\gamma}}{1 - \gamma} dt \Big| X_0 = X \right] = \frac{\gamma}{1 - \gamma} \frac{X K^{1-\gamma}}{r - \mu}.$$

152 Accounting for the expected producer surplus $PS(X, K)$, which is equal to the value of the project for
153 the firm, given by (2), i.e.

$$PS(X, K) = \frac{X K^{1-\gamma}}{r - \mu} - \delta_0 - \delta_1 K,$$

154 the total expected surplus is given by

$$W(X, K) = CS(X, K) + PS(X, K) = \frac{X K^{1-\gamma}}{(1 - \gamma)(r - \mu)} - \delta_0 - \delta_1 K. \quad (6)$$

155 Following the same steps as in Section 2.2 we can then derive that for a given GBM level X , the corresponding
 156 social optimal investment capacity is equal to

$$K_W(X) = \left(\frac{X}{\delta_1(r - \mu)} \right)^{1/\gamma}.$$

157 For a given capacity size K , the socially optimal investment threshold reads

$$X_W(K) = \frac{\beta(r - \mu)(1 - \gamma)(\delta_0 + \delta_1 K)}{(\beta - 1)K^{1-\gamma}}.$$

158 Combining $K_W(X)$ and $X_W(K)$ yields the socially optimal investment timing and capacity presented in
 159 Proposition 2.

160 **Proposition 2** *The socially optimal investment threshold X_W^* and the corresponding optimal investment*
 161 *capacity K_W^* are given by*

$$\begin{aligned} X_W^* &= \delta_1(r - \mu) \left(\frac{\beta\delta_0(1 - \gamma)}{\delta_1(\beta\gamma - 1)} \right)^\gamma, \\ K_W^* &= \frac{\beta\delta_0(1 - \gamma)}{\delta_1(\beta\gamma - 1)}. \end{aligned}$$

162 Comparing the regulator's and the firm's optimal investment, we find that the firm invests later than in
 163 the social optimum, but with the same capacity size. Note that this is different than in Huisman and Kort
 164 (2015). That paper employs a linear demand function to find that the firm invests at the socially optimal
 165 time but with a capacity size that is half of the socially optimal capacity. However, under iso-elastic demand
 166 the profit maximizing firm thus invests too late from a social planner perspective. The resulting welfare loss
 167 discounted to the investment moment of the profit maximizing firm is given by the following expression:

$$\left(\frac{X_F^*}{X_W^*} \right)^\beta W(X_W^*, K_W^*) - W(X_F^*, K_F^*) = \left(\left(\frac{1}{1 - \gamma} \right)^\beta - \frac{\beta\gamma + 1 - \gamma}{1 - \gamma} \right) \frac{\delta_0}{\beta\gamma - 1} > 0.^1$$

168 3 Subsidy

169 Denote the subsidy flow as $s(X_t, K, S_i)$, $i \in \{P, F\}$ for a given capacity level K and a subsidy rate parameter
 170 S_i . This flow can be implemented in the form of FIP. On the one hand it can be a flexible price support,
 171 where it is a proportional add-on to the market price, i.e. $s(X_t, K, S_P) = p_t(X_t)KS_P$. On the other hand
 172 it can be a fixed price support, where it is a fixed add-on to the market price, i.e. $s(X_t, K, S_F) = KS_F$.
 173 These types of subsidies have been predominantly used in European countries in the previous two decades
 174 in an attempt to encourage investment in renewables. The regulator can also subsidize through a lump sum
 175 transfer, which often reimburses part of the investment costs (a one-time remuneration transfer presented as
 176 a fraction of investment costs), i.e. $s(K, S_G) = S_G(\delta_0 + \delta_1 K)$. Here we analyze mainly the subsidy scheme
 177 that is applied in Italy, which is a fixed add-on S_F to the market price. This type of subsidy scheme is
 178 applied in several other countries as well².

¹The welfare difference can be treated as a function of γ . The first order derivative with respect to γ is positive. This expression is positive for $\gamma = 0$, so $\gamma > 0$ would also make it positive.

²As of 2017 16 European countries have provided support for renewables in the form of Feed-in-premiums (CEER, 2018; IRENA, 2018; IRENA, 2019)).

179 Subsidies can be implemented for two reasons. The first reason is to increase welfare. From this per-
 180 spective, in this section we first determine the subsidy level that changes the investment decision of a profit
 181 maximizing firm in such a way that welfare is increased as much as possible. We check whether the first-best
 182 solution is obtainable in this way, i.e. whether the obtained investment decision mimics the one that should
 183 be chosen by the social planner.

184 The second reason is to change the firm's investment behavior in such a way that a certain policy target
 185 is reached. Such a policy target implies that the firm should invest in a certain minimal capacity size within
 186 a certain time frame. Changing the firm's investment behavior has welfare consequences, which is the main
 187 topic of our study.

188 A policy target frequently results from an international agreement to solve or mitigate some environmental
 189 problem. Countries sign the corresponding contract and then have to incentivize firms to undertake the
 190 necessary investments. They can do so by implementing a subsidy. However, a firm is not obliged to invest,
 191 and will especially refrain from doing so if the demand realization is such that the process X stays below
 192 the threshold level. This can also happen even if a subsidy makes an investment more attractive. Therefore,
 193 despite offering a certain subsidy, a country could still fail to reach the policy target. If this happens, the
 194 country usually has to pay a fine. This section finally studies the implications of such a fine for subsidy
 195 implementation and resulting welfare consequences.

196 3.1 The welfare maximizing subsidy

197 As the firm maximizes profit and thus does not take into account the consumer surplus, the firm's investment
 198 generates an externality and does not lead to the first-best outcome. In an attempt to align the firm's
 199 investment with the social optimum, a regulator can implement a policy instrument with the aim that the
 200 firm internalizes this externality when undertaking the investment. To determine to what extent this is
 201 possible, we start out by presenting the two objective functionals of the firm and the regulator. Where the
 202 profit-maximizing firm has the objective to maximize the producer surplus:

$$\max_{T \geq 0, K \geq 0} \mathbb{E} \left[\int_{t=T}^{\infty} p(X_t, K) K \exp(-rt) dt - (\delta_0 + \delta_1 K) \exp(-rT) \middle| X_0 = X \right],$$

203 the regulator's objective is to maximize the sum of producer and consumer surplus, i.e.

$$\max_{T \geq 0, K \geq 0} \mathbb{E} \left[\int_{t=T}^{\infty} (p(X_t, K) K + cs(X_t, K)) \exp(-rt) dt - (\delta_0 + \delta_1 K) \exp(-rT) \middle| X_0 = X \right].$$

204 From these two expressions it follows that if a subsidy flow $s(X_t, K)$ satisfies $s(X_t, K) = cs(X_t, K)$ for all
 205 $t \in [T, \infty)$, it aligns the decisions of the social planner and the firm. The subsidy as such does not influence
 206 social welfare directly since it is added to the producer surplus and at the same time has to be deducted as
 207 subsidy costs. Instead the subsidy affects social welfare indirectly by influencing the timing and size of the
 208 investment of the profit-maximizing firm.

209 Let $\tilde{S}(X, K)$ be the expected discounted future subsidy transfer from government to firm, and $CS(X, K)$
 210 the expected consumer surplus. In order to align the firm's investment decision with the social optimum,
 211 the subsidy needs to be set such that the following conditions hold:

$$\begin{aligned} \tilde{S}(X_W^*, K_W^*) &= CS(X_W^*, K_W^*), \\ \frac{\partial \tilde{S}(X_W^*, K_W^*)}{\partial X} &= \frac{\partial CS(X_W^*, K_W^*)}{\partial X}, \end{aligned} \tag{7}$$

$$\frac{\partial \tilde{S}(X_W^*, K_W^*)}{\partial K} = \frac{\partial CS(X_W^*, K_W^*)}{\partial K}. \quad (8)$$

212 These conditions are straightforward in the sense that, to get to the same investment decision, the value
 213 matching and smooth pasting conditions, as well as the first order condition with respect to the investment
 214 size, need to be similar. It follows that if the subsidy can be set such that these three conditions hold, the
 215 investment decision of the profit maximizing firm results in the first-best welfare outcome.

216 Let the expected discounted producer surplus be $PS_F(X, K, S_F)$ for a given GBM level X and a capacity
 217 size K under the subsidy rate S_F . The firm's optimal investment decision is $(X^*(S_F), K^*(S_F))$. The
 218 corresponding social welfare is $W(X^*(S_F), K^*(S_F))$. If S_F makes the firm's optimal decision to be such that
 219 $(X^*(S_F), K^*(S_F)) = (X_W^*, K_W^*)$, then the subsidy scheme is optimal and denoted by S_F^* , which maximizes
 220 welfare $W(\cdot, \cdot)$.

221 We proceed by analyzing how the subsidy influences the firm's investment decision. If the regulator
 222 provides a subsidy rate S_F at the beginning of the firm's planning period the firm will take it into account
 223 when deciding about its investment. If the firm invests at GBM level X in capacity size K , and the subsidy
 224 is provided in the form of a fixed price support, the expected discounted producer surplus can be expressed
 225 as

$$PS_F(X, K) = \frac{XK^{1-\gamma}}{r - \mu} + \frac{S_F K}{r} - \delta_0 - \delta_1 K.$$

226 Maximizing $PS_F(X, K)$ with respect to K yields that the optimal capacity is given by

$$K(X, S_F) = \left(\frac{X(1-\gamma)}{(r-\mu)(\delta_1 - S_F/r)} \right)^{1/\gamma}.$$

227 The investment threshold for a given capacity size K and subsidy rate S_F is equal to

$$X(K, S_F) = \frac{\beta(r-\mu)(r\delta_0 + r\delta_1 K - S_F K)}{r(\beta-1)K^{1-\gamma}}.$$

228 Combining these two equations results in the following proposition.

Proposition 3 *When the subsidy flow is $s(X_t, K, S_F) = S_F K$, and provided that $S_F < r\delta_1^3$, the firm's optimal investment threshold $X^*(S_F)$ and corresponding investment capacity $K^*(S_F)$ are given by*

$$X^*(S_F) = \frac{r-\mu}{1-\gamma} \left(\delta_1 - \frac{S_F}{r} \right) \left(\frac{\delta_0 \beta (1-\gamma)}{(\delta_1 - S_F/r)(\beta\gamma - 1)} \right)^\gamma,$$

$$K^*(S_F) = \frac{\delta_0 \beta (1-\gamma)}{(\delta_1 - S_F/r)(\beta\gamma - 1)}.$$

229 In the previous section we had the same result but then for $S_F = 0$ (see Proposition 1). After comparing
 230 Propositions 1 and 2 we learned that, compared to the social optimum, in case of no subsidy the profit
 231 maximizing firm invests too late in the right capacity size. Proposition 3 shows that introducing a subsidy
 232 has two effects. On the one hand it speeds up the investment, which is thus a good thing from a welfare
 233 perspective. However, on the other hand it raises the investment size, which then grows beyond the socially
 234 optimal level.⁴ We conclude that implementing this subsidy S_F will never result in a first best solution, i.e.

