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Renewable energy policy in the presence of innovation: does government pre-commitment matter?

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Abstract

In a perfectly competitive market with a possibility of technological innovation we contrast guaranteed feed-in tariffs for electricity from renewables and tradable green certificates from a dynamic efficiency and social welfare point of view. Specifically, we model decisions about the technological innovation with convex costs within the framework of a game-theoretic model, and discuss implications for optimal policy design under different assumptions regarding regulatory pre-commitment. We find that for the case of technological innovation with convex costs subsidy policies are preferable over quota-based policies. Further, in terms of dynamic efficiency, no pre-commitment policies are shown to be at least as good as the pre-commitment ones. Thus, a government with a preference for innovation being performed if the achievable cost reduction is high should be in favor of the no pre-commitment regime.

Keywords: Renewable electricity; Feed-in tariffs; Regulatory pre-commitment; Tradable green certificates; Quota target; Innovation; Energy policy

JEL classification: Q42, Q48

1 Introduction

Renewable energy is considered an important element in a sustainable energy development. In many countries renewable energy promotion policies have been put into place. As far as electricity generation from renewables is concerned, there has been much debate in recent years about the relative merits of guaranteed feed-in tariffs (FIT) and tradable green certificates (TGC), mainly in the form of qualitative discussion (e.g. Menanteau et al., 2003; Nielsen and Jeppesen, 2003; Berry, 2002), and much less so in the form of more rigorous formal analysis (e.g. Amundsen and Mortensen, 2001, 2002; Amundsen and Nese, 2002).

Building on seminal work by Weitzman (1974, 1978), Pizer (1999a,b) studies the non-equivalence of tax and quota policies given uncertainty and shows that uncertainty causes the optimal amount of emission abatement to increase, which justifies a preference for price over quantity control. Madlener et al. (2009) show that in terms of static efficiency a price (subsidy) policy to promote renewable energy is equivalent to a quantity (quota) policy for a competitive but not generally a duopoly market for power when competitors have different production costs for renewable (but not conventional) energy. In this paper, we extend the static analysis to incorporate technological innovation that lowers the (increasing) marginal cost of production of electricity from renewable sources.

From environmental economics it is known that the dynamic efficiency of a policy depends on whether or not the government pre-commits to a certain policy target (e.g. Denicolò, 1999). In our analysis we want to find out which of the two policy instruments provides a stronger incentive for innovation favoring renewable or "green" electricity in two cases, (1) when the government adjusts its policy in response to innovation (no pre-commitment), and (2) when it cannot react immediately to innovation (pre-commitment). In contrast to Denicolò (1999), we find that the relative merits of the subsidy and quota policies are the same in the two scenarios from the point of view of social welfare maximization. However, in terms of dynamic efficiency, this equivalence does not necessarily hold. Rather, the no pre-commitment policy is shown to support equilibrium outcomes with innovations that might not be attainable under pre-commitment.

The remainder of the paper is organized as follows. Section 2 derives optimal subsidy and quota policies for assuming no pre-commitment on the part of the government when innovation is present. Section 3 contains the analogous analysis for the pre-commitment case. Section 4 discusses the results obtained in Sections 2 and 3 and concludes.

2 Optimal policy in the presence of innovation: no pre-commitment case

In the no pre-commitment case, the government is assumed to have the information, ability and obligation to respond to technological innovation by adjusting its subsidy or quota policy, respectively. Let there be $N+1$ competitive electricity generators in the market, one of them being the potential innovator, assumed to possess the patent covering the rights for the new technology. Innovation reduces the marginal cost of green electricity, and the innovator can license the new technology to other producers in return of a royalty. Let us assume that prior to innovation all firms have an identical cost structure for producing green electricity of the simplistic form

$$C_{\mathrm{g}}(x_{\mathrm{g}}) = b_1 x_{\mathrm{g}} + b_2 {x_{\mathrm{g}}}^2, \tag{1}$$

with $b_1 > 0$, $b_2 > 0$, to reflect decreasing marginal returns (DMR) in the production of green electricity. DMR is a sensible assumption because the use of renewables (in particular solar and wind) involves technologies that have not yet reached maturity. Accordingly, there is scope for (exogenous) innovation, resulting in a new cost function of the form

$$C_{\mathrm{gn}}(x_{\mathrm{g}}) = b_{1\mathrm{n}} x_{\mathrm{g}} + b_2 {x_{\mathrm{g}}}^2, \tag{2}$$

where C_{gn} denotes the cost function after innovation and $b_{1\mathrm{n}} < b_1$ the reduced part of the marginal cost. Note that b_2 is unaffected by the innovation for simplicity ($b_{1\mathrm{n}} < b_1$ is sufficient to mitigate DMR). Thus, $(b_1 - b_{1n})$ reflects the importance of the innovation.

The cost function for brown electricity (i.e. from conventional sources such as coal, nuclear etc.) is assumed to be linear, $C_{\mathrm{b}}(x_{\mathrm{b}}) = c_{\mathrm{b}} x_{\mathrm{b}}$.

The R&D investment required for the innovation is denoted by $R[C_{\mathrm{g}}(x_{\mathrm{g}}) - C_{\mathrm{gn}}(x_{\mathrm{g}})]$, with $R'(\cdot) > 0$ and $R''(\cdot) > 0$. This means that the R&D outlay increases progressively as a function of the size of the achievable cost reduction. Therefore, R&D does not display increasing marginal returns, reflecting the fact that no particular technology has dominated the market for renewable electricity to this day. Given the continuity assumptions made in (1) and (2), for any fixed value of x_{g}, $R[C_{\mathrm{g}}(x_{\mathrm{g}}) - C_{\mathrm{gn}}(x_{\mathrm{g}})]$ can be rewritten as $R(b_1 - b_{1\mathrm{n}})$. We consider a parametric version of function $R(\cdot)$ of the form $R(b_1 - b_{1\mathrm{n}}) = r(b_1 - b_{1\mathrm{n}})^2$, with parameter $r > 0$ reflecting the concavity of the function. In particular, the higher r, the higher the marginal cost of innovation.

On the demand side, we assume that brown and green electricity are perfect substitutes. Thus the demand function for electricity takes the following linear form:

$$p(Q) = a - Q = a - \sum_{i=1}^{N+1} (x_{\mathrm{ib}} + x_{\mathrm{ig}}) \,,$$

where Q denotes the total quantity of electricity supplied in the market, x_{ib}, the quantity of conventional electricity produced by firm i, and x_{ig}, that of green electricity. Further, we assume that $b_1 < c_b$, i.e. marginal costs of green electricity are lower than those of brown electricity for small quantities, and $(c_b - b_{1n})$ is sufficiently smaller than $b_2(a - c_b)$, i.e. the average electricity price on the market, p, will always be given by the marginal cost of brown electricity c_b.

The government observes whether a firm operates with the old or the new technology[1] and is assumed to maximize social welfare. The externality function of green electricity[2] (including avoided social cost of producing brown electricity) is assumed to have a simple,

[1]This is a plausible assumption since, in reality, the electricity producers are required to file the technical description of their power generating technology to the regulator.

[2]Note that, in the real world, the quantification of the (positive and negative) externalities associated with power generation from renewables is subject to several complications (e.g. Söderholm and Sundqvist, 2003). The value of the external benefits (including avoided environmental damages and learning-by-doing effects) is likely to depend on the particular composition of the technology portfolio used to produce

linear-quadratic form:

$$D(x_{\mathrm{g}}) = d_1 x_{\mathrm{g}} - d_2 x_{\mathrm{g}}^2, \qquad d_1,\ d_2 > 0. \tag{3}$$

The quadratic term reflects the fact that marginal avoided social cost of brown electricity decreases with higher quantities of green electricity produced and might attain negative values if large quantities of green electricity are produced.[3] In order to exclude the possibility of extremely high social cost of additional production of green power, we additionally assume that parameter d_2 is sufficiently small such that $d_2(N+1)(c_{\mathrm{b}} - b_{1\mathrm{n}}) < b_2 d_1$.

2.1 Subsidy policy

Subsidy (or negative tax) here refers to a transfer paid by the government or electricity consumers to the suppliers of green electricity. Thus, producers receive a surcharge s per unit of green electricity.[4] The decisions of the agents can be represented by a game with the following players: firms 1, 2, ..., $N+1$, and government G. Without loss of generality, let us assume that firm no. 1 is the potential innovator.

Now we analyze the decision sequencing under subsidy control with no pre-commitment. There are three decision stages, described in the following and summarized in Figure 1.

Stage I. Firm 1 decides either not to innovate (NI), to innovate and offer N licenses in the competition stage III (I_N), or to innovate and offer no licenses in stage III (I_0).

Stage II. Given the decision of firm 1 in stage I, the government determines the subsidy levels for non-innovating and innovating firms in order to maximize social welfare.

(IIa) If firm 1 did not innovate, the government introduces a subsidy s_{NI} per unit of output for all firms (decision node G_1).

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electricity, and thus also the amount of the brown electricity displaced and the (environmental) benefit incurred.

[3] This can be motivated by arguing that with more intensive utilization of renewables, environmentally and socially less benign projects are also being realized.

[4] In reality it is usually the power fed into the grid that counts, which due to on-site electricity consumption and transmission losses may be considerably less than gross production. This difference is neglected here for simplicity.

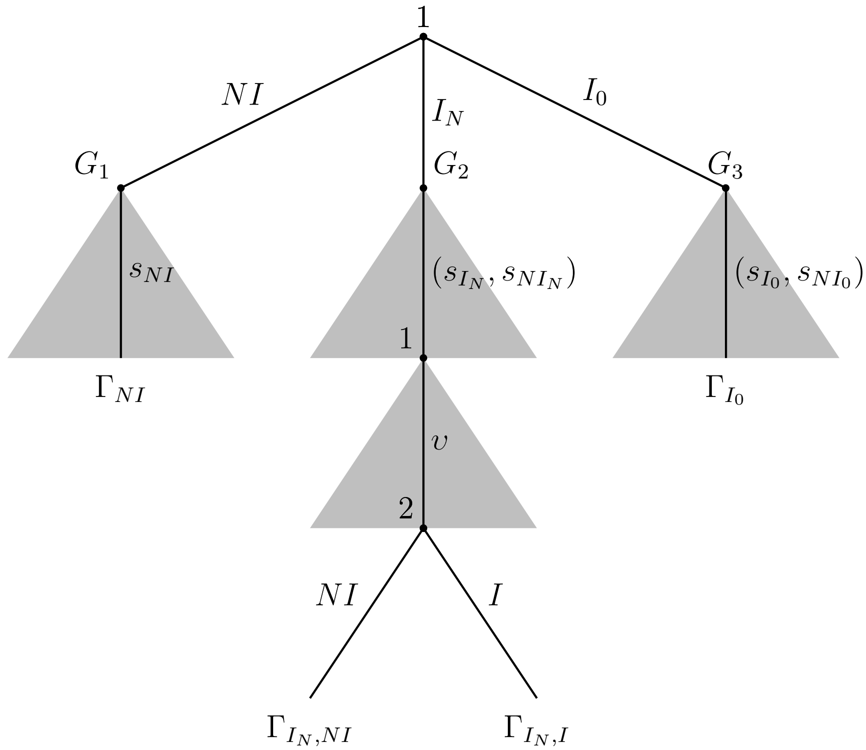

Figure 1: Extensive-form game representation, no pre-commitment case, subsidy policy

(IIb) If firm 1 did innovate and announced to offer N licenses in stage III, the government introduces two levels of subsidy: s_{I_N} for the innovator and the firms that adopted the new technology and s_{NI_N} for the firms that did not adopt the new technology (decision node G_2).

(IIc) Finally, if firm 1 did innovate but announced that it will offer no licenses in stage III, the subsidies are s_{I_0} for the innovator and s_{NI_0} for the competitors (decision node G_3).

Stage III. Given the innovation decision of firm 1 and the decision of the government about the subsidy level, firms 1, 2, …, $N+1$ compete in quantities.

(IIIa) If firm 1 did not innovate, all firms have identical cost functions $C_{\mathrm{g}}(\cdot)$ and compete in quantities given subsidy level s_{NI} per unit of green electricity (subgame Γ_{NI}).

(IIIb) If firm 1 did innovate and committed to offer N licenses in stage III, then it first offers licenses to N competitors in return of a royalty υ given subsidy levels s_{I_N} and s_{NI_N}. Firms $2, \ldots, N+1$ can either accept (I) or reject (NI) this offer. Since firms $2, \ldots, N+1$ are identical, we assume that either all of them will reject the offer and operate with cost function $C_{\mathrm{g}}(\cdot)$ (competition in quantities will take place in subgame $\Gamma_{I_N,NI}$) or all of them will accept it and operate with cost function $C_{\mathrm{gn}}(\cdot)$ (competition in subgame $\Gamma_{I_N,I}$).

(IIIc) If firm 1 did innovate but announced that it will offer no licenses in stage III, then firm 1, operating with cost function $C_{\mathrm{gn}}(\cdot)$, and firms $2, \ldots, N+1$, operating with cost function $C_{\mathrm{g}}(\cdot)$, respectively, compete in quantities given their subsidy levels s_{I_0} and s_{NI_0} (subgame Γ_{I_0}).

These three decision stages define an extensive-form game as shown in Figure 1. The information revealed in the earlier stages of this game is taken as given in the corresponding subsequent stages. Thus, in the earlier stages, rational players anticipate the equilibrium outcomes in every subsequent stage. Each game branch starting with an information set can thus be considered as a subgame, giving rise to the Subgame Perfect Equilibrium (SPE) as the solution concept to be applied. As usual, the SPE solution can be obtained by backward induction.

Lemma 2.1.1. *In subgame Γ_{NI} (stage IIIa), all firms' quantities of green electricity are given by*

$$x_{i\mathrm{g}}(NI, s_{NI}) \quad = \quad \frac{c_{\mathrm{b}} - b_1 + s_{NI}}{2b_2}. \tag{4}$$

Proof: see Appendix on p.25.

Lemma 2.1.2. *In stage IIIb, firm 1's equilibrium offer υ^* is given by*

$$\upsilon^* = \begin{cases} (b_1 - b_{1\mathrm{n}}) - (s_{NI_N} - s_{I_N}) & \textit{if } (b_1 - b_{1\mathrm{n}}) - (s_{NI_N} - s_{I_N}) < \dfrac{c_{\mathrm{b}} - b_{1\mathrm{n}} + s_{I_N}}{2}; \\ \dfrac{c_{\mathrm{b}} - b_{1\mathrm{n}} + s_{I_N}}{2} & \textit{otherwise.} \end{cases}$$

This offer is always accepted by a firm of type 2 in equilibrium[5]. *Quantities of green electricity produced by firm 1 and firms of type 2 are*

$$x_{1\text{g}}(I_N,(s_{NI_N},s_{I_N})) \;=\; \frac{c_\text{b}-b_{1\text{n}}+s_{I_N}}{2b_2};$$

$$x_{2\text{g}}(I_N,(s_{NI_N},s_{I_N})) \;=\; \begin{cases} \dfrac{(c_\text{b}-b_1+s_{NI_N})}{2b_2} & \textit{if } (b_1-b_{1\text{n}})-(s_{NI_N}-s_{I_N}) < \dfrac{c_\text{b}-b_{1\text{n}}+s_{I_N}}{2}; \\ \dfrac{c_\text{b}-b_{1\text{n}}+s_{I_N}}{4b_2} & \textit{otherwise.} \end{cases}$$

Proof: see Appendix on p.26.

Lemma 2.1.3. *In subgame Γ_{I_0} (stage IIIc), quantities of green electricity produced by firm 1 and firms of type 2 are given by*

$$x_{1\text{g}}(I_0,(s_{NI_0},s_{I_0})) \;=\; \frac{c_\text{b}-b_{1\text{n}}+s_{I_0}}{2b_2};$$

$$x_{2\text{g}}(I_0,(s_{NI_0},s_{I_0})) \;=\; \frac{c_\text{b}-b_1+s_{NI_0}}{2b_2}.$$

Proof: see Appendix on p.28.

Lemma 2.1.4. *In stage IIa (subgame starting at node G_1), the government chooses subsidy level*

$$s^*_{NI} = \frac{b_2 d_1 - d_2(N+1)(c_\text{b}-b_1)}{b_2+d_2(N+1)}.$$

Proof: see Appendix on p.28.

Lemma 2.1.5. *In stage IIb (subgame starting at node G_2), the government chooses any combination of subsidy levels*

$$(s^*_{NI_N},s^*_{I_N}) = \left(s^*_{NI_N}, \frac{[2b_2N-d_2(N+2)^2](c_\text{b}-b_{1\text{n}})+2(N+2)b_2d_1}{d_2(N+2)^2+4b_2}\right),$$

where

$$s^*_{NI_N} \geq (b_1-b_{1\text{n}}) + \frac{[b_2(N-2)-d_2(N+2)^2](c_\text{b}-b_{1\text{n}})+(N+2)b_2d_1}{d_2(N+2)^2+4b_2}.$$

[5] As usual, we assume that in the case of indifference firms of type 2 decide in favor of the adoption of the new technology.

Proof: see Appendix on p.29.

Lemma 2.1.6. *In stage IIc (subgame starting at node G_3), the government chooses subsidy levels*

$$s^*_{NI_0} = s^*_{I_0} = \frac{b_2 d_1 - d_2(N+1)(c_\mathrm{b} - b_1) - d_2(b_1 - b_{1\mathrm{n}})}{b_2 + d_2(N+1)}.$$

Proof: see Appendix on p.30.

Proposition 2.1.7. *The subgame-perfect equilibrium strategies on the equilibrium path of the innovation game with subsidy control and no pre-commitment policy are given as follows. Firm 1 does not innovate (NI) if* $(r-1)(\Delta b_1)^2 + 2\beta\Delta b_1 - \alpha\beta^2 \leq 0$ *where*

$$\begin{aligned}
\alpha &= \frac{b_2}{4}\left(\frac{2(N+2)^3}{[4b_2 + d_2(N+2)^2]^2} - \frac{1}{[b_2 + d_2(N+1)]^2}\right) > 0; \\
\beta &= c_\mathrm{b} - b_{1\mathrm{n}} + d_1 > 0; \\
\Delta b_1 &= b_1 - b_{1\mathrm{n}}
\end{aligned}$$

and innovates and offers N licenses (I_N) otherwise. The royalty and quantities in equilibrium are given by

$$v^* = \frac{b_2(N+2)(c_\mathrm{b} - b_{1\mathrm{n}} + d_1)}{d_2(N+2)^2 + 4b_2};$$

$$x^*_{1\mathrm{g}}(NI) = \frac{c_\mathrm{b} - b_1 + d_1}{2[b_2 + d_2(N+1)]};\ x^*_{1\mathrm{g}}(I_N) = \frac{(N+2)(c_\mathrm{b} - b_{1\mathrm{n}} + d_1)}{d_2(N+2)^2 + 4b_2}.$$

Government sets subsidy levels

$$\begin{aligned}
s^*_{NI} &= \frac{b_2 d_1 - d_2(N+1)(c_\mathrm{b} - b_1)}{b_2 + d_2(N+1)}, \\
s^*_{NI_N} &\in \left\{s:\ s \leq \frac{[b_2(N-2) - d_2(N+2)^2](c_\mathrm{b} - b_1 + d_1) + b_2(N+2)(b_1 - b_{1\mathrm{n}})}{4b_2 + d_2(N+2)^2} + d_1\right\}, \\
s^*_{I_N} &= \frac{[2b_2 N - d_2(N+2)^2](c_\mathrm{b} - b_{1\mathrm{n}}) + 2(N+2)b_2 d_1}{d_2(N+2)^2 + 4b_2}.
\end{aligned}$$

Firms of type 2 innovate (I) if firm 1 chooses I_N and produce quantities

$$\begin{aligned}
x^*_{2\mathrm{g}}(NI) &= \frac{c_\mathrm{b} - b_1 + d_1}{2[b_2 + d_2(N+1)]}, \\
x^*_{2\mathrm{g}}(I_N) &= \frac{(N+2)(c_\mathrm{b} - b_{1\mathrm{n}} + d_1)}{2[d_2(N+2)^2 + 4b_2]}.
\end{aligned}$$

Proof: see Appendix on p.30.