³Note that S_F/r is the discounted marginal support from the government by investing one unit and δ_1 is the marginal cost of investing one unit. So $S_F/r < \delta_1$ implies that the firm incurs at least part of the marginal cost.

⁴Our results differ from Bigerna et al. (2019) where a subsidy leads to a firm investing earlier and in a smaller capacity. The difference is due to the difference in demand functions. Bigerna et al. (2019) has a linear inverse demand function of the form $p_t = X_t - \eta K$.

235 it will not align the firm's and the socially optimal investment decision. The intuition is that at the same
 236 time one instrument cannot steer two different investment dimensions, timing and size, such that *both* admit
 237 their socially optimal level.

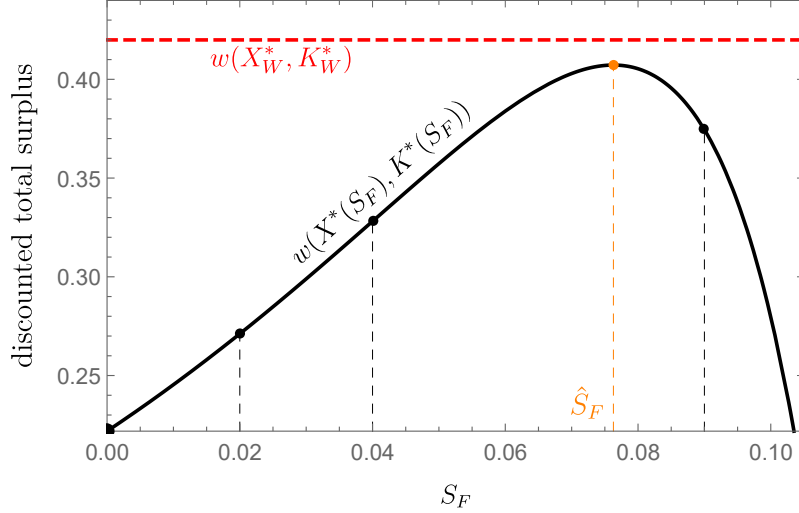


Figure 1: Illustration of the welfare as a function of subsidy rate S_F . Parameter values: $\mu = 0.015$, $r = 0.1$, $\sigma = 0.05$, $\gamma = 0.3$, $\delta_0 = 7.74$, $\delta_1 = 2.365$ and $X_0 = 0.25$.

238 Figure 1 depicts the social welfare $w(X^*(S_F), K^*(S_F))$, generated by the profit-maximizing investment
 239 decision, as a function of the subsidy rate S_F . The underlying parameter values for the numerical results
 240 and illustrations in this section are taken from the empirical analysis provided in Section 4. In particular,
 241 $w(X^*(S_F), K^*(S_F))$ stands for the expected stream of social welfare discounted to the initial point in time,
 242 where the GBM process admits the value X_0 . Therefore, $w(X^*(S_F), K^*(S_F))$ is equal to

$$w(X^*(S_F), K^*(S_F)) = \left(\frac{X_0}{X^*(S_F)} \right)^\beta W(X^*(S_F), K^*(S_F)),$$

243 and it reaches its maximum⁵ when the subsidy rate is equal to

$$\hat{S}_F = \frac{r\delta_1\beta\gamma}{\beta\gamma^2 + (\beta + 1)(1 - \gamma)}. \quad (9)$$

244 In Figure 1 this corresponds to $\hat{S}_F = 0.091$. At the same time, indeed the figure clearly shows that the first
 245 best solution, represented by the red dashed line, is out of reach.

246 Figure 2 depicts iso-welfare curves in the (X, K) plane. Every curve corresponds to a subsidy rate
 247 S_F and connects points (X, K) resulting in the same welfare level for investments taking place when the
 248 current GBM level is X and the investment size is K . One of these points, denoted by a large dot on the
 249 corresponding curve, is the optimal investment decision $(X^*(S_F), K^*(S_F))$ corresponding to this subsidy
 250 level. More specifically, for a given subsidy rate S_F , all the points on the corresponding iso-welfare curve

⁵ $w(\cdot, \cdot)$ is a convex function of S_F when $S_F < (r\delta_1(\beta\gamma + \gamma - 1))/(\beta\gamma^2 + (\beta + 1)(1 - \gamma))$ and concave otherwise. On the convex part, $w(\cdot, \cdot)$ increases with S_F , so that $w(\cdot, \cdot)$ will always admit its maximum value in the concave domain of S_F .

251 satisfy the following equation,⁶

$$\frac{XK^{1-\gamma}}{(r-\mu)(1-\gamma)} - \delta_0 - \delta_1 K - \left(\frac{X}{X^*(S_F)}\right)^\beta W(X^*(S_F), K^*(S_F)) = 0.$$

252 A curve represents a higher total surplus if it is closer to the red node (X_W^*, K_W^*) , which represents the
 253 socially optimal decision. Note that in Figure 2, $(X^*(0), K^*(0))$ and (X_W^*, K_W^*) are on the same horizontal
 254 level, confirming that the firm installs the socially optimal capacity size when $S_F = 0$. As S_F gradually
 255 increases, $K^*(S_F)$ increases and therewith, deviates from the socially optimal capacity size K_W^* , while at the
 256 same time the optimal investment threshold $X^*(S_F)$ gets closer to the socially optimal investment threshold
 257 X_W^* . Along the welfare dimension the combination $(X^*(S_F), K^*(S_F))$ is getting closer to the socially optimal
 258 point (X_W^*, K_W^*) for increasing S_F up until \hat{S}_F . As S_F continues to increase from \hat{S}_F on, $(X^*(S_F), K^*(S_F))$
 259 gets further away from (X_W^*, K_W^*) , implying a decrease in the generated social welfare.

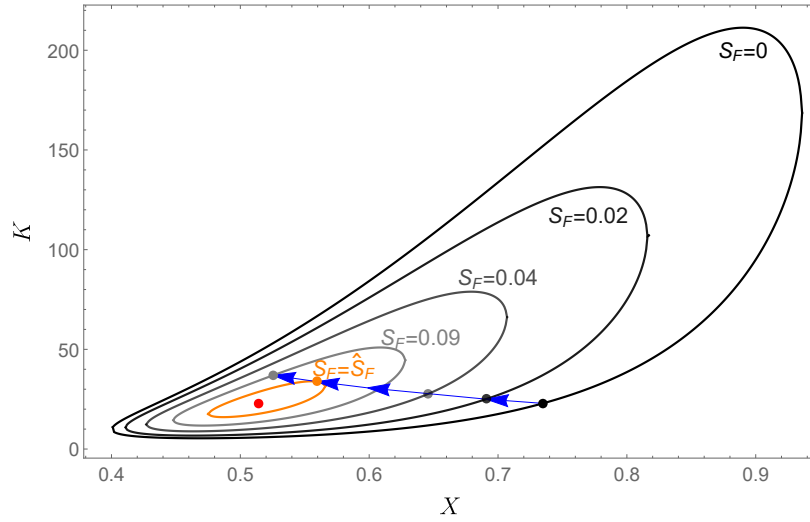


Figure 2: Illustration of the iso-welfare as a function of the subsidy rate S_F for the set of parameter values: $\mu = 0.015$, $r = 0.1$, $\sigma = 0.05$, $\gamma = 0.3$, $\delta_0 = 7.74$ and $\delta_1 = 2.365$.

260 Finally, let us do some comparative statics analysis, where we depart from the situation that we want
 261 to keep the investment size K fixed. This is relevant if a certain investment target needs to be reached.
 262 Consider an increase of the uncertainty parameter σ . From Proposition 3 we learn that, given the subsidy
 263 level, it raises K^* . This implies that an increase of σ has to be accompanied by a reduction in the subsidy
 264 level S_F to keep the investment size K^* at the same level. The increase of σ then has two effects on the
 265 investment threshold $X^*(S_F)$. First there is a *direct effect*, indicating that an increase of σ raises $X^*(S_F)$.
 266 Second there is an *indirect effect*, representing the mechanism that an increase of σ is accompanied by a
 267 decrease in S_F , where the latter also raises X^* . We conclude that in case of the uncertainty parameter σ
 268 both the direct and the indirect effect result in an increase of X^* , implying that the investment will be
 269 delayed. The following corollary gives a complete overview of the comparative statics results.

270 **Corollary 1** *For an increase in the market uncertainty σ and the fixed investment cost δ_0 , $X^*(S_F)$ increases*
 271 *under both the direct effect and the indirect effect, so the investment is delayed. For changes in the market*

⁶On an iso-welfare curve, the welfare generated by any point is compared at a reference time that corresponds to the GBM level $X^*(S_F)$.

272 trend μ and the discount rate r , the influence of the direct effect is not straightforward, which also holds for
 273 the total effect.

274 3.2 The subsidy and the policy target

275 The regulator is considered to apply a subsidy policy while taking into account that there exists a policy
 276 target regarding investment. In particular, the policy target involves installing a minimally desired level
 277 of investment capacity \bar{K} within a designated period of time from $t = 0$ to \bar{T} . In case the target is not
 278 reached in time, a penalty, say a monetary transfer of C , is levied on the regulator. For instance, in 2014
 279 the EU brought a case against Ireland for failing to fully implement the 2009 Renewable Energy Directive,
 280 recommending a penalty payment of €25,445.505 for each day that Ireland had not fully implemented the
 281 directive.⁷ Although the subsidy is intended to be there to reach the target, still it will have its own welfare
 282 implications. The latter also holds for the target itself. Below we establish these welfare effects.

283 Let us depart from the reasonable scenario that $\bar{K} > K_F^* = K_W^*$, i.e. the international treaty requires a
 284 larger investment than that the firm or the social planner would undertake by itself. From Proposition 3 we
 285 obtain that the subsidy level needed to incentivize the firm to invest in a capacity of size \bar{K} , is equal to

$$S_F(\bar{K}) = r\delta_1 - \frac{r\delta_0\beta(1-\gamma)}{\bar{K}(\beta\gamma-1)}, \quad (10)$$

286 whereas the corresponding investment threshold level is given by

$$X(\bar{K}) := X(\bar{K}, S_F(\bar{K})) = \frac{\beta(r-\mu)}{\bar{K}^{1-\gamma}(\beta-1)} \left(\delta_0 + \delta_1\bar{K} - \frac{S_F(\bar{K})\bar{K}}{r} \right) = \frac{\beta\delta_0(r-\mu)}{(\beta\gamma-1)\bar{K}^{1-\gamma}}. \quad (11)$$

287 Note that this investment threshold decreases with the capacity policy target \bar{K} . To explain this result, we
 288 have to recognize that there is a direct and an indirect effect. The *direct effect* is known from the literature
 289 (e.g. Dangl (1999) or Huisman and Kort (2015)) indicating that for a larger investment to be optimal, better
 290 market conditions are needed, which translates in the investment threshold to be higher. The *indirect effect*
 291 is due to the subsidy rate S_F , which, according to (10), increases with the capacity target \bar{K} , and, therefore,
 292 makes a larger investment relatively cheaper for the firm. This reduces the investment threshold $X(\bar{K})$. Our
 293 result in (11) shows that the *indirect effect* dominates the *direct effect*. The fact that a larger capacity \bar{K}
 294 corresponds to a smaller investment threshold is thus contradictory to the standard real options literature.

295 The policy target also involves that the investment should take place before a certain time \bar{T} . We know
 296 that the investment time is time $\bar{\tau}$, where $\bar{\tau} := \inf\{t \geq 0 | x_t \geq X(\bar{K})\}$, implying that $\bar{\tau}$ is stochastic. The
 297 policy target is thus reached when $\bar{\tau} \leq \bar{T}$, in which case the subsidy policy works as planned and a capacity
 298 size \bar{K} is installed in time. In the other case, thus when $\bar{\tau} > \bar{T}$, however, the necessary investment is not
 299 undertaken in time, implying that the regulator faces a penalty.

Until now we analyzed a subsidy level exactly corresponding to an investment of size \bar{K} . However, the
 regulator has an alternative in announcing a higher subsidy rate. This results in the firm investing more, so
 that still the target is reached upon investment, but also earlier, as our above equation (11) learns. Hence,
 the advantage of a subsidy rate being higher is that the probability goes up that the investment policy
 target is reached in time. Denoting the investment time by τ^* , so that $\tau^* := \inf\{t \geq 0 | x_t \geq X^*(S_F)\}$, this
 probability can be expressed as

$$\text{Prob}(\tau^* \leq \bar{T}) = \phi \left(\frac{-\ln \left(\frac{X^*(S_F)}{X_0} \right) + (\mu - \frac{1}{2}\sigma^2)\bar{T}}{\sigma\sqrt{\bar{T}}} \right)$$

⁷https://ec.europa.eu/commission/presscorner/detail/en/IP_14_44.

$$+ \left(\frac{X^*(S_F)}{X_0} \right)^{2\frac{\mu}{\sigma}-1} \phi \left(\frac{-\ln \left(\frac{X^*(S_F)}{X_0} \right) - (\mu - \frac{1}{2}\sigma^2)\bar{T}}{\sigma\sqrt{\bar{T}}} \right),$$

where $\phi(\cdot)$ denotes the cumulative distribution function of a standard normal random variable.

In deciding about the subsidy rate, not only the probability of reaching the policy target is an important input, but also the effect on welfare should be taken into account. Taking a welfare perspective, we learned from the previous section that without a subsidy the firm is too late in investing in the right size. Then a gradual increase of the subsidy rate makes the firm investing earlier in a larger capacity, where the latter is thus bad for welfare. The fact that it accelerates the investment timing has a positive welfare effect as long as $X^*(S_F) \geq X^*(\hat{S}_F)$.

To quantify the effects of the policy target (\bar{K}, \bar{T}) and the subsidy rate S_F on welfare, we first define a welfare function denoted by $\text{WPT}(S_F, \bar{K}, \bar{T})$, where WPT stands for "the expected Welfare corresponding to the Policy Target". This function can be expressed as

$$\text{WPT}(S_F, \bar{K}, \bar{T}) = \begin{cases} \text{Prob}(\tau^* \leq \bar{T}, X^*(S_F)) \left(\frac{X_0}{X^*(S_F)} \right)^\beta W(X^*(S_F), K^*(S_F)) & \text{if } X^*(S_F) > X_0 \text{ and } K^*(S_F) < \bar{K}, \\ -e^{-r\bar{T}}C, & \\ \text{Prob}(\tau^* \leq \bar{T}, X^*(S_F)) \left(\frac{X_0}{X^*(S_F)} \right)^\beta W(X^*(S_F), K^*(S_F)) & \text{if } X^*(S_F) > X_0 \text{ and } K^*(S_F) \geq \bar{K}, \\ - (1 - \text{Prob}(\tau^* \leq \bar{T}, X^*(S_F))) e^{-r\bar{T}}C, & \\ \frac{X_0 K^{1-\gamma}(X_0, S_F)}{(1-\gamma)(r-\mu)} - \delta_0 - \delta_1 K(X_0, S_F) - e^{-r\bar{T}}C, & \text{if } X^*(S_F) \leq X_0 \text{ and } K(X_0, S_F) < \bar{K}, \\ \frac{X_0 K^{1-\gamma}(X_0, S_F)}{(1-\gamma)(r-\mu)} - \delta_0 - \delta_1 K(X_0, S_F), & \text{if } X^*(S_F) \leq X_0 \text{ and } K(X_0, S_F) \geq \bar{K}. \end{cases} \quad (12)$$

Equation (12) distinguishes that essentially four different outcomes are possible, depending on whether the current demand is such that immediate investment is optimal, and whether the resulting optimal investment size for the given subsidy is large enough to satisfy the capacity target \bar{K} . If immediate investment is not optimal, i.e. $X^*(S_F) > X_0$, we distinguish two cases. First, if the resulting investment size is smaller than the capacity target, the penalty needs to be paid anyhow. Then the WPT is equal to the welfare resulting from the capacity investment if the firm invests before time \bar{T} , minus the imposed penalty at time \bar{T} .

Second, if the resulting investment size is sufficiently high, i.e. $K^*(S_F) \geq \bar{K}$, the penalty only needs to be paid if the investment does not take place before time \bar{T} . It follows that the WPT is equal to the welfare resulting from installing capacity size $K^*(S_F)$ multiplied by the probability that the investment threshold is reached in time, minus the cost of the penalty times the probability that the investment threshold is not reached in time.

If it is optimal for the firm to invest immediately, i.e. $X^*(S_F) \leq X_0$, we also have to distinguish two cases depending on whether the installed capacity size at $t = 0$, i.e. $K(X_0, S_F)$, is sufficient to reach the capacity target. If the capacity size is not sufficient, the WPT is equal to the welfare resulting from immediate investment in capacity $K(X_0, S_F)$ reduced by the penalty incurred at the policy deadline \bar{T} . In case the capacity installed is large enough, the WPT is just equal to the welfare resulting from immediate investment in capacity $K(X_0, S_F)$.

A higher subsidy rate results in the firm investing more but also earlier. It follows that in the initial situation the firm will only invest immediately if the subsidy rate is large enough. In both situations the subsidy needs to be large enough for the investment size to exceed the capacity target. Hence, for the subsidy rate four different regions could possibly exist that are associated with the four different expressions of $\text{WPT}(S_F, \bar{K}, \bar{T})$ in equation (12). In particular we have

- 329 Case 1: $S_F < S_F^{1,2}$: $X^*(S_F) > X_0$ and $K^*(S_F) < \bar{K}$,
- 330 Case 2: $S_F^{1,2} \leq S_F < S_F^{2,3}$: $X^*(S_F) > X_0$ and $K^*(S_F) \geq \bar{K}$,
- 331 Case 3: $S_F^{2,3} \leq S_F < S_F^{3,4}$: $X^*(S_F) \leq X_0$ and $K^*(S_F) < \bar{K}$,
- 332 Case 4: $S_F \geq S_F^{3,4}$: $X^*(S_F) \leq X_0$ and $K^*(S_F) \geq \bar{K}$,

in which

$$\begin{aligned} S_F^{1,2}(\bar{K}) &= r\delta_1 - \frac{r\delta_0\beta(1-\gamma)}{(\beta\gamma-1)\bar{K}}, \\ S_F^{2,3} &= r\delta_1 - \frac{r\beta\delta_0(1-\gamma)}{\beta\gamma-1} \left(\frac{X_0(\beta\gamma-1)}{\delta_0\beta(r-\mu)} \right)^{\frac{1}{1-\gamma}}, \\ S_F^{3,4}(\bar{K}) &= r\delta_1 - \frac{rX_0(1-\gamma)}{(r-\mu)\bar{K}^\gamma}. \end{aligned}$$

333 However, not all four cases can occur within the same scenario. To see this define the capacity level⁸

$$\tilde{K} = \frac{1}{r} \left(\frac{\delta_0\beta(r-\mu)}{X_0(\beta\gamma-1)} \right)^{\frac{1}{1-\gamma}}.$$

Straightforward calculations reveal that for a capacity target level $\bar{K} = \tilde{K}$, it holds that $S_F^{1,2} = S_F^{2,3} = S_F^{3,4}$, and thus

$$\begin{aligned} S_F < S_F^{1,2} &: X^*(S_F) > X_0, K^*(S_F) < \bar{K}, \\ S_F = S_F^{1,2} &: X^*(S_F^{2,3}) = X_0, K^*(S_F^{2,3}) = \bar{K}, \\ S_F > S_F^{1,2} &: X^*(S_F) < X_0, K^*(S_F) > \bar{K}. \end{aligned}$$

If the capacity target is relatively small, i.e. $\bar{K} < \tilde{K}$, it follows that $S_F^{1,2} < S_F^{3,4} < S_F^{2,3}$, implying

$$\begin{aligned} S_F < S_F^{1,2} &: X^*(S_F) > X_0, K^*(S_F) < \bar{K}, \\ S_F^{1,2} \leq S_F < S_F^{3,4} &: X^*(S_F) \geq X_0, K^*(S_F) \geq \bar{K}, \\ S_F^{3,4} \leq S_F &: X^*(S_F) \leq X_0, K^*(S_F) \geq \bar{K}. \end{aligned} \tag{13}$$

Finally, if the capacity target is relatively large, $\bar{K} > \tilde{K}$, we get that $S_F^{1,2} > S_F^{3,4} > S_F^{2,3}$, which results into

$$\begin{aligned} S_F < S_F^{2,3} &: X^*(S_F) > X_0, K^*(S_F) < \bar{K}, \\ S_F^{2,3} \leq S_F < S_F^{3,4} &: X^*(S_F) \leq X_0, K^*(S_F) < \bar{K}, \\ S_F^{3,4} \leq S_F &: X^*(S_F) \leq X_0, K^*(S_F) \geq \bar{K}. \end{aligned}$$

334 This is all summarized in Figure 3a.

335 For a given policy target, specified by the capacity size \bar{K} and the deadline \bar{T} , the regulator has to set
 336 the subsidy rate \bar{S}_F to maximize the expected social welfare WPT. Let us take, for example, $\bar{K} = 40$ for
 337 which it holds that $\bar{K} = 40 < \tilde{K} = 106.8$. This implies that the capacity target is relatively small so that
 338 we are in scenario (13), as confirmed in Figure 3a. This example with $\bar{K} = 40$ is illustrated in Figure 3b,
 339 where three different social welfare as functions of the subsidy rate S_F are demonstrated: the expected social

⁸When $X_0 < \frac{\beta\delta_0(r-\mu)}{\beta\gamma-1} \left(\frac{\delta_1(\beta\gamma-1)}{\beta\delta_0(1-\gamma)} \right)^{1-\gamma}$, it holds that $\tilde{K} > K_W^*$; Otherwise, it holds that $\tilde{K} \leq K_W^*$.