2.2 Quota-based policy

Instead of subsidizing green electricity, the government can also impose a quota target for green power on each generator.[6] For each unit of green electricity produced, the firm receives a certificate providing evidence of partial satisfaction of the target imposed[7]. If a firm falls short of achieving the quota target, it faces a fine f that increases with the shortfall (cf. Madlener et al., 2009).

As with the subsidy-based policy, we consider an extensive-form game with the following structure. There are three decision stages.

Stage I. Firm 1 decides either not to innovate (NI), to innovate and offer N licenses in the competition stage III (I_N), or to innovate and offer no royalties in stage III (I_0).

Stage II. Given the decision of firm 1 in stage I, the government determines the quotas to be satisfied and the fines for firms falling short of the quota for non-innovating and innovating firms, in order to maximize social welfare.

(IIa) If firm 1 did not innovate, the government introduces a quota $\bar{x}_{NI}$ and a fine f_{NI} per unit of output falling short of the quota for all firms (decision node G_1).

(IIb) If firm 1 did innovate and announced to offer N licenses in stage III, the government introduces two pairs of quotas and fines: $(\bar{x}_{I_N}, f_{I_N})$ for the innovator and those firms that adopted the new technology and $(\bar{x}_{NI_N}, f_{NI_N})$ for those firms that did not adopt the new technology (G_2).

(IIc) Finally, if firm 1 did innovate but announced that it will offer no licenses in stage III, the quotas and fines set by the government are $(\bar{x}_{I_0}, f_{I_0})$ for the innovator and $(\bar{x}_{NI_0}, f_{NI_0})$ for the competitors (G_3).

[6] In practice it is often the wholesalers or retailers, and sometimes even the final consumers of electricity, that are obligated to fulfil the quota target.

[7] Admittedly, the assumption that the market for tradable certificates is perfectly competitive and efficient may, especially in poorly designed or managed schemes, be quite a strong one (e.g. Amundsen and Bergman, 2004; Nilsson and Sundqvist, 2007; Söderholm, 2008).

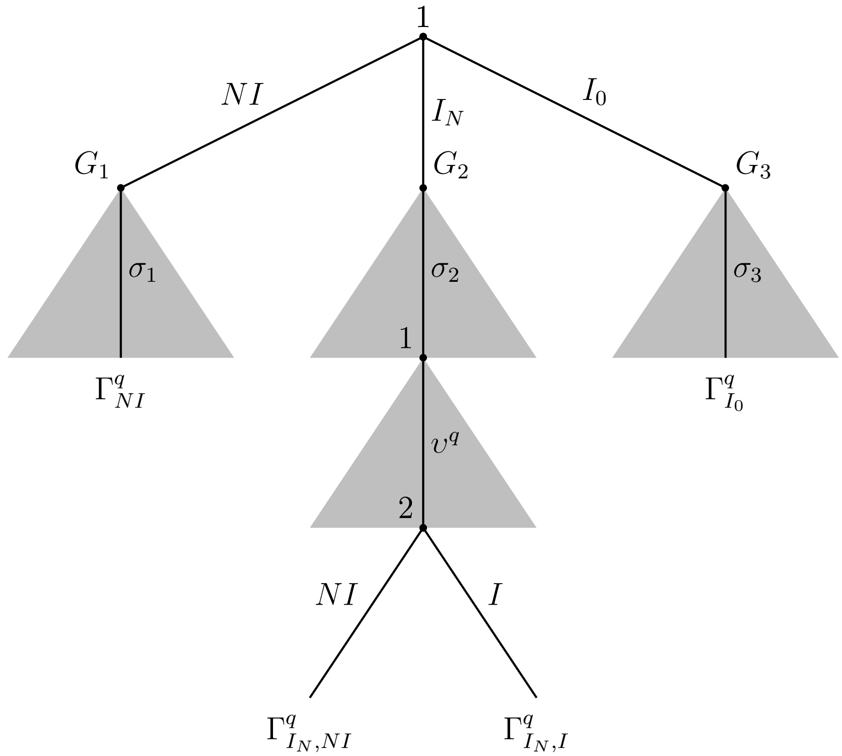

Figure 2: Extensive-form game representation, no pre-commitment case, quota policy. The actions of the government σ_i for each node G_i, $i = 1, 2, 3$, are defined as follows: $\sigma_1 = (\bar{x}_{NI}, f_{NI})$, $\sigma_2 = ((\bar{x}_{NI_N}, f_{NI_N}), (\bar{x}_{I_N}, f_{I_N}))$, $\sigma_3 = ((\bar{x}_{I_0}, f_{I_0}), (\bar{x}_{NI_0}, f_{NI_0}))$.

Stage III. Given the innovation decision of firm 1 and the decision of the government about the quotas and fines, firms 1, 2, ..., $N+1$ compete in quantities.

(IIIa) If firm 1 did not innovate, all firms have an identical cost function $C_{\mathrm{g}}(\cdot)$ and compete in quantities given the quota and fine levels $(\bar{x}_{NI}, f_{NI})$ (subgame Γ^q_{NI}).

(IIIb) If firm 1 did innovate and announced to offer N licenses in stage III, then firm 1 first offers licenses to N competitors for a royalty υ^q, given the quota and the fine levels $(\bar{x}_{I_N}, f_{I_N})$, $(\bar{x}_{NI_N}, f_{NI_N})$. Firms 2, 3, ..., $N+1$ (firms of type 2) can accept or reject this offer. Since firms of type 2 are identical, we assume that either all of them will reject the offer and operate with the new cost function $C_{\mathrm{g}}(\cdot)$ (competition in quantities will take place in subgame $\Gamma^q_{I_N,NI}$) or all of them will accept it and operate with cost function $C_{\mathrm{gn}}(\cdot)$ (competition in subgame $\Gamma^{q}_{I_N,I}$).

(IIIc) If firm 1 did innovate but announced that it will offer no licenses in stage III, then firm 1, operating with cost function $C_{\mathrm{gn}}(\cdot)$, and firms of type 2, operating with cost function $C_{\mathrm{g}}(\cdot)$, compete in quantities, given their quota and fine levels $(\bar{x}_{I_0}, f_{I_0})$, $(\bar{x}_{NI_0}, f_{NI_0})$ (subgame $\Gamma^{q}_{I_0}$).

These three decision stages define an extensive-form game as shown in Figure 2. Like in the subsidy case, we apply the solution concept of the Subgame Perfect Equilibrium (SPE).

Lemma 2.2.1. *In stage IIIa (subgame Γ^{q}_{NI}), all firms produce quantity*

$$x_{i\mathrm{g}}(NI, f_{NI}) = \frac{c_{\mathrm{b}} - b_1 + f_{NI}}{2b_2}.$$

Proof: see Appendix on p.31.

Lemma 2.2.2. *In stage IIIb, firm 1's equilibrium offer υ^{q*} is given by*

$$\upsilon^{*q} = \begin{cases} \upsilon^{q\max} & \text{if } \upsilon^{q\max} < \dfrac{c_{\mathrm{b}} - b_{1\mathrm{n}} + f_{I_N}}{2}; \\ \dfrac{c_{\mathrm{b}} - b_{1\mathrm{n}} + f_{I_N}}{2} & \text{otherwise.} \end{cases}$$

where

$$\upsilon^{q\max} = \sqrt{(c_{\mathrm{b}} - b_1 + f_{I_N})^2 + 4b_2(f_{NI_N}\bar{x}_{NI_N} - f_{I_N}\bar{x}_{I_N})} - (c_{\mathrm{b}} - b_{1\mathrm{n}} + f_{I_N}).$$

This offer is always accepted by firms of type 2 in the equilibrium[8]. *Firm 1 produces quantity*

$$x_{1\mathrm{g}}(I_N, (f_{NI_N}, f_{I_N}), \upsilon^q) = \frac{c_{\mathrm{b}} - b_{1\mathrm{n}} + f_{I_N}}{2b_2}.$$

The quantity of green electricity produced by any firm of type 2, $x_{2\mathrm{g}}(I_N, (f_{NI_N}, f_{I_N}, \bar{x}_{I_N}, \bar{x}_{NI_N}))$, amounts to

$$\begin{cases} \dfrac{2(c_b - b_1 + f_{NI_N}) - \sqrt{(c_{\mathrm{b}} - b_1 + f_{I_N})^2 + 4b_2(f_{NI_N}\bar{x}_{NI_N} - f_{I_N}\bar{x}_{I_N})}}{2b_2} & \text{if } \upsilon^{q\max} < \dfrac{c_{\mathrm{b}} - b_{1\mathrm{n}} + f_{I_N}}{2}; \\ \dfrac{c_{\mathrm{b}} - b_{1\mathrm{n}} + f_{I_N}}{4b_2} & \text{otherwise.} \end{cases}$$

[8] By assumption, firms of type 2 adopt the new technology if indifferent.

Proof: see Appendix on p.32.

Lemma 2.2.3. *In stage IIIb (subgame $\Gamma^q_{I_0}$), quantities of green electricity produced by firm 1 and firms of type 2, respectively, are given by*

$$\begin{aligned} x_{1\text{g}}(I_0, f_{NI_0}) &= \frac{c_\text{b} - b_{1\text{n}} + f_{I_0}}{2b_2}; \\ x_{2\text{g}}(I_0, f_{NI_0}) &= \frac{c_\text{b} - b_1 + f_{NI_0}}{2b_2}. \end{aligned}$$

Proof: see Appendix on p.34.