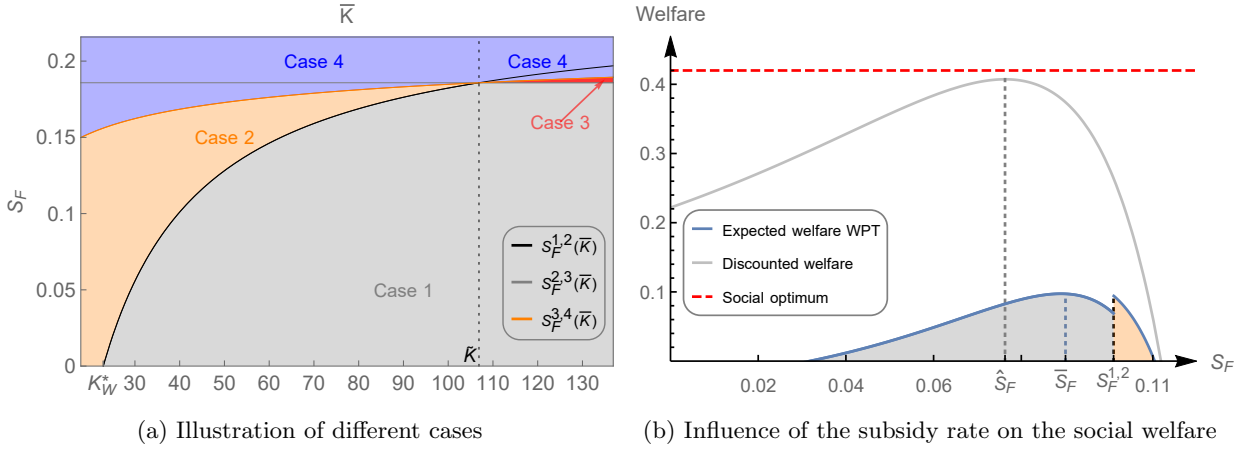


Figure 3: Illustration of different cases and the welfare function. The parameter values are $\mu = 0.015$, $r = 0.1$, $\sigma = 0.05$, $\gamma = 0.3$, $\delta_0 = 7.74$, $\delta_1 = 2.365$ and $C = 2$. It is assumed that $X_0 = 0.25$ and $T = (2030 - 2018) \times 4 = 48$.

welfare WPT, the discounted welfare generated by subsidy from the previous section thus ignoring the policy
 deadline and without the fine C , i.e., $\left(\frac{X_0}{X^*(S_F)}\right)^\beta W(X^*(S_F), K^*(S_F))$, and the socially optimal welfare, i.e.
 $\left(\frac{X_0}{X^*_W}\right)^\beta W(X^*_W, K^*_W)$.

It turns out that immediate investment in a large capacity, $K^*(S_F) \geq \bar{K}$, is not profitable (for $S_F^{3,4} = 0.168$
 the corresponding WPT is negative), so this implies that the welfare maximizing subsidy rate is either Case
 1 or Case 2. This means that investment will not take place immediately. Only when the subsidy is large
 enough the investment size will be such that $K \geq \bar{K}$. The result is that WPT is maximized by setting a
 subsidy level $\bar{S}_F < S_F^{1,2}$, so that we are in Case 1. It follows that, even when the firm invests in time, still
 the policy target is not reached, because $K^*(\bar{S}_F) < \bar{K}$. Hence, it will always be the case that the penalty
 has to be paid. Apparently the fine C is not big enough to avoid this outcome.

Note that, when ignoring the policy target, the optimal fine would be smaller, i.e. $\hat{S}_F < \bar{S}_F$. This is
 because in the WPT only investments before the policy deadline \bar{T} are counted. Therefore, there is additional
 stimulus for the firm to invest sooner, which explains the higher subsidy level.

4 Empirical estimation for the 2030 EU policy: The case of Italy

We conduct an empirical analysis to study the policy for renewable energy sources (RES) of Italy, in light of
 the new EU target for the year 2030. We use official data from the International Energy Agency (IAE, 2018),
 the International Renewable Energy Agency (IRENA, 2018), the Italian Government (Italian Government,
 2018 and 2019) and other technical relevant sources referenced below.

This section is organized as follows. First, we estimate the model parameters, and then we do the
 simulations.

4.1 Parameter estimation

The policy strategy of Italy is to design measures for the electricity sector focusing on the support of
 construction of new plants and revamping of existing ones, also with specific incentives. The typical FIP,

363 which depends on size and type and vintage according to the Italian regulatory framework, can be estimated
364 on average to be around 8-10% of the electricity market price in 2017. According to the 2030 EU target, the
365 share of energy from renewable sources in gross final consumption of energy in 2030 should increase from
366 17.4% in 2016 to 30% in 2030, which implies a 55.4% RES share in the electricity sector. RES capacity is
367 expected to grow up to 93.2 GW in 2030, with almost 40 additional GW compared to the level of 53.2 in
368 2017.

369 The investment cost worldwide ranges between 0.9 and 6 USD/W in the present period. This depends on
370 the location and the technology. With respect to the latter it is known that PV and on shore wind are less
371 costly, while concentrated solar and off-shore wind are more costly (IEA, 2018 and IRENA, 2018). For our
372 calculations we take a prudent value of 2.51 USD/W (Table 1), which is consistent with the new indicator
373 released by the International Energy Agency (2019), the value-adjusted levelized cost of energy (VALCOE)
374 that is in the range of 150-160 USD/MWh (IEA, 2018 and EEA, 2017).

	Cost USD/W	Average plant size MW	Capacity investment per year GW	Price elasticity
world range	0.9–6	3–64	85	-0.3 – -0.05
United States	1.64	11.2	15	-0.11
Asia	1.41	22.5	45	-0.09
Europe	2.51	25	20	-0.20

Table 1: Main economic variables for the calibration of the demand parameters (2017-2018). Sources: own computations based on data from IRENA (2018), Elshurafa et al. (2018), Eurostat (2018), and Ilas et al. (2018).

375 We know that the current total capacity installed in Italy is 53.2 GW in 2018. Departing from the
376 currently estimated investment cost in 2018 (2.51 USD/W), we can estimate the value of the existing capacity
377 in 2018 to amount to 133.6 billion USD ($133.6 = 2.512 \times 10^9 \times 53.2$).

378 We define the units as follows. We assume that p is expressed in USD /KWh and K is expressed in
379 GW, so that the policy target corresponds to $\bar{K} = 40$ GW. We use a unit conversion factor from GW to
380 KW (10^{-6}) to maintain coherence in the units of measurement. In order to calibrate the parameter of the
381 demand function for Italy we take that $p_t = X_t K_t^{-\gamma}$ and use $\gamma = .3$, which is an elasticity consistent with
382 the range in Table 1 and with previous findings for Italy (Elshurafa et al., 2018; Bigerna et al., 2019). In this
383 way, from the above formula with the data available in 2018 for the unit energy price, 0.0759 USD/KWh,
384 we get that $0.0759 = X_0 \times 53.2^{-0.3}$, i.e., $X_0 = 0.25$.

385 The investment cost function per GW is calibrated in the initial year 2018, using the estimated value
386 of the existing capacity (133.6 billion USD), and using engineering and other costs (Ilas et al., 2018) as a
387 proxy for the fixed component δ_0 . To do so, we estimate the fixed component at about 5.8% of the total
388 cost (value taken from the report IRENA (2012)). Then we obtain that $\delta_0 = 7.74$ and $\delta_1 = 2.365$, i.e.
389 $133.6 = 7.74 + 2.365 \times 53.2$.

390 Concerning the discount rate, we use the computation of the Italian Industry Association published in a
391 White book on renewable investment to 2030. Knowing that the so called balance-of-system costs (technical
392 installation, administrative and bureaucratic costs) are relevant in Italy (Andreuzzi et al., 2017), we get to
393 a value for the discount rate $r = 10\%$. The parameters for the simulations are summarized in Table 2.

394 Straightforward calculations learn that the firm's and the socially optimal investment decisions without
395 subsidy correspond to investment thresholds of $X_F^* = 0.735$, $X_W^* = 0.514$, and capacity size $K_F^* = K_W^* =$

r	μ	σ	δ_0	δ_1	γ	K_0	X_0
0.1	0.015	0.05	7.74	2.365	0.30	53.2	0.25

Table 2: Estimation of parameter values in 2017 for the EU 28 member states. Sources: own computations based on data from Elshurafa et al. (2018), Eurostat (2018), Ilas et al. (2018), and Andreuzzi et al. (2017).

396 22.91 GW. Hence, to reach the political target of $\bar{K} = 40$ GW, a subsidy policy is necessary to incentivize
397 the firm to invest more. The target of 40 GW can be reached with a subsidy of about $S_F = 0.101$, which is
398 about 4% of the price ($0.101/2.512$). Based on the European Commission (2019) report, a rough estimation
399 of the subsidies in 2017 is that S_F is around 10% of the price, and also for Italy it is around 8-10%.

400 However, the policy target is not only about size but also about timing: the required investment should
401 be undertaken before 2030. In that respect, the previous section has shown that a higher subsidy not only
402 increases the size of the investment but also accelerates it, which thus raises the probability of reaching the
403 target in time. We conclude that it could be optimal to have a subsidy larger than $S_F = 0.101$. This is
404 taken into account in Sections 4.2 and 5.

405 4.2 Model simulation 2018-2030

406 We simulate the model for the 2018-2030 period to investigate the probability of reaching the 2030 target.
407 The simulation of the geometric Brownian motion is carried out with 10000 replications.

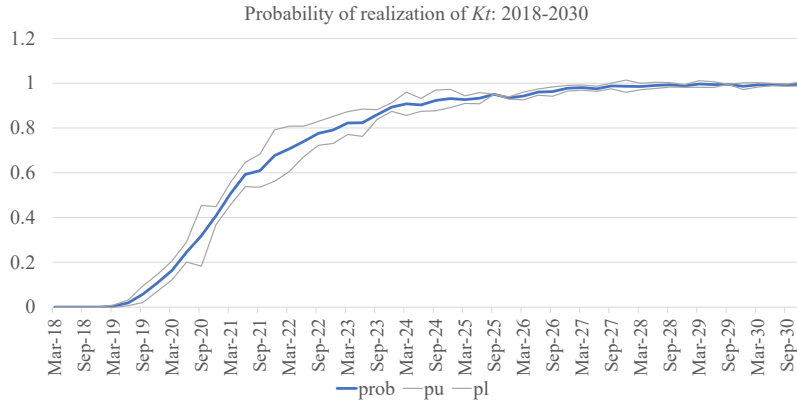


Figure 4: Probability of realization of K_t over the period of 2018-2030.