Lemma 2.2.4. *In stage IIa (subgame starting at node G_1), the government chooses fine level*

$$f^*_{NI} = \frac{b_2 d_1 - d_2(N+1)(c_\text{b} - b_1)}{b_2 + d_2(N+1)},$$

while the quota level $\bar{x}_{NI}$ can be deliberately set by the government.

Proof: see Appendix on p.34.

Lemma 2.2.5. *In stage IIb (subgame starting at node G_2), the optimal decision of the government is given by any combination of fines*

$$(f^*_{NI_N}, f^*_{I_N}) = \left(f^*_{NI_N}, \frac{[2b_2 N - d_2(N+2)^2](c_\text{b} - b_{1\text{n}}) + 2(N+2)b_2 d_1}{d_2(N+2)^2 + 4b_2} \right)$$

where $f^*_{NI_N}$ satisfies inequality

$$\sqrt{(c_\text{b} - b_1 + f^*_{I_N})^2 + 4b_2(f^*_{NI_N}\bar{x}_{NI_N} - f^*_{I_N}\bar{x}_{I_N})} \;\geq\; \frac{3}{2}(c_\text{b} - b_{1\text{n}} + f^*_{I_N}). \tag{5}$$

The government's choice of quotas $\bar{x}_{NI_N}, \bar{x}_{I_N}$ is constrained by inequality (5).

Proof: see Appendix on p.35.

Lemma 2.2.6. *In stage IIc (subgame starting at node G_3), government chooses fine levels*

$$f^*_{NI_0} = f^*_{I_0} = \frac{b_2 d_1 - d_2(N+1)(c_\text{b} - b_1) - d_2(b_1 - b_{1\text{n}})}{b_2 + d_2(N+1)}.$$

Proof: see Appendix on p.36.

Proposition 2.2.7. *The subgame-perfect equilibrium strategies on the equilibrium path of this game are given as follows. Firm 1 does not innovate (NI) if* $\Delta b_1 \in \left(0, \frac{\sqrt{B^2-4AC}-B}{2A}\right]$, *where*

$$\begin{aligned}
A &= \frac{b_2}{4[b_2+d_2(N+1)]^2+r} > 0; \\
B &= \frac{d_2(N+1)}{b_2+d_2(N+1)}\bar{x}_{NI} - \frac{2b_2}{4[b_2+d_2(N+1)]^2\beta}; \\
C &= -\alpha\beta^2 - \left(\frac{d_2(N+1)}{b_2+d_2(N+1)} + d_1\right)\bar{x}_{NI} - \left(\frac{d_2(N+2)^2-2b_2N}{4b_2+d_2(N+2)^2}\beta + d_1\right)\bar{x}_I < 0
\end{aligned}$$

with

$$\begin{aligned}
\alpha &= \frac{b_2}{4}\left(\frac{2(N+2)^3}{[4b_2+d_2(N+2)^2]^2} - \frac{1}{[b_2+d_2(N+1)]^2}\right) > 0; \\
\beta &= c_\mathrm{b} - b_{1\mathrm{n}} + d_1 > 0,
\end{aligned}$$

and innovates and offers N licenses (I_N) *otherwise. It offers N licenses in return of a royalty*

$$v^{*q} = \frac{b_2(N+2)(c_\mathrm{b}-b_{1\mathrm{n}}+d_1)}{d_2(N+2)^2+4b_2}$$

and produces quantities of green electricity

$$\begin{aligned}
x^*_{1\mathrm{g}}(NI) &= \frac{c_\mathrm{b}-b_1+d_1}{2[b_2+d_2(N+1)]}, \\
x^*_{1\mathrm{g}}(I_N) &= \frac{(N+2)(c_\mathrm{b}-b_{1\mathrm{n}}+d_1)}{d_2(N+2)^2+4b_2}.
\end{aligned}$$

Government chooses fine levels

$$\begin{aligned}
f^*_{NI} &= \frac{b_2d_1 - d_2(N+1)(c_\mathrm{b}-b_1)}{b_2+d_2(N+1)}, \\
f^*_{NI_N} &\geq \frac{\{[2b_2N-(N+2)^2d_2](c_\mathrm{b}-b_{1\mathrm{n}}) + 2(N+2)b_2d_1\}\,\bar{x}_I}{\bar{x}_{NI}} \\
&\quad + \frac{5\left[2b_2N(c_\mathrm{b}-b_{1\mathrm{n}}) - d_2(N+2)^2(b_1-b_{1\mathrm{n}}) + 2(N+2)b_2d_1 - 4b_2b_1\right]^2}{16b_2[4b_2+(N+2)^2d_2]^2\bar{x}_{NI}}, \\
f^*_{I_N} &= \frac{[2b_2N - d_2(N+2)^2](c_\mathrm{b}-b_{1\mathrm{n}}) + 2(N+2)b_2d_1}{d_2(N+2)^2+4b_2}.
\end{aligned}$$

Firms of type 2 innovate (I) if firm 1 offered N licenses and produce quantities

$$\begin{aligned} x^*_{2\mathrm{g}}(NI) &= \frac{c_\mathrm{b} - b_1 + d_1}{2[b_2 + d_2(N+1)]}, \\ x^*_{2\mathrm{g}}(I_N) &= \frac{(N+2)(c_\mathrm{b} - b_{1\mathrm{n}} + d_1)}{2[d_2(N+2)^2 + 4b_2]}. \end{aligned}$$

Proof: see Appendix on p.36.

2.3 Comparison between subsidy and quota-based policies

In Madlener et al. (2009) it is shown that, in perfectly competitive markets, subsidy and quota policies are equivalent in terms of social welfare maximization. In this study, we have particularly shown that in the subgame-perfect equilibria all fine levels correspond to the subsidy levels.

However, the allocation of welfare to producer vs. consumer surplus differs under these two alternative policies. In particular, the profits achieved by the potential innovator as well as by its competitors are lower under the quota policy (π^q) than under the subsidy policy (π^s) regime:

$$\begin{aligned} \pi^q_1(NI) &= \pi^s_1(NI) - f^*(NI)\bar{x}_{NI}; \\ \pi^q_2(NI) &= \pi^s_2(NI) - f^*(NI)\bar{x}_{NI}; \\ \pi^q_1(I_N) &= \pi^s_1(I_N) - f^*(I_N)\bar{x}_{I_N}; \\ \pi^q_2(I_N) &= \pi^s_2(I_N) - f^*(I_N)\bar{x}_{I_N}. \end{aligned}$$

Thus, given a no pre-commitment policy, the firms have a strict preference for price rather then quantity controls.

Next, we want to investigate under which policy regime (subsidy or quota) the incentives to innovate are higher. Therefore, we compare the differences of profits of the potential innovator (firm 1) with or without innovation under both regimes. For the subsidy policy, this gain from innovation amounts to

$$\Delta\pi^s_1 = \pi^s_1(I_N) - \pi^s_1(NI).$$

Under the quota policy, the corresponding profit difference is

$$\Delta\pi_1^q \;=\; \pi_1^q(I_N) - \pi_1^q(NI).$$

The incentives to innovate are higher under the subsidy policy if

$$\Delta\pi_1^s - \Delta\pi_1^q \;=\; f_{I_N}^*\bar{x}_{I_N} - f_{NI}^*\bar{x}_{NI} > 0. \tag{6}$$

Suppose that the difference between the quota levels $(\bar{x}_{I_N} - \bar{x}_{NI})$ is sufficiently small. Then it can be shown that under the assumption that $d_2(N+1)(c_{\mathrm{b}} - b_{1\mathrm{n}}) < b_2 d_1$, as made in our model, condition (6) is satisfied. Therefore, not only is the subsidy policy preferred by profit-maximizing firms but it also provides a higher incentive to innovate, which is an interesting finding.

3 Optimal policy in the presence of innovation: pre-commitment case

In the pre-commitment case, the government is assumed to stick to its green electricity policy (in terms of subsidy and quota) even under innovation. Possible reasons for pre-commitment include: imperfect information, limited ability for short-run policy adjustments etc. Compared to the no pre-commitment assumption, pre-commitment appears to be more realistic, because in the real world there are always difficulties in adjusting policies, for reasons like the ones described above. Besides, there may be other costs associated with policy adjustment, similar to the menu costs in the price adjustment case, that further stymies quick policy reaction to innovations.

We maintain the basic assumptions made in the no pre-commitment case, except that the quota and subsidy levels remain unchanged after the innovation has occurred.

3.1 Subsidy policy

We consider an extensive-form game presented in Fig. 3. There are two decision stages.