408 Figure 4 illustrates the average probability that the investment threshold has been reached. As we know,
409 the capacity is equal to the target $\bar{K} = 40$ GW, which corresponds to a subsidy level $S_F = 0.101$, and the
410 investment threshold equals $X^*(S_F) = 0.497$. Figure 4 also includes error bands pu (upper) and pl (lower)
411 of two standard deviations.⁹ We determine for each simulation $j \in [1, 10000]$ the value $X_{t,j}$. As long as $X_{t,j}$
412 stays below $X^*(S_F)$ the firm does not invest so that $K_{t,j} = 0$. As soon as $X_{t,j}$ hits $X^*(S_F)$ from below, the
413 firm invests and $K_{t,j} = \bar{K}$ from that moment on. We then average $K_{t,j}$, $t \in [\text{March 2018}, \text{December 2030}]$,
414 over all 10000 simulations. The result is that the sample probability of reaching the target \bar{K} is approximately
415 95% at the end of 2029 and 100% at the end of 2030.

⁹The error bands are empirical confidence intervals of 95% of the probability mass of a normal distribution. It relies on the idea of large numbers, given that we make 10000 simulations.

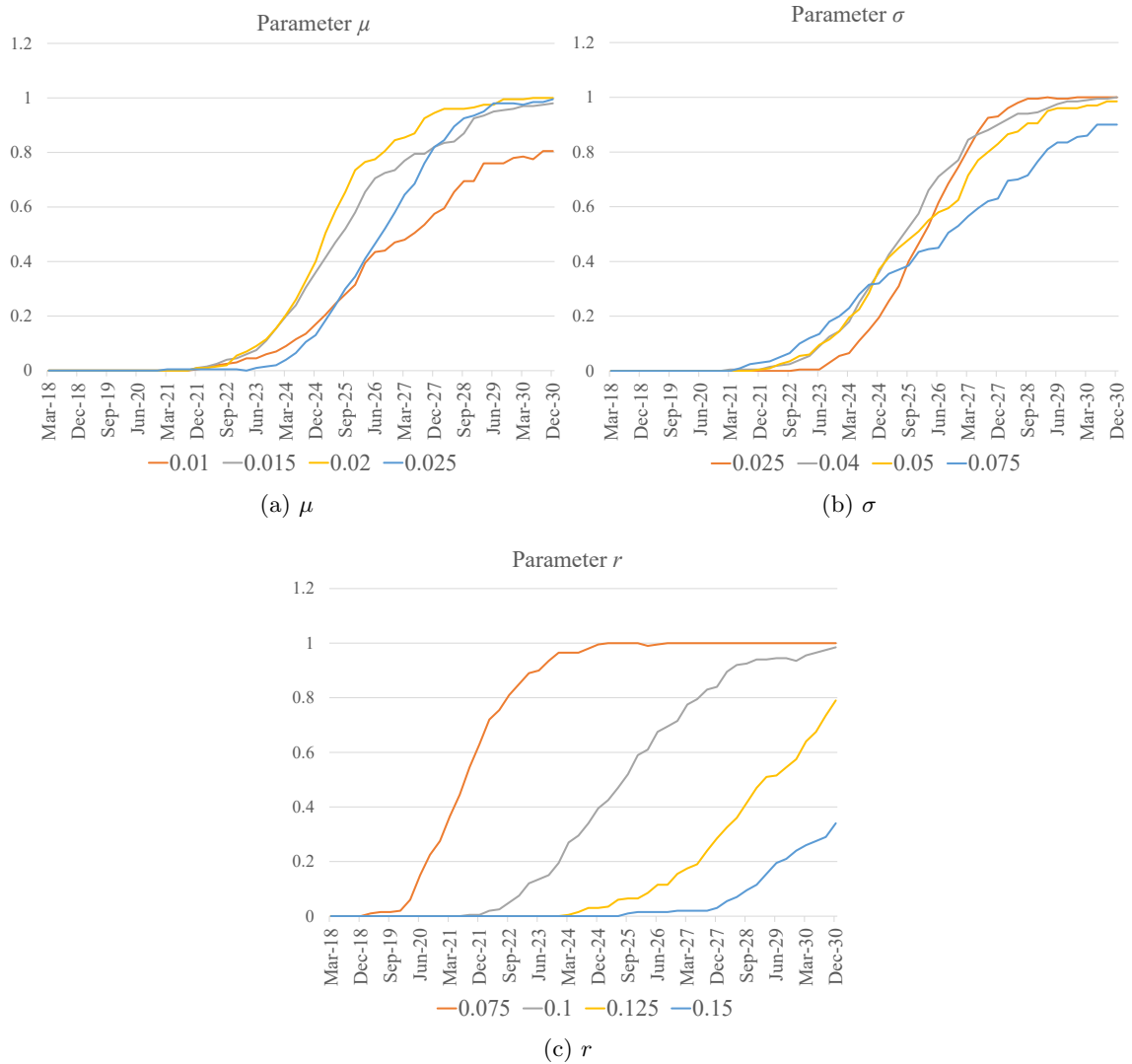


Figure 5: Sensitivity analysis for parameter changes in μ , σ and r influencing the probability of realization.

416 We perform a sensitivity analysis of the parameters μ , σ and r , and take four different values for each
 417 of them. The other parameter values are the ones reported in Table 2. Concerning the GBM trend μ it
 418 can be concluded from Figure 5a that for three out of four values it is almost sure that the policy target is
 419 reached in time. Only when $\mu = 0.01$, which is the lowest considered value, there is a 20% probability that
 420 the target will not be fulfilled. In such a situation a raise of the subsidy rate may be desirable so that the
 421 firm is incentivized to invest earlier.

422 We know from standard real options analysis (e.g. Dixit and Pindyck (1994)) that a more uncertain
 423 economic environment delays investment. This explains that Figure 5b shows that for a high uncertainty
 424 parameter value, i.e. $\sigma = 0.075$, the probability that the policy target will be reached stays relatively far
 425 from the 100% level. We conclude that more uncertainty could make that a higher subsidy is needed to
 426 tempt the firm to undertake the necessary investment earlier.

427 A low discount rate goes along with a large net present value of the firm's investment. This is the reason
 428 why for higher values of r the probability that the policy target is reached can be quite low (see Figure 5c).

429 For such cases an increase of the subsidy rate can still incentivize the firm to invest in time.

430 5 Comparative Statics Analysis: the Policy Target and the Sub- 431 subsidy Type

432 The policy target consists of three parameters, which we consecutively analyze in this section. We start out
433 with the deadline \bar{T} , then followed by the required investment size \bar{K} and the penalty C , respectively. The
434 section finishes off by considering other subsidy types than the fixed price support S_F .

435 5.1 The deadline \bar{T}

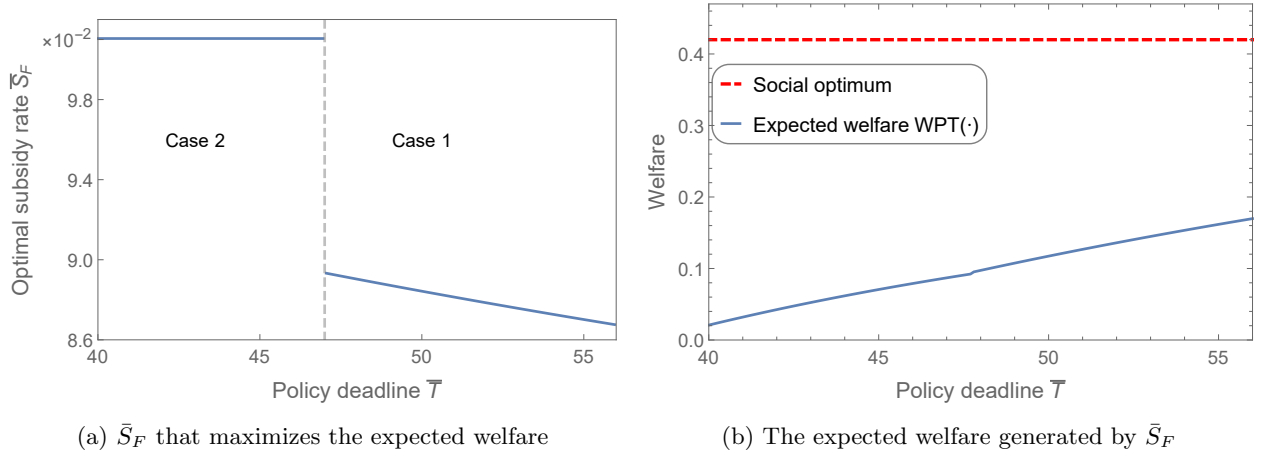


Figure 6: Influence of the policy deadline adjustment on the optimal subsidy rate \bar{S}_F and the corresponding expected social welfare. The parameter values are $\mu = 0.015$, $r = 0.1$, $\sigma = 0.05$, $\gamma = 0.3$, $\delta_0 = 7.74$, $\delta_1 = 2.365$ and $C = 2$. It is assumed that $X_0 = 0.25$ and $\bar{K} = 40$.

436 Figure 6a shows how the optimal subsidy rate depends on the policy deadline \bar{T} . From Figure 3b we already
437 know that either Case 1 or Case 2 applies, i.e. in any case there is no immediate investment. If the policy
438 deadline is sufficiently tight, $\bar{T} \leq 47$, the optimal subsidy is a constant subsidy level exactly corresponding
439 to an investment of size \bar{K} . This implies that it is given by expression (10) and equals $S_F(\bar{K}) = 0.101$ for
440 the parameter values of Table 2.

441 When $\bar{T} \geq 48$ the policy deadline lies far in the future, so that, whenever a penalty needs to be paid, the
442 corresponding discounted cost is less. Therefore, it is less important for the regulator to reach the target.
443 The regulator prefers to set a subsidy level such that it corresponds to an investment size lower than the
444 target \bar{K} , which is closer to the unconstrained welfare maximizing investment size K_F , and leads to larger
445 welfare as shown in Figure 6b. The implication is that, independent of whether the investment will take
446 place before the deadline \bar{T} or not, the country has to pay the penalty in any case.

447 Figure 6a also shows that the subsidy level is decreasing when the deadline becomes less tight. The
448 reason is that in the WPT the investment payoff only counts when the investment takes place before the
449 deadline is over. A larger subsidy rate accelerates investment and therefore subsidy is large for small \bar{T} in
450 this domain.

451 5.2 The Capacity Target \bar{K}

452 Setting a subsidy accelerates investment, which is good for welfare, because without a subsidy the firm
 453 invests too late from a welfare perspective. Without a policy target the optimal subsidy rate is given by (9).
 454 With a policy target of $\bar{K} = 40$ there is an additional incentive to accelerate investment, leading to a higher
 455 subsidy rate than (9) as illustrated in Figure 3b.

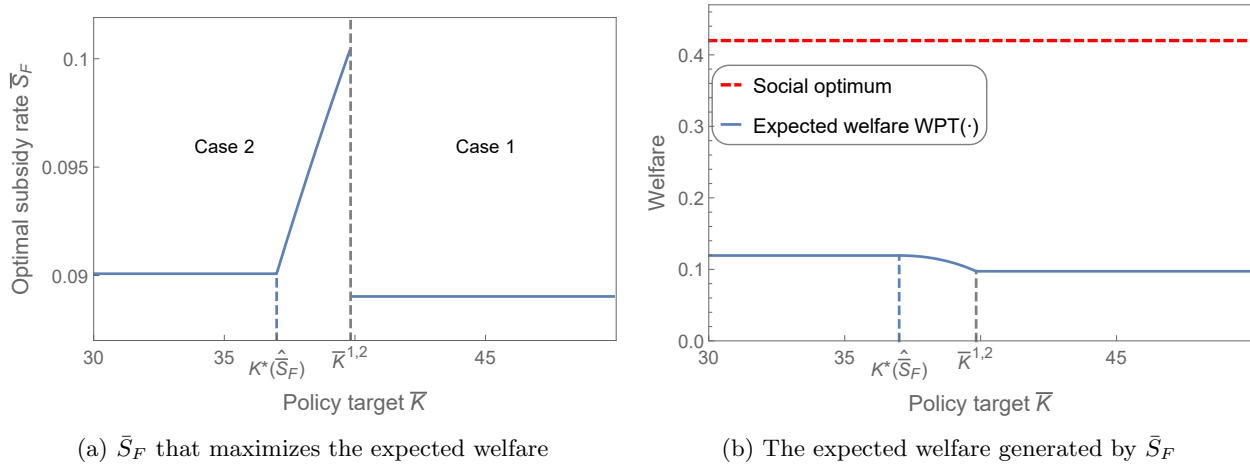


Figure 7: Influence of policy capacity target adjustment on the optimal subsidy rate \bar{S}_F and the corresponding expected social welfare. The parameter values are $\mu = 0.015$, $r = 0.1$, $\sigma = 0.05$, $\gamma = 0.3$, $\delta_0 = 7.74$, $\delta_1 = 2.365$ and $C = 2$. It is assumed that $X_0 = 0.25$ and $\bar{T} = 48$.

456 Figure 7a shows that for low target levels the subsidy level is constant, say \hat{S}_F , which, via (10), corresponds
 457 to $K^*(\hat{S}_F)$. As long as the target level remains below $K^*(\hat{S}_F)$, the penalty does not need to be paid upon
 458 investment. When the target level raises beyond the level $K^*(\hat{S}_F)$ the corresponding subsidy is increasing
 459 too, and well in such a way that the firm invests exactly the amount corresponding to the target level. In
 460 other words, the subsidy increases with \bar{K} such that expression (10) is satisfied.

461 If the target level increases beyond a level denoted by $\bar{K}^{1,2}$, the required capacity size deviates too much
 462 from the unconstrained socially optimal level K_F . Consequently, for a target level $\bar{K} > \bar{K}^{1,2}$ the regulator
 463 gives up reaching the target. In particular, it sets the subsidy at a lower level but still higher than the
 464 unconstrained level (9), because there is an incentive to speed up firm investment, due to the fact that the
 465 investment payoff only counts for WPT if the investment takes place before the policy deadline. The firm's
 466 investment size is such that it is lower than the policy target level \bar{K} . It follows that the regulator for sure
 467 knows it has to pay the penalty at the deadline \bar{T} , even if the investment takes place before this time.

468 In Figure 7b the corresponding welfare levels are depicted. For $\bar{K} \leq K^*(\hat{S}_F)$ the subsidy as well as the
 469 firm's investment decision and also the probability of reaching the policy target are constant, which then
 470 also holds for WPT. In the capacity target domain $(K^*(\hat{S}_F), \bar{K}^{1,2})$ satisfying the policy target requires the
 471 firm to invest in a capacity level that deviates more and more from the socially optimal level. Consequently,
 472 WPT decreases. For a policy target even larger, subsidy is constant and set at a relatively low level, and
 473 the resulting firm's investment decision remains constant there. This then also holds for the resulting WPT
 474 that is diminished by the penalty to be paid at the policy deadline. As a result, Figure 7b depicts that social
 475 welfare can be damaged by an increasing capacity target level.

476 **5.3 The Penalty C**

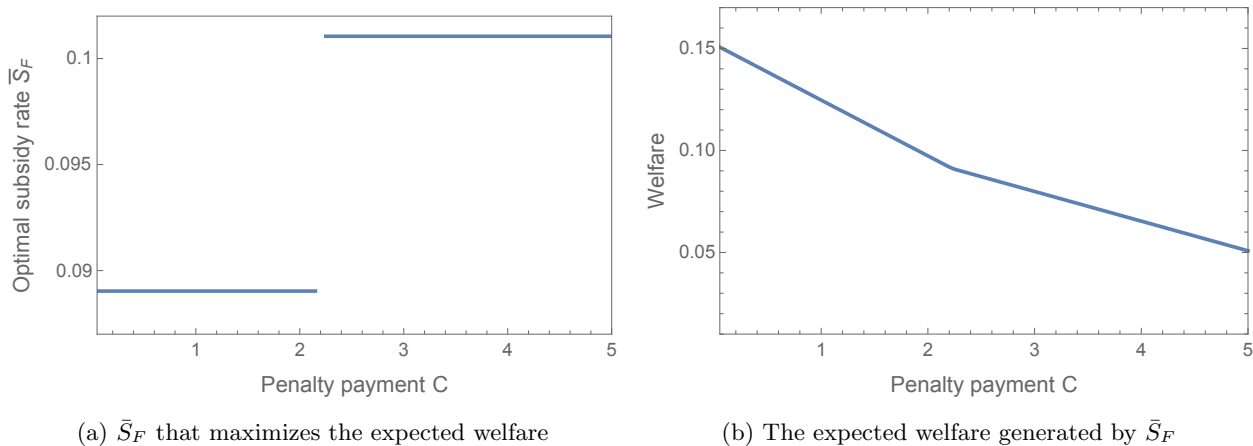


Figure 8: Influence of the penalty punishment adjustment on the optimal subsidy rate \bar{S}_F and the corresponding expected social welfare. The parameter values are $\mu = 0.015$, $r = 0.1$, $\sigma = 0.05$, $\gamma = 0.3$, $\delta_0 = 7.74$ and $\delta_1 = 2.365$. It is assumed that $X_0 = 0.25$, $\bar{T} = 48$ and $\bar{K} = 40$.

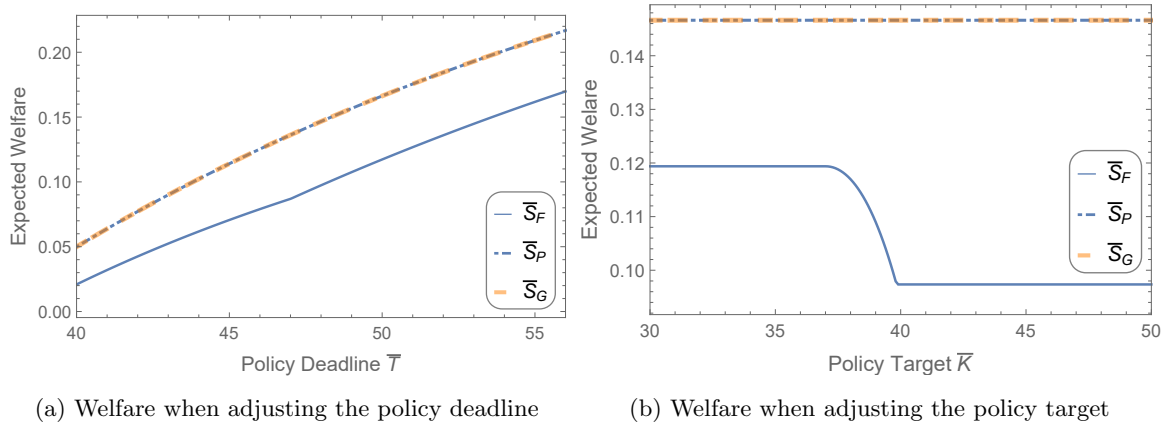
477 Figure 8 shows how changes in the penalty payment C influences the optimal subsidy rate \bar{S}_F and the
 478 corresponding expected welfare. Figure 8a shows that there are essentially two domains of penalty levels.
 479 For C low the regulator is not incentivized enough to satisfy the policy target. Therefore it sets a relatively
 480 low subsidy level. Consequently, the firm invests too less to satisfy the target level and the regulator pays
 481 the (low) penalty for sure at the policy deadline.

482 For C large the subsidy rate is higher. This is because the regulator does not want to pay a large penalty.
 483 For this reason it sets the subsidy such that the associated investment size is exactly equal to the target level
 484 \bar{K} . As we know this requires that the subsidy rate corresponds to the target level \bar{K} via expression (10).

485 It can be expected that in both domains WPT is decreasing in C , because of the larger penalty that
 486 needs to be incurred. This also holds for the area where the firm invests according to target level, because
 487 then there is a positive probability that the investment is not undertaken before the deadline. Figure 8b
 488 confirms.

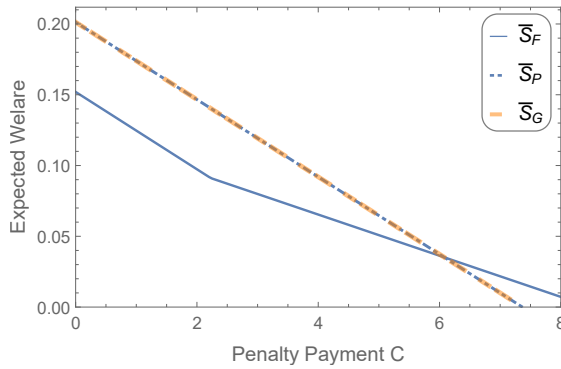
489 **5.4 A Different Subsidy Type**

490 This section considers a different type of feed-in-premium subsidy S_P , which stands for flexible price support
 491 rather than the fixed price support S_F , and a lump-sum transfer subsidy S_G . The theoretical derivation of
 492 the optimal investment decision and the expected social welfare for these two subsidies can be found in
 493 Appendix B. The first insight is that subsidy rates S_P and S_G do not affect the firm's investment capacity,
 494 but accelerate the timing of the investment. Considering the situation without the policy target, and given
 495 that without subsidy the firm invests too late in the right size, this makes it possible to align the private
 496 firm's and the social optimal investment decision, where the required subsidy rates are $S_P^* = \gamma/(1 - \gamma)$ and
 497 $S_G^* = \gamma$, respectively.



(a) Welfare when adjusting the policy deadline

(b) Welfare when adjusting the policy target



(c) Welfare when adjusting the penalty payment

Figure 9: Effect of the policy adjustment on the expected welfare under subsidy P and G. The parameter values are $\mu = 0.015$, $r = 0.1$, $\sigma = 0.05$, $\gamma = 0.3$, $\delta_0 = 7.74$ and $\delta_1 = 2.365$. The default policy is $\bar{T} = 48$, $\bar{K} = 40$ and $C = 2$.