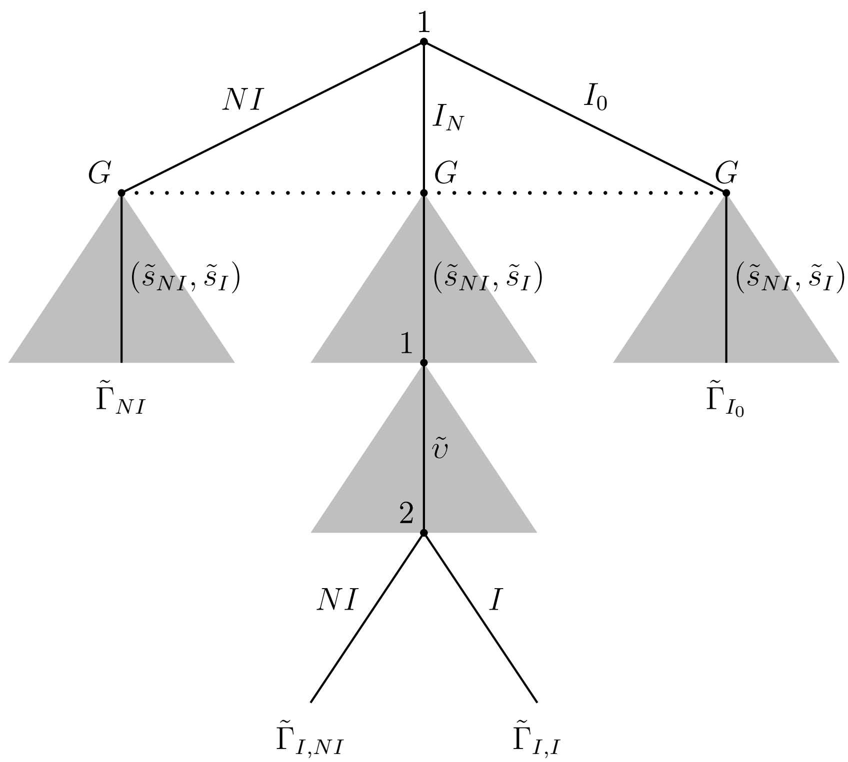

Figure 3: Extensive-form game representation, pre-commitment case, subsidy policy

Stage I. Firm 1 decides either not to innovate (NI), to innovate and offer N licenses in the competition stage II (I_N), or to innovate and offer no licenses in stage II (I_0). Simultaneously, the government determines the subsidy levels $\tilde{s}_{NI}$ for non-innovating and $\tilde{s}_I$ for innovating firms in order to maximize social welfare.

Stage II. Given the innovation decision of firm 1 and the decision of the government about the subsidy level, firms 1, 2, ..., $N+1$ compete in quantities.

(IIa) If firm 1 did not innovate, all firms have identical cost functions $C_{\mathrm{g}}(\cdot)$ and compete in quantities given the subsidy level $\tilde{s}_{NI}$ per unit of green electricity (subgame $\tilde{\Gamma}_{NI}$).

(IIb) If firm 1 did innovate and announced to offer N licenses in stage II, then it first offers licenses to N competitors in return of a royalty $\tilde{v}$ given the subsidy levels $\tilde{s}_I$ and $\tilde{s}_{NI}$. Firms 2, 3, ..., $N+1$ can either accept or reject this offer. Since firms 2, 3, ...,

$N+1$ are identical, we assume that either all of them will reject the offer and operate with cost function $C_{\mathrm{g}}(\cdot)$ (competition in quantities will take place in subgame $\tilde{\Gamma}_{I,NI}$) or all of them will accept it and operate with cost function $C_{\mathrm{gn}}(\cdot)$ (competition in subgame $\tilde{\Gamma}_{I,I}$).

(IIc) If firm 1 did innovate but announced that it will offer no licenses in stage 3, then firm 1, operating with cost function $C_{\mathrm{gn}}(\cdot)$, and firms 2, 3, …, $N+1$, operating with cost function $C_{\mathrm{g}}(\cdot)$, compete in quantities given their subsidy levels $\tilde{s}_I$ and $\tilde{s}_{NI}$, respectively.

Proposition 3.1.1. *There exist two sets of subgame-perfect equilibria in the innovation game with subsidy control and pre-commitment policy. The subgame-perfect equilibrium strategies on the equilibrium path of these two sets are given as follows.*

Set 1. *Firm 1 does not innovate (NI) and produces quantity*

$$x^*_{1\mathrm{g}}(NI, (\tilde{s}^{*1}_{NI}, \tilde{s}^{*1}_I)) \;=\; \frac{c_{\mathrm{b}} - b_1 + d_1}{2[b_2 + d_2(N+1)]}$$

of green electricity. Government chooses subsidy levels $(\tilde{s}^{*1}_{NI}, \tilde{s}^{*1}_I)$ *such that*

$$\begin{aligned}
\tilde{s}^{*1}_{NI} &= \frac{b_2 d_1 - d_2(N+1)(c_{\mathrm{b}} - b_1)}{b_2 + d_2(N+1)};\\
\tilde{s}^{*1}_{I} &\in \left[-(c_{\mathrm{b}} - b_{1\mathrm{n}}) \pm \sqrt{\frac{2b_2}{N+2}\left(\frac{b_2(c_{\mathrm{b}} - b_1 + d_1)^2}{[b_2 + d_2(N+1)]^2} + 4r(\Delta b_1)^2\right)}\right].
\end{aligned}$$

Firms of type 2 produce quantity

$$x^*_{2\mathrm{g}}(NI, (\tilde{s}^{*1}_{NI}, \tilde{s}^{*1}_I)) \;=\; \frac{c_{\mathrm{b}} - b_1 + d_1}{2[b_2 + d_2(N+1)]}$$

of green electricity.

Set 2. *Firm 1 innovates and offers N licenses* (I_N) *in return of a royalty*

$$\tilde{v}^* \;=\; \frac{b_2(N+2)(c_{\mathrm{b}} - b_1 + d_1)}{d_2(N+2)^2 + 4b_2}$$

per unit of green electricity produced by firms of type 2 and itself produces quantity

$$x^*_{1\mathrm{g}}(I_N, (\tilde{s}^{*2}_{NI}, \tilde{s}^{*2}_I) \;=\; \frac{(N+2)(c_{\mathrm{b}} - b_{1\mathrm{n}} + d_1)}{d_2(N+2)^2 + 4b_2}$$

of green electricity. Government sets subsidy levels $(\tilde{s}^{*2}_{NI}, \tilde{s}^{*2}_{I})$ *such that*

$$\begin{aligned} \tilde{s}^{*2}_{NI} &\in \left[-(c_\mathrm{b} - b_1) \pm \sqrt{b_2\left(\frac{b_2(N+2)^3(c_\mathrm{b} - b_{1\mathrm{n}} + d_1)^2}{[4b_2 + d_2(N+2)^2]^2} - 4r(\Delta b_1)^2\right)}\right]; \\ \tilde{s}^{*2}_{I} &= \frac{[2b_2N - d_2(N+2)^2](c_\mathrm{b} - b_{1\mathrm{n}}) + 2(N+2)b_2d_1}{d_2(N+2)^2 + 4b_2}. \end{aligned}$$

Firms of type 2 innovate (I) and produce quantity

$$x^*_{2\mathrm{g}}(I_N, (\tilde{s}^{*2}_{NI}, \tilde{s}^{*2}_{I}) = \frac{(N+2)(c_\mathrm{b} - b_{1\mathrm{n}} + d_1)}{2[d_2(N+2)^2 + 4b_2]}$$

of green electricity.

Proof: see Appendix on p.37.

3.2 Quota-based policy

Now we consider an extensive-form game with the structure presented in Figure 4. As under the subsidy policy, there are two decision stages.

Stage I. Firm 1 decides either not to innovate (NI), to innovate and offer N licenses in the competition stage II (I_N), or to innovate and offer no licenses in stage II (I_0). Simultaneously, the government determines the fine levels $\tilde{f}_{NI}$ for non-innovating and $\tilde{f}_I$ for innovating firms in order to maximize social welfare.

Stage II. Given the innovation decision of firm 1 and the decision of the government about the subsidy level, firms 1, 2, ..., $N+1$ compete in quantities.

(IIa) If firm 1 did not innovate, all firms have identical cost functions $C_\mathrm{g}(\cdot)$ and compete in quantities given the fine level $\tilde{f}_{NI}$ per unit of green electricity (subgame $\tilde{\Gamma}^q_{NI}$).

(IIb) If firm 1 did innovate and announced to offer N licenses in stage II, then it first offers licenses to N competitors in return of a royalty $\tilde{v}^q$ given the fine levels $\tilde{f}_I$ and $\tilde{f}_{NI}$. Firms 2, 3, ..., $N+1$ can either accept or reject this offer. Since firms 2, 3, ..., $N+1$ are identical, we assume that either all of them will reject the offer and operate with cost function $C_\mathrm{g}(\cdot)$ (competition in quantities will take place in subgame $\tilde{\Gamma}^q_{I,NI}$)

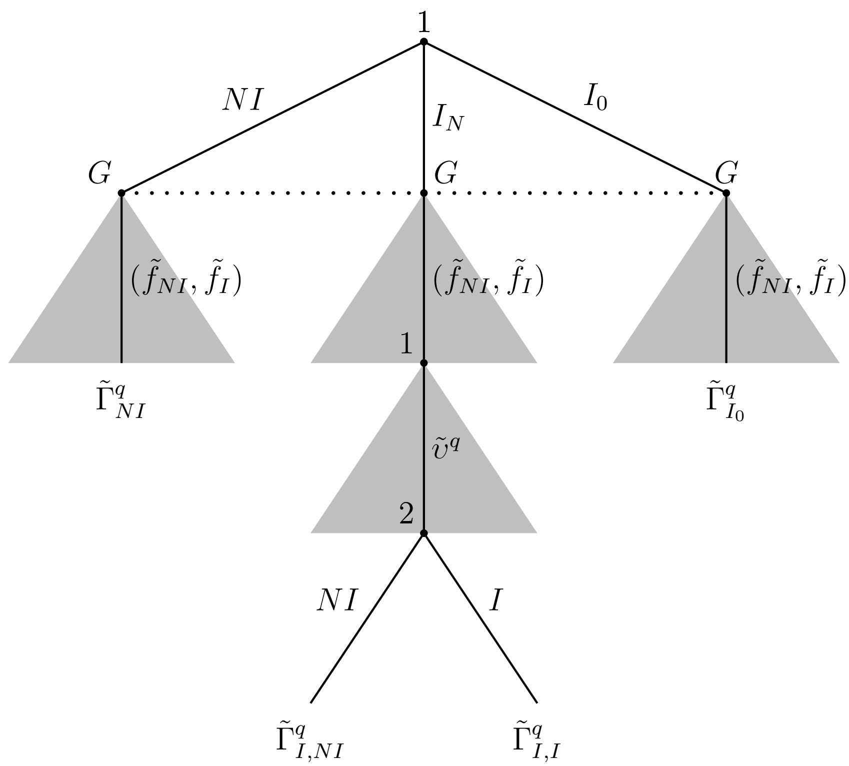

Figure 4: Extensive-form game representation, pre-commitment case, quota policy

or all of them will accept it and operate with cost function $C_{\rm gn}(\cdot)$ (competition in subgame $\tilde{\Gamma}^q_{I,I}$).