498 To compare the welfare effect by the optimal subsidy rate \bar{S}_P and \bar{S}_G , which maximizes the expected
 499 social welfare $WPT(S_i)$ with $i \in \{P, G\}$ as in equation (18), we conduct a similar numerical analysis as for
 500 \bar{S}_F , which is shown in Figure 9. When adjusting the policy target, the welfare generated by \bar{S}_P and \bar{S}_G
 501 is identical, where we get that $K_i^*(S_i) = 22.9$, $i = S, G$, $X_P^*(S_P) > X_0$ if $S_P < 1.93$ and $X_G^*(S_G) > X_0$ if
 502 $S_G < 0.659$. Given the capacity target $\bar{K} = 40$, the policy target will never be reached. Hence, the penalty
 503 has to be paid at the deadline, and the expected welfare function is defined either in Case 1 or Case 3. This
 504 is because, as just noted, the subsidy rates S_P and S_G do not influence the investment size. In that sense
 505 they are not the suitable policy instruments to incentivize the firm to invest more in order to reach the policy
 506 target.

507 Figure 9a basically shows that, regarding the welfare effects, the conclusions drawn from the analysis
 508 with subsidy S_F carry over to subsidies S_P and S_G . A stricter deadline as well as a higher penalty have a
 509 negative effect on the WPT. Since S_P and S_G are unable to influence investment size, the capacity target
 510 \bar{K} will never be reached. Consequently, the penalty has to be incurred for sure and WPT is not affected for
 511 different values of \bar{K} as long as \bar{K} exceeds $K_i^*(S_i)$, $i = S, G$.

512 6 Conclusion

513 As a result of international environmental agreements countries have to fulfill policy targets, for instance in
514 the form of commitments regarding green investments. In that light the EU wants from its member states
515 that in 2030 30% of the energy consumption comes from renewable resources. To deal with such a target
516 a country has the possibility to stimulate firm investments by offering subsidies. The aim of this paper
517 is to disentangle the corresponding welfare effects. To reach that aim, this paper develops a new welfare
518 measure, “the expected Welfare corresponding to the Policy Target”, abbreviated by WPT. The WPT takes
519 into account all welfare effects of a subsidy, including the fine a country needs to incur upon not reaching
520 the target. This enables us to determine the optimal subsidy rate.

521 The paper mostly concentrates on a FIP subsidy in the form of a fixed price support, which is applied
522 in Italy with regard to the 2030 EU target. Implementing this subsidy lets the firm invest earlier, which is
523 good for welfare, but also more, where the latter is too much from a welfare perspective. In that light an
524 international policy target can cause a tradeoff in the sense that a large investment is required to achieve the
525 target, while at the same time such a large investment is bad for welfare. Taking into account the penalty a
526 country needs to incur upon not reaching the 2030 EU target, we obtain that a fixed price support of 4% is
527 optimal in the Italian situation.

528 The paper builds on the real options framework where a risk-neutral decision maker can only invest once.
529 Future work could focus on relaxing these assumptions, i.e. allow for the decision maker to invest multiple
530 times and consider risk-averse preferences. It also seems relevant to take into account technological progress
531 due to which later investments are more efficient.

A Proofs

Proof of Proposition 1 and 2: The calculation and derivation of the firm's optimal investment decision is similar as the derivation given in Pindyck (1999) and Huisman and Kort (2015).

Proof of Proposition 3: For a given capacity size K and $X_t = X$, the value of the discounted profit flow at X is equal to

$$V(X, K, S_F) = \frac{XK^{1-\gamma}}{r-\mu} + \frac{S_F K}{r} - \delta_0 - \delta_1 K.$$

Maximizing $V(X, K, S_F)$ with respect to K yields that the optimal capacity for a given X is given by

$$K(X, S_F) = \left(\frac{X(1-\gamma)}{(r-\mu)(\delta_1 - S_F/r)} \right)^{1/\gamma}.$$

Substituting $K(X, S_F)$ into $V(X, K, S_F)$ gives the expected value as a function of X and S_F , i.e., $V(X, S_F)$.

Let the value before investment threshold X^* be AX^β . Then the value matching and smooth pasting conditions at X^* yield

$$X^*(S_F) = \frac{r-\mu}{1-\gamma} (\delta_1 - S_F/r) \left(\frac{\delta_0 \beta (1-\gamma)}{(\delta_1 - S_F/r)(\beta\gamma - 1)} \right)^\gamma.$$

From the optimal investment threshold $X^*(S_F)$, we can get that the optimal investment capacity $K^*(S_F)$ is equal to

$$K^*(S_F) \equiv K^*(X^*(S_F)) = \frac{\delta_0 \beta (1-\gamma)}{(\delta_1 - S_F/r)(\beta\gamma - 1)}.$$

Proof of Corollary 1: According to $K(X, S_i)$ in Proof of Proposition 3, if there are changes in the uncertainty parameter σ , the regulator can adjust the subsidy rate S_F and still attain the target size of investment such that

$$\frac{dK^*}{d\sigma} = \frac{\partial K^*}{\partial S_F} \frac{\partial S_F}{\partial \sigma} + \frac{\partial K^*}{\partial \beta} \frac{\partial \beta}{\partial \sigma} = \frac{\beta(\beta\gamma - 1)}{r} \frac{\partial S_F}{\partial \sigma} - \left(\delta_1 - \frac{S_F}{r} \right) \frac{\partial \beta}{\partial \sigma} = 0.$$

There are two effects shown in the above equation. One effect, denoted by $(\partial K^*/\partial \beta)(\partial \beta/\partial \sigma)$, is the standard real options result that the increase of uncertainty parameter σ makes the firm invest more because $\partial \beta/\partial \sigma < 0$. In order to maintain the investment capacity level, the other effect, denoted by $(\partial K^*/\partial S_F)(\partial S_F/\partial \sigma)$, has to balance the first effect. This implies the adjustment of S_F should be given by

$$\frac{\partial S_F}{\partial \sigma} = \frac{r\delta_1 - S_F}{\beta(\beta\gamma - 1)} \frac{\partial \beta}{\partial \sigma} < 0.$$

S_F decreasing with σ implies that the regulator has to lower the subsidy rate in order to discourage the firm to invest more. This adjustment of subsidy also influences the firm's optimal investment timing, and the effect on X^* is equal to

$$\frac{dX^*}{d\sigma} = \frac{\partial X^*}{\partial S_F} \frac{\partial S_F}{\partial \sigma} + \frac{\partial X^*}{\partial \beta} \frac{\partial \beta}{\partial \sigma} = -\frac{r-\mu}{r(1-\gamma)} \frac{r\delta_1 - S_F}{\beta(\beta\gamma - 1)} \left(\frac{\delta_0 \beta (1-\gamma)}{(\delta_1 - S_F/r)(\beta\gamma - 1)} \right)^\gamma \frac{\partial \beta}{\partial \sigma} > 0.$$

This implies that the increases in uncertainty would delay the firm's investment threshold,¹⁰ when the regulator adjusts the subsidy rate to maintain the same level of investment capacity. There are two effects

¹⁰This can be derived from the expected hitting time of a geometric Brownian motion, i.e.,

$$\mathbb{E}[T(X = X^*)] = \begin{cases} \frac{1}{\mu - \sigma^2/2} \ln(X^*/X_0) & \text{if } \mu > \sigma^2/2, \\ \infty & \text{if } \mu \leq \sigma^2/2. \end{cases}$$

555 caused by changes in σ , one direct effect represented by $(\partial X^*/\partial\beta)(\partial\beta/\partial\sigma)$, and one indirect effect represented
 556 by $(\partial X^*/\partial S_F)(\partial S_F/\partial\sigma)$. In our non-linear model, both effects are positive and an increase in σ delays the
 557 investment. Note that this result is different from Bigerna et al. (2019), where as the uncertainty increases,
 558 the adjustment of subsidy rate actually decreases the investment threshold, because there a negative indirect
 559 effect dominates the positive direct effect.

560 Similar analysis can be conducted on other parameters. For changes in the fixed investment cost param-
 561 eter δ_0 , in order to maintain the same level of investment size, it holds that

$$\frac{dK^*}{d\delta_0} = \frac{\partial K^*}{\partial S_F} \frac{\partial S_F}{\partial \delta_0} + \frac{\partial K^*}{\partial \delta_0} = \frac{\beta(1-\gamma)}{(\beta\gamma-1)(\delta_1-S_F/r)^2} \left(\delta_1 - \frac{S_F}{r} + \frac{\delta_0}{r} \frac{\partial S_F}{\partial \delta_0} \right) = 0,$$

562 which yields that the adjustment on the subsidy rate satisfies

$$\frac{\partial S_F}{\partial \delta_0} = -\frac{r\delta_1 - S_F}{\delta_0} < 0.$$

563 Because the increase in the fixed investment costs makes the firm invest more as implied by $\partial K_F^*/\partial\delta_0 > 0$,
 564 the regulator has to discourage the firm to invest less by lowering the subsidy rate S_F to maintain the same
 565 investment capacity size. The corresponding influence on X^* is equal to

$$\frac{dX^*}{d\delta_0} = \frac{\partial X^*}{\partial S_F} \frac{\partial S_F}{\partial \delta_0} + \frac{\partial X^*}{\partial \delta_0} = -\frac{r-\mu}{r(1-\gamma)} \frac{\partial S_F}{\partial \delta_0} \left(\frac{\delta_0\beta(1-\gamma)}{(\delta_1-S_F/r)(\beta\gamma-1)} \right)^\gamma > 0.$$

566 Similar as the influence of σ , the direct effect represented by $\partial X^*/\partial\sigma > 0$, and the indirect effect by
 567 $(\partial X^*/\partial S_F)(\partial S_F/\partial\delta_0)$ is also positive. So we observe the effect that an increase in δ_0 delays the firm's
 568 investment.

569 For the changes in the unit cost parameter δ_1 , in order to keep the target size of investment, it holds that

$$\frac{dK^*}{d\delta_1} = \frac{\partial K^*}{\partial S_F} \frac{\partial S_F}{\partial \delta_1} + \frac{\partial K^*}{\partial \delta_1} = -\frac{\delta_0\beta(1-\gamma)}{(\beta\gamma-1)(\delta_1-S_F/r)^2} \left(1 - \frac{\partial S_F/\partial\delta_1}{r} \right) = 0.$$

570 Thus, the adjustment of the subsidy with respect to the unit investment cost is equal to $\partial S_F/\partial\delta_1 = r$.
 571 Because the increase in δ_1 makes the firm invest less, the regulator has to encourage the firm's investment by
 572 increasing the subsidy rate in order to main the same level of capacity size. Moreover, the provision of the
 573 subsidy is based on the installed capacity size, and S_F/r can be treated as the marginal support for one unit
 574 of the installed capacity. $\partial S_F/(r\partial\delta_1) = 1$ implies the changes in the marginal support offsets the changes in
 575 the marginal cost for the investment capacity. Thus, the adjustment of subsidy rate S_F with respect to δ_1
 576 does not influence the investment threshold X^* and $dX^*/d\delta_1 = 0$.