(IIc) If firm 1 did innovate but announced that it will offer no licenses in stage 3, then firm 1, operating with cost function $C_{\rm gn}(\cdot)$, and firms 2, 3, …, $N+1$, operating with cost function $C_{\rm g}(\cdot)$, compete in quantities given their fine levels $\tilde{f}_I$ and $\tilde{f}_{NI}$, respectively.

Proposition 3.2.1. *There exist two sets of subgame-perfect equilibria strategies in the pre-commitment game with quotas. The subgame-perfect equilibrium strategies on the equilibrium path of this game are given as follows.*

Set 1. *Firm 1 does not innovate (NI) and produces quantity*

$$x^*_{1\rm g}(NI, (\tilde{f}^{*1}_{NI}, \tilde{f}^{*1}_I)) \quad = \quad \frac{c_{\rm b} - b_1 + d_1}{2[b_2 + d_2(N+1)]}$$

of green electricity. Government sets fine levels $(\tilde{f}_{NI}^{*1}, \tilde{f}_I^{*1})$ *such that*

$$\begin{aligned}
\tilde{f}_{NI}^{*1} &= \frac{b_2 d_1 - d_2(N+1)(c_{\mathrm{b}} - b_1)}{b_2 + d_2(N+1)}; \\
\tilde{f}_I^{*1} &\in \left[-(c_{\mathrm{b}} - b_{1\mathrm{n}}) + 4b_2\bar{x}_I \pm \frac{\xi\sqrt{2b_2}}{(N+2)[b_2 + (N+1)d_2]}\right],
\end{aligned}$$

where $\bar{x}_I$ *denotes the minimum quota to be produced by an innovating firm, and*

$$\xi = \sqrt{8b_2^3\bar{x}_I^2 + 4(N+1)^2(N+2)d_2^2\delta + 4b_2^2\epsilon + b_2\eta},$$

with

$$\begin{aligned}
\delta &= r(\Delta b_1)^2 - (c_{\mathrm{b}} - b_{1\mathrm{n}})\bar{x}_I - (c_{\mathrm{b}} - b_1)\bar{x}_{NI}; \\
\epsilon &= (N+2)r(\Delta b_1)^2 + 4(N+1)d_2\bar{x}_I^2 - (N+2)[(c_{\mathrm{b}} - b_{1\mathrm{n}})\bar{x}_I + d_1\bar{x}_{NI}]; \\
\eta &= (N+2)[(c_{\mathrm{b}} - b_1 + d_1)^2 - 2c_{\mathrm{b}}d_1] + \\
&\quad +4(N+1)d_2[2(N+2)r(\Delta b_1)^2 + 2(N+1)d_2\bar{x}_I^2 + 2b_{1\mathrm{n}}\bar{x}_I - (N+2)(c_{\mathrm{b}} + b_1)\bar{x}_{NI})].
\end{aligned}$$

Firms of type 2 produce quantity

$$x_{2\mathrm{g}}^*(NI, (\tilde{f}_{NI}^{*1}, \tilde{f}_I^{*1})) = \frac{c_{\mathrm{b}} - b_1 + d_1}{2[b_2 + d_2(N+1)]}$$

of green electricity.

Set 2. *Firm 1 innovates and offers N licenses* (I_N) *in return of a royalty*

$$\tilde{\upsilon}^{*q} = \frac{b_2(N+2)(c_{\mathrm{b}} - b_{1\mathrm{n}} + d_1)}{d_2(N+2)^2 + 4b_2}$$

per unit of green electricity produced by firms of type 2 and itself produces quantity

$$x_{1\mathrm{g}}^*(I_N, (\tilde{f}_{NI}^{*2}, \tilde{f}_I^{*2}) = \frac{(N+2)(c_{\mathrm{b}} - b_{1\mathrm{n}} + d_1)}{d_2(N+2)^2 + 4b_2}$$

of green electricity. Government sets fine levels $(\tilde{f}_{NI}^{*2}, \tilde{f}_I^{*2})$ *such that*

$$\begin{aligned}
\tilde{f}_{NI}^{2} &\in \left[-(c_{\mathrm{b}} - b_{1\mathrm{n}}) + 2b_2\bar{x}_{NI} \pm \frac{\psi\sqrt{2b_2}}{4b_2 + (N+2)^2 d_2}\right]; \\
\tilde{f}_I^{*2} &= \frac{[2b_2N - d_2(N+2)^2](c_{\mathrm{b}} - b_{1\mathrm{n}}) + 2(N+2)b_2 d_1}{d_2(N+2)^2 + 4b_2},
\end{aligned}$$

where $\bar{x}_{NI}$ denotes the minimum quota to be produced by a non-innovating firm, and

$$\psi = \sqrt{32b_2^3\bar{x}_{NI}^2 - 2(N+2)^4\kappa - 16b_2^2\mu + (N+2)^2 b_2\nu + 2b_{1\mathrm{n}}\rho + 2d_2\tau}$$

with

$$\begin{aligned}
\kappa &= r(\Delta b_1)^2 - (c_{\mathrm{b}} - b_{1\mathrm{n}})\bar{x}_I - (c_{\mathrm{b}} - b_1)\bar{x}_{NI};\\
\mu &= 2r(\Delta b_1)^2 + [N(c_{\mathrm{b}} - b_{1\mathrm{n}} + d_1) + 2d_1]\bar{x}_I + [2(c_{\mathrm{b}} - b_1) - (N+2)^2 d_2\bar{x}_{NI}]\bar{x}_{NI};\\
\nu &= (N+2)[(c_{\mathrm{b}} - b_{1\mathrm{n}} + d_1)^2 + 2b_{1\mathrm{n}}(c_{\mathrm{b}} + d_1) - 4(N+2)d_2\bar{x}_I;\\
\rho &= 2(N-2)d_2\bar{x}_I - (N+2)(c_{\mathrm{b}} + d_1);\\
\tau &= \bar{x}_{NI}[(N+2)^2 d_2\bar{x}_{NI} - 8(c_{\mathrm{b}} - b_1)] - 2c_{\mathrm{b}}(N-2)\bar{x}_I - 8r(\Delta b_1)^2.
\end{aligned}$$

Firms of type 2 innovate (I) and each produce quantity

$$x^*_{2\mathrm{g}}(I_N, (\tilde{f}^{*2}_{NI}, \tilde{f}^{*2}_I) = \frac{(N+2)(c_{\mathrm{b}} - b_{1\mathrm{n}} + d_1)}{2[d_2(N+2)^2 + 4b_2]}$$

of green electricity.

Proof: see Appendix on p.39.

3.3 Comparison between subsidy and quota-based policy

Under pre-commitment, the subsidy and quota policies again are equivalent in terms of social welfare. However, the firms prefer the subsidy policy since they achieve higher profits than under the quota policy.

Furthermore, as under no pre-commitment, the profits achieved by the potential innovator as well as by its competitors are lower under the quota policy (π^q) than under the subsidy policy (π^s):

$$\begin{aligned}
\pi_1^q(NI) &= \pi_1^s(NI) - \tilde{f}^*(NI)\bar{x}_{NI};\\
\pi_2^q(NI) &= \pi_2^s(NI) - \tilde{f}^*(NI)\bar{x}_{NI};\\
\pi_1^q(I_N) &= \pi_1^s(I_N) - \tilde{f}^*(I_N)\bar{x}_{I_N};\\
\pi_2^q(I_N) &= \pi_2^s(I_N) - \tilde{f}^*(I_N)\bar{x}_{I_N}.
\end{aligned}$$

Thus, the firms have a strict preference for the subsidy policy under pre-commitment, too.

Again, as in the no pre-commitment case, the innovation incentives are higher under the subsidy policy:

$$\Delta\pi_1^s - \Delta\pi_1^q \;=\; \tilde{f}^*_{I_N}\bar{x}_{I_N} - \tilde{f}^*_{NI}\bar{x}_{NI} > 0. \qquad (7)$$

4 Discussion and Conclusions

Madlener et al. (2009) found that the conventional wisdom related to the equivalence of tax (subsidy) and quota (certificate) schemes in terms of static efficiency may not hold if markets for electric power are imperfectly competitive. Due to the inequivalence found in terms of social welfare, the authors recommend targeted subsidies as being the preferable policy instrument.

In this paper, we have followed up studying the merits of price and quantity control policies for promoting renewable electricity generation. In particular, we study the role of government regulatory pre-commitment when technical innovation is present.

In the pre-commitment case, the government is assumed to stick to its green electricity policy (in terms of subsidy and quota) even under innovation. Possible reasons for pre-commitment include: imperfect information, limited ability for short-run policy adjustments etc. Compared to the no pre-commitment assumption, pre-commitment appears to be more realistic, because in the real world there are always difficulties in adjusting policies, for reasons like the ones described above. Besides, there may be other costs associated with policy adjustment, similar to the menu costs in the price adjustment case, that further stymies quick policy reaction to innovations.

We maintain the basic assumptions made in the no pre-commitment case, except that the quota and subsidy levels remain unchanged after the innovation occurred. We can conclude that the difference is larger without pre-commitment, i.e. the subsidy scheme is preferred more in the case of no pre-commitment.

Thus we find that the price (subsidy) policy is again preferred in terms of promoting innovation of green electricity technology. The intuition behind the result is also the same as that under the no pre-commitment case. Since technological improvement and innovation mainly represent the dynamic aspect of energy efficiency for a firm (and also for an economy), our results strongly support the subsidy policy in terms of its dynamic efficiency in general, no matter which policy regime, pre-commitment or no pre-commitment, is feasible (or followed) in the real world.

An important finding concerns the issue whether the existence of equilibrium solutions depend on pre-commitment. The sets of subgame-perfect equilibria derived in this paper confirm that pre-commitment can influence the equilibrium conditions. In particular, under no pre-commitment a sufficiently high cost reduction would necessarily lead to innovation and exclude the possibility that no innovation occurs. By way of contrast, both equilibria are possible under pre-commitment even if the cost reduction by the innovation is high. Still, under pre-commitment an equilibrium with innovation remains possible in a case of a relatively low cost reduction as opposed to the no pre-commitment case. It follows that a government with a preference for innovations being performed if the achievable cost reduction is high (and otherwise not) should be in favor of the no pre-commitment regime.

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A Appendix

Proof of Lemma 2.1.1 Suppose that firm 1 does not innovate in stage I, i.e. it chooses action NI. The subsidy level chosen by the government for all firms in stage II is s_{NI}. Given a competitive market in stage III, a representative power generator i faces the optimization problem

$$\max_{x_{i\mathrm{b}},x_{i\mathrm{g}}} [px_{i\mathrm{b}} + (p + s_{NI})x_{i\mathrm{g}} - C_{\mathrm{b}}(x_{i\mathrm{b}}) - C_{\mathrm{g}}(x_{i\mathrm{g}})], \tag{A.1}$$

where $x_{i\mathrm{b}}$ and $x_{i\mathrm{g}}$ denote the amounts of electricity produced by firm i from fossil/nuclear ('brown') and renewable ('green') energy sources, respectively, and p, the average market price for electricity. The f.o.c. for an interior solution are

$$p \quad -C'_{\mathrm{b}}[x^*_{i\mathrm{b}}] = 0 \tag{A.2}$$

$$p \quad +s_{NI} - C'_{\mathrm{g}}[x^*_{i\mathrm{g}}] = 0. \tag{A.3}$$

Inserting (A.2) into (A.3) reveals that in an optimum with $x_{i\mathrm{b}} > 0$ and $x_{i\mathrm{g}} > 0$, the government subsidy s_{NI} has to be equal to the difference (in absolute terms) between $C'_{\mathrm{g}}[x^*_{i\mathrm{g}}]$ and c_{b}, i.e. the marginal costs of green electricity evaluated at the optimum and the constant marginal cost of brown electricity. The intuition behind this result from an economic perspective is that if $s_{NI} > C'_{\mathrm{g}}[x^*_{i\mathrm{g}}] - c_{\mathrm{b}}$, then all generators will exclusively supply green electricity. In contrast, if $s_{NI} < C'_{\mathrm{g}}[x^*_{i\mathrm{g}}] - c_{\mathrm{b}}$, no green electricity at all will be provided. Given the assumptions of a competitive market and homogeneous costs, the subgame solution is described by (A.2) and (A.3). In particular, all firms produce the same quantity of green electricity given by

$$x_{i\mathrm{g}}(NI, s_{NI}) \quad = \quad \frac{c_{\mathrm{b}} - b_1 + s_{NI}}{2b_2}, \tag{A.4}$$

while each firm's profit amounts to

$$\pi_i(NI, s_{NI}) = \frac{(c_{\mathrm{b}} - b_1 + s_{NI})^2}{4b_2}. \tag{A.5}$$

Proof of Lemma 2.1.2 Suppose that firm 1 innovates and announces to offer N licenses. The government determines welfare-maximizing subsidy levels s_{NI_N} for non-innovating and s_{I_N} for innovating firms. We denote the royalty for the new technology per unit of green power as υ. In equilibrium, it must not exceed the cost difference $C_{\mathrm{g}}(x_{2\mathrm{g}}) - C_{\mathrm{gn}}(x_{2\mathrm{g}})$, as otherwise there is no incentive to switch to the new technology.

Subgame $\Gamma_{I_N,NI}$. Suppose that firms 2, 3, ..., $N+1$ (from here on: firms of type 2) rejected firm 1's offer. Then firm 1 operates with the new cost function $C_{\mathrm{gn}}(x_{1\mathrm{g}})$ while firms of type 2 continue to operate with the cost function $C_{\mathrm{g}}(x_{2\mathrm{g}})$. Thus, firm 1's profit maximization problem is given by

$$\max_{x_{1\mathrm{b}},x_{1\mathrm{g}}} [px_{1\mathrm{b}} + (p + s_{I_N})x_{1\mathrm{g}} - C_{\mathrm{b}}(x_{1\mathrm{b}}) - C_{\mathrm{gn}}(x_{1\mathrm{g}}) - R(b_1 - b_{1\mathrm{n}})], \tag{A.6}$$

while firm 2's profit maximization problem corresponds to (A.1) with $i = 2$ and $s_{NI} = s_{NI_N}$. Thus, quantities of green electricity produced by firm 1 and firms of type 2 are given by

$$\begin{aligned} x_{1\mathrm{g}}(I_N, (s_{NI_N}, s_{I_N}), \upsilon, NI) &= \frac{c_{\mathrm{b}} - b_{1\mathrm{n}} + s_{I_N}}{2b_2}; \\ x_{2\mathrm{g}}(I_N, (s_{NI_N}, s_{I_N}), \upsilon, NI) &= \frac{c_{\mathrm{b}} - b_1 + s_{NI_N}}{2b_2}, \end{aligned}$$

and firms' profits therefore amount to

$$\begin{aligned} \pi_1(I_N, (s_{NI_N}, s_{I_N}), \upsilon, NI) &= \frac{(c_{\mathrm{b}} - b_{1\mathrm{n}} + s_{I_N})^2}{4b_2} - R(b_1 - b_{1\mathrm{n}}); \\ \pi_2(I_N, (s_{NI_N}, s_{I_N}), \upsilon, NI) &= \frac{(c_{\mathrm{b}} - b_1 + s_{NI_N})^2}{4b_2}. \end{aligned}$$

Subgame $\Gamma_{I_N,I}$. Now suppose that firms of type 2 accept firm 1's offer and pay a royalty of υ per unit of green electricity produced. Then all firms operate with the new cost function $C_{\mathrm{gn}}(x_{\mathrm{g}})$. The profit maximization problems of firm 1 and firms of type 2 are respectively given by

$$\max_{x_{1\mathrm{b}},x_{1\mathrm{g}}} [px_{1\mathrm{b}} + (p + s_{I_N})x_{1\mathrm{g}} - C_{\mathrm{b}}(x_{1\mathrm{b}}) - C_{\mathrm{gn}}(x_{1\mathrm{g}}) + N\upsilon x_{2\mathrm{g}} - R(b_1 - b_{1\mathrm{n}})]; \tag{A.7}$$

$$\max_{x_{2\mathrm{b}},x_{2\mathrm{g}}} [px_{2\mathrm{b}} + (p + s_{I_N})x_{2\mathrm{g}} - C_{\mathrm{b}}(x_{2\mathrm{b}}) - C_{\mathrm{gn}}(x_{2\mathrm{g}}) - \upsilon x_{2\mathrm{g}}]; \tag{A.8}$$

the quantities of green electricity produced are

$$\begin{aligned} x_{1\mathrm{g}}(I_N, (s_{NI_N}, s_{I_N}), \upsilon, I) &= \frac{c_{\mathrm{b}} - b_{1\mathrm{n}} + s_{I_N}}{2b_2}; \\ x_{2\mathrm{g}}(I_N, (s_{NI_N}, s_{I_N}), \upsilon, I) &= \frac{c_{\mathrm{b}} - (b_{1\mathrm{n}} + \upsilon) + s_{I_N}}{2b_2}. \end{aligned}$$

The firms' profits thus amount to

$$\pi_1(I_N,(s_{NI_N},s_{I_N}),\upsilon,I) = \frac{(c_\mathrm{b}-b_{1\mathrm{n}}+s_{I_N})^2}{4b_2}+N\upsilon\frac{c_\mathrm{b}-(b_{1\mathrm{n}}+\upsilon)+s_{I_N}}{2b_2}-R(b_1-b_{1\mathrm{n}});$$

$$\pi_2(I_N,(s_{NI_N},s_{I_N}),\upsilon,I) = \frac{(c_\mathrm{b}-(b_{1\mathrm{n}}+\upsilon)+s_{I_N})^2}{4b_2}.$$

Firms of type 2 decide in stage IIIb whether to reject (NI) or accept (I) the offer, depending on the comparison of the maximum profits calculated for subgames $\Gamma_{I_N,NI}$ and $\Gamma_{I_N,I}$. Thus, their subgame-perfect equilibrium actions are given as follows:

$$\begin{cases} NI & \text{if} \quad \upsilon > \upsilon^{\max} := (b_1-b_{1\mathrm{n}})-(s_{NI_N}-s_{I_N}) \\ I & \text{if} \quad \text{otherwise.} \end{cases}$$

In other words, $\upsilon^{\max}$ is the highest possible royalty level at which firms of type 2 innovate.