577 When there are changes in the demand trend parameter μ , in order to keep the desired level of investment,
 578 the regulator adjusts S_F in such a way that

$$\frac{dK^*}{d\mu} = \frac{\partial K^*}{\partial \beta} \frac{\partial \beta}{\partial \mu} + \frac{\partial K^*}{\partial S_F} \frac{\partial S_F}{\partial \mu} = \frac{\delta_0(1-\gamma)}{(\delta_1-S_F/r)^2(\beta\gamma-1)^2} \left(\frac{\beta(\beta\gamma-1)}{r} \frac{\partial S_F}{\partial \mu} - \left(\delta_1 - \frac{S_F}{r} \right) \frac{\partial \beta}{\partial \mu} \right) = 0.$$

579 Given that $\partial\beta/\partial\mu < 0$, it holds $(\partial K^*/\partial\beta)(\partial\beta/\partial\mu) > 0$, which is the standard real options result that the
 580 firm invests more if the trend of the market demand grows larger. To maintain the same size of investment,
 581 this effect has to be offset by a lowered subsidy rate S_F , which discourages the firm to invest more. More
 582 specifically, the adjustment of S_F with respect to changes in μ is equal to

$$\frac{\partial S_F}{\partial \mu} = \frac{r\delta_1 - S_F}{\beta(\beta\gamma-1)} \frac{\partial \beta}{\partial \mu} < 0.$$

583 The total influence of changes in μ and adjustment of S_F on investment timing is given by

$$\begin{aligned}\frac{dX^*}{d\mu} &= \frac{\partial X^*}{\partial \mu} + \frac{\partial X^*}{\partial \beta} \frac{\partial \beta}{\partial \mu} + \frac{\partial X^*}{\partial S_F} \frac{\partial S_F}{\partial \mu} \\ &= -\frac{\delta_1 - S_F/r}{1 - \gamma} \left(\frac{\delta_0 \beta (1 - \gamma)}{(\delta_1 - S_F/r)(\beta \gamma - 1)} \right)^\gamma \left(1 + \frac{r - \mu}{\beta(\beta \gamma - 1)} \frac{\partial \beta}{\partial \mu} \right).\end{aligned}$$

584 The sign of $dX^*/d\mu$ depends on the other parameters. The direct effect of μ on X^* is denoted by $\partial X^*/\partial \mu +$
585 $(\partial X^*/\partial \beta)(\partial \beta/\partial \mu)$, where the first term is negative and the second term is positive. So the sign of this
586 direct effect is positive depends on the parameter values, which makes the overall effect of μ on X^* not
587 straightforward, even though the indirect effect $(\partial X^*/\partial S_F)(\partial S_F/\partial \mu)$ is positive.

588 Similar analysis can be done on the discount rate r . We can first derive that the adjustment of S_F
589 satisfies

$$\begin{aligned}\frac{dK^*}{dr} &= \frac{\partial K^*}{\partial r} + \frac{\partial K^*}{\partial \beta} \frac{\partial \beta}{\partial r} + \frac{\partial K^*}{\partial S_F} \frac{\partial S_F}{\partial r} \\ &= \frac{\delta_1(1 - \gamma)}{(\delta_1 - S_F/r)^2(\beta \gamma - 1)^2} \left(\frac{\beta(\beta \gamma - 1)}{r} \left(\frac{\partial S_F}{\partial r} - \frac{S_F}{r} \right) - \left(\delta_1 - \frac{S_F}{r} \right) \frac{\partial \beta}{\partial r} \right) = 0.\end{aligned}$$

590 The adjustment of S_F with respect to r is given by

$$\frac{\partial S_F}{\partial r} = \frac{r\delta_1 - S_F}{\beta(\beta \gamma - 1)} \frac{\partial \beta}{\partial r} + \frac{S_F}{r} > 0,$$

591 because $\partial \beta/\partial r > 0$. The corresponding influence on the optimal investment timing is

$$\begin{aligned}\frac{dX^*}{dr} &= \frac{\partial X^*}{\partial r} + \frac{\partial X^*}{\partial \beta} \frac{\partial \beta}{\partial r} + \frac{\partial X^*}{\partial S_F} \frac{\partial S_F}{\partial r} \\ &= \frac{\delta_1 - S_F/r}{1 - \gamma} \left(\frac{\delta_0 \beta (1 - \gamma)}{(\delta_1 - S_F/r)(\beta \gamma - 1)} \right)^\gamma \left(1 - \frac{r - \mu}{\beta(\beta \gamma - 1)} \frac{\partial \beta}{\partial r} \right).\end{aligned}$$

592 The sign of dX^*/dr depends on the comparison between $\partial \beta/\partial r$ and $\frac{r - \mu}{\beta(\beta \gamma - 1)}$. In the direct effect, it can be
593 derived that $(\partial X^*/\partial \beta)(\partial \beta/\partial r) < 0$, but the sign of $\partial X^*/\partial r$ is not straightforward. The indirect effect is
594 $(\partial X^*/\partial S_F)(\partial S_F/\partial r) < 0$.

595 B Subsidy P and subsidy G

596 Under the non-linear demand structure, for the subsidy flow $p_t(X_t)KSP$ and lump sum subsidy $S_G(\delta_0 + \delta_1 K)$,
597 Wen (2017) calculates the firm's investment decision and the corresponding social welfare.

598 B.1 Subsidy P

599 When the subsidy is such that $s(X_t, K, S_P) = p_t(X_t)KSP$, the optimal capacity for a given X is given by

$$K_P(X, S_P) = \left(\frac{X(1 - \gamma)(1 + S_P)}{\delta_1(r - \mu)} \right)^{1/\gamma}.$$

600 The firm's investment threshold $X_P^*(S_P)$, given that $X_P^*(S_P) > X_0$, and capacity $K_P^*(S_P)$ for a given subsidy
601 rate S_G read

$$X_P^*(S_P) = \frac{\delta_1(r - \mu)}{(1 - \gamma)(1 + S_P)} \left(\frac{\delta_0 \beta (1 - \gamma)}{\delta_1(\beta \gamma - 1)} \right)^\gamma. \quad (14)$$

$$K_P^*(S_P) = \frac{\delta_0 \beta (1 - \gamma)}{\delta_1 (\beta \gamma - 1)}. \quad (15)$$

602 The corresponding social welfare generated by S_P is given by

$$W_P(S_P) \equiv W(X^*(S_P), K^*(S_P)) = -\frac{(1 + S_P - \beta S_P + (1 + S_P)(\beta - 1)\gamma)\delta_0}{(1 + S_P)(1 - \gamma)(1 - \beta\gamma)}.$$

603 Because $X_P^*(S_P = 0) > X_W^*$, and the subsidy makes firm invest earlier, it is possible to align firm's and social
604 optimal investment threshold by choosing appropriate subsidy rate S_P^* . This implies that the regulator can
605 align the firm's decision to the social optimal investment with a subsidy rate S_P^* such that,

$$S_P^* = \frac{\gamma}{1 - \gamma}.$$

606 If $X_0 \geq X_P^*(S_P)$, the firm invests at X_0 with capacity $K_P(X_0, S_P)$, which leads to a welfare level $W(X_0, K_P(X_0, S_P))$.

607 B.2 Subsidy G

608 When the subsidy is a lump-sum transfer $S_G(\delta_0 + \delta_1 K)$ to the investing firm, the investment capacity for a
609 given GBM level X and subsidy rate S_G is equal to

$$K_G(X, S_G) = \left(\frac{X(1 - \gamma)}{(r - \mu)(1 - S_G)\delta_1} \right)^{1/\gamma}.$$

610 The investment decision when $X_G^*(S_G) > X_0$ for the subsidy rate S_G is given by

$$X_G^*(S_G) = \frac{\delta_1 (r - \mu)(1 - S_G)}{1 - \gamma} \left(\frac{\delta_0 \beta (1 - \gamma)}{\delta_1 (\beta \gamma - 1)} \right)^\gamma, \quad (16)$$

$$K_G^*(S_G) = \frac{\delta_0 \beta (1 - \gamma)}{\delta_1 (\beta \gamma - 1)}. \quad (17)$$

611 The regulator can align the firm's and the social optimal investment decision by implementing a subsidy
612 rate $S_G^* = \gamma$. The corresponding social welfare generated by the subsidy rate S_G is given by

$$W_G(S_G) \equiv W(X^*(S_G), K^*(S_G)) = \frac{(\beta S_G - 1 + \gamma - \beta \gamma)\delta_0}{(1 - \gamma)(1 - \beta \gamma)}.$$

613 If $X_0 \geq X_G^*(S_G)$, the firm invests at X_0 with capacity $K_G(X_0, S_G)$, which yields the welfare level $W(X_0, K_G(X_0, S_G))$.

614 Because neither S_P nor S_G influences the firm's investment capacity, under a RES policy specified by \bar{T} ,
615 \bar{K} and C , the expected social welfare generated by S_i with $i \in \{P, G\}$ is equal to

$$WPT(S_i, \bar{K}, \bar{T}) = \begin{cases} \text{Prob}(\tau^* \leq \bar{T}, X_i^*(S_i)) \left(\frac{X_0}{X_i^*(S_i)} \right)^\beta W_i(S_i) - \left(\frac{X_0}{X_T} \right)^\beta C & \text{if } X_i^*(S_i) > X_0 \text{ and } \bar{K} > \frac{\delta_0 \beta (1 - \gamma)}{\delta_1 (\beta \gamma - 1)}, \\ \text{Prob}(\tau^* \leq \bar{T}, X_i^*(S_i)) \left(\frac{X_0}{X_P^*(S_i)} \right)^\beta W_i(S_i) & \text{if } X_i^*(S_i) > X_0 \text{ and } \bar{K} \leq \frac{\delta_0 \beta (1 - \gamma)}{\delta_1 (\beta \gamma - 1)}, \\ - (1 - \text{Prob}(\tau^* \leq \bar{T}, X_i^*(S_i))) \left(\frac{X_0}{X_T} \right)^\beta C & \\ \frac{X_0 K_i^{1-\gamma}(X_0, S_i)}{(r - \mu)(1 - \gamma)} - \delta_0 - \delta_1 K_i(X_0, S_i) - \left(\frac{X_0}{X_T} \right)^\beta C & \text{if } X_i^*(S_i) \leq X_0 \text{ and } K_i(X_0, S_i) < \bar{K}, \\ \frac{X_0 K_i^{1-\gamma}(X_0, S_i)}{(r - \mu)(1 - \gamma)} - \delta_0 - \delta_1 K_i(X_0, S_i) & \text{if } X_i^*(S_i) \leq X_0 \text{ and } K_i(X_0, S_i) \geq \bar{K}. \end{cases} \quad (18)$$

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