Firm 1's decision in stage IIIb is based on the maximization of its profits w.r.t. royalty level υ. Notice that firm 1's profit, provided firms of type 2 accept the offer $\pi_1(I_N,(s_{NI_N},s_{I_N}),\upsilon,I)$, is always at least as high as if they reject it as long as $\upsilon\in[0,c_\mathrm{b}-b_{1\mathrm{n}}+s_{I_N}]$. Moreover, the profit function $\pi_1(I_N,(s_{NI_N},s_{I_N}),\upsilon,I)$ attains its maximum in υ at the royalty level $\upsilon=(c_\mathrm{b}-b_{1\mathrm{n}}+s_{I_N})/2$. Thus, taking into consideration the possible case of a corner solution, firm 1's equilibrium offer υ^* in stage IIIb is given by

$$\upsilon^* = \begin{cases} \upsilon^{\max}=(b_1-b_{1\mathrm{n}})-(s_{NI_N}-s_{I_N}) & \text{if } (b_1-b_{1\mathrm{n}})-(s_{NI_N}-s_{I_N}) < \dfrac{c_\mathrm{b}-b_{1\mathrm{n}}+s_{I_N}}{2}; \\ \dfrac{c_\mathrm{b}-b_{1\mathrm{n}}+s_{I_N}}{2} & \text{otherwise.} \end{cases}$$

This offer will always be accepted by a firm of type 2 in the equilibrium[9]. Green electricity produced by firm 2 in the subgame starting at node G_2 thus amounts to

$$x_{2\mathrm{g}}(I_N,(s_{NI_N},s_{I_N}),I) = \begin{cases} \dfrac{(c_b-b_1+s_{NI_N})}{2b_2} & \text{if } (b_1-b_{1\mathrm{n}})-(s_{NI_N}-s_{I_N}) < \dfrac{c_\mathrm{b}-b_{1\mathrm{n}}+s_{I_N}}{2}; \\ \dfrac{c_\mathrm{b}-b_{1\mathrm{n}}+s_{I_N}}{4b_2} & \text{otherwise.} \end{cases}$$

Firms' profits in this subgame are thus given by

$$\pi_1(I_N,(s_{NI_N},s_{I_N}),I) = \qquad \text{(A.9)}$$

$$= \begin{cases} \dfrac{(c_b-b_{1\mathrm{n}}+s_{I_N})^2}{4b_2}-R(b_1-b_{1\mathrm{n}})+ & \\ +N[(b_1-b_{1\mathrm{n}})-(s_{NI_N}-s_{I_N})]\frac{c_b-b_1+s_{NI_N}}{2b_2} & \text{if } (b_1-b_{1\mathrm{n}})-(s_{NI_N}-s_{I_N}) < \dfrac{c_\mathrm{b}-b_{1\mathrm{n}}+s_{I_N}}{2}; \\ \dfrac{(N+2)(c_\mathrm{b}-b_{1\mathrm{n}}+s_{I_N})^2}{8b_2}-R(b_1-b_{1\mathrm{n}}) & \text{otherwise,} \end{cases}$$

[9]As usual, we assume that in a case of indifference firms of type 2 decide in favor of the adoption of the new technology.

$$\pi_2(I_N,(s_{NI_N},s_{I_N}),I)=\begin{cases}\dfrac{(c_b-b_1+s_{NI_N})^2}{4b_2} & \text{if } (b_1-b_{1n})-(s_{NI_N}-s_{I_N})<\dfrac{c_b-b_{1n}+s_{I_N}}{2};\\ \dfrac{(c_b-b_{1n}+s_{I_N})^2}{8b_2} & \text{otherwise.}\end{cases}$$

Proof of Lemma 2.1.3 Suppose that firm 1 innovates but offers no licenses to competitors (I_0). The government determines welfare-maximizing subsidy levels (s_{NI_0}, s_{I_0}). Firm 1, after innovating, operates with the new cost function $C_{gn}(x_{1g})$ and firms of type 2 continue to operate with the cost function $C_g(x_{2g})$. Thus, firm 1's profit maximization problem is given by

$$\max_{x_{1b},x_{1g}}[px_{1b}+(p+s_{I_0})x_{1g}-C_b(x_{1b})-C_{gn}(x_{1g})-R(b_1-b_{1n})], \tag{A.10}$$

while firm 2's profit maximization problem corresponds to (A.1) with $i=2$ and $s_{NI}=s_{NI_0}$. The quantities of green electricity produced by firm 1 and firms of type 2 are therefore given by

$$\begin{aligned} x_{1g}(I_0,(s_{NI_0},s_{I_0})) &= \frac{c_b-b_{1n}+s_{I_0}}{2b_2};\\ x_{2g}(I_0,(s_{NI_0},s_{I_0})) &= \frac{c_b-b_1+s_{NI_0}}{2b_2}. \end{aligned}$$

Firms' profits therefore amount to

$$\pi_1(I_0,(s_{NI_0},s_{I_0})) = \frac{(c_b-b_{1n}+s_{I_0})^2}{4b_2}-R(b_1-b_{1n}); \tag{A.11}$$

$$\pi_2(I_0,(s_{NI_0},s_{I_0})) = \frac{(c_b-b_1+s_{NI_0})^2}{4b_2}. \tag{A.12}$$

Proof of Lemma 2.1.4 Given the decision of firm 1 not to innovate, the government anticipates all firms' optimal quantity decisions in the subgame Γ_{NI} and maximizes the social welfare function

$$\begin{aligned} W_{NI}(s_{NI}) &= Q\left(a-\frac{Q}{2}\right)+(N+1)\pi_i(NI,s_{NI})-s_{NI}(N+1)x_g(NI,s_{NI})\\ &\quad +d_1(N+1)x_g(NI,s_{NI})-d_2[(N+1)x_g(NI,s_{NI})]^2 \qquad (A.13)\\ &= \frac{(a-c_b)(a+c_b)}{2}+(N+1)\frac{(c_b-b_1+s_{NI})^2}{4b_2}-(N+1)s_{NI}\frac{c_b-b_1+s_{NI}}{2b_2}\\ &\quad +(N+1)d_1\frac{c_b-b_1+s_{NI}}{2b_2}-d_2(N+1)^2\frac{(c_b-b_1+s_{NI})^2}{4b_2^2} \qquad (A.14) \end{aligned}$$

with respect to s_{NI}. The socially optimal subsidy level is thus given by

$$s^*_{NI} = \frac{b_2d_1-d_2(N+1)(c_b-b_1)}{b_2+d_2(N+1)}, \tag{A.15}$$

while the equilibrium quantities and profits are

$$\begin{aligned} x_{ig}(NI) &= \frac{c_b-b_1+d_1}{2[b_2+d_2(N+1)]};\\ \pi_i(NI) &= \frac{b_2(c_b-b_1+d_1)^2}{4[b_2+d_2(N+1)]^2}. \end{aligned}$$

Proof of Lemma 2.1.5 Given the decision of firm 1 to innovate and offer N licenses, the government anticipates the equilibrium outcomes of subgames $\Gamma_{I_N,NI}$, $\Gamma_{I_N,I}$, as well as that of the royalty bargaining subgame, and faces the social welfare function

$$\begin{aligned} W_{I_N}(s_{NI_N}, s_{I_N}) &= Q\left(a - \frac{Q}{2}\right) + \pi_1(I_N, (s_{NI_N}, s_{I_N})) + N\pi_2(I_N, (s_{NI_N}, s_{I_N})) \\ &\quad - s_{I_N} x_{1\text{g}}(NI, (s_{NI_N}, s_{I_N})) - N s_{I_N} x_{2\text{g}}(NI, (s_{NI_N}, s_{I_N})) \\ &\quad + d_1 \left[x_{1\text{g}}(NI, (s_{NI_N}, s_{I_N})) + N x_{2\text{g}}(NI, (s_{NI_N}, s_{I_N}))\right] \\ &\quad - d_2 \left[x_{1\text{g}}(NI, (s_{NI_N}, s_{I_N})) + N x_{2\text{g}}(NI, (s_{NI_N}, s_{I_N}))\right]^2 . \end{aligned}$$

Since the outcome of the following subgame crucially depends on whether condition

$$(b_1 - b_{1\text{n}}) - (s_{NI_N} - s_{I_N}) \geq \frac{c_\text{b} - b_{1\text{n}} + s_{I_N}}{2} \tag{A.16}$$

is satisfied, the welfare function in stage IIb is a piecewise-defined continuous function. We distinguish two cases, depending on whether or not condition (A.16) is fulfilled.

Case 1: condition (A.16) is satisfied. The government maximizes the welfare function

$$\begin{aligned} W_{I_N}(s_{NI_N}, s_{I_N}) &= \frac{(a - c_\text{b})(a + c_\text{b})}{2} + 2(N+1)\,\frac{(c_\text{b} - b_{1\text{n}} + s_{I_N})^2}{8b_2} - R(b_1 - b_{1\text{n}}) \\ &\quad - s_{I_N}(N+2)\frac{c_\text{b} - b_{1\text{n}} + s_{I_N}}{4b_2} \\ &\quad + d_1(N+2)\frac{c_\text{b} - b_{1\text{n}} + s_{I_N}}{4b_2} - d_2(N+2)^2\frac{(c_\text{b} - b_{1\text{n}} + s_{I_N})^2}{16b_2^2} \end{aligned}$$

with respect to (s_{NI_N}, s_{I_N}) and subject to constraint (A.16). The socially optimal subsidy level is given by

$$s^*_{I_N} = \frac{[2b_2 N - d_2(N+2)^2](c_\text{b} - b_{1\text{n}}) + 2(N+2)b_2 d_1}{d_2(N+2)^2 + 4b_2}. \tag{A.17}$$

The maximum welfare level attained in this case is

$$W^*(I_N) = \frac{(N+2)^2(c_\text{b} - b_{1\text{n}} + d_1)^2}{4[(N+2)^2 d_2 + 4b_2]} - R(b_1 - b_{1\text{n}}).$$

Case 2: condition (A.16) is not satisfied. The government maximizes the welfare function

$$\begin{aligned} W'_{I_N}(s'_{NI_N}, s'_{I_N}) &= \frac{(a - c_\text{b})(a + c_\text{b})}{2} + \frac{(c_\text{b} - b_{1\text{n}} + s'_{I_N})^2}{4b_2} - R(b_1 - b_{1\text{n}}) \\ &\quad + N[(b_1 - b_{1\text{n}}) - (s'_{NI_N} - s'_{I_N})]\frac{c_\text{b} - b_1 + s'_{NI_N}}{2b_2} + N\,\frac{(c_\text{b} - b_1 + s'_{NI_N})^2}{4b_2} \\ &\quad - s'_{I_N}\frac{c_\text{b} - b_{1\text{n}} + s'_{I_N}}{2b_2} - N s'_{I_N}\frac{c_\text{b} - b_1 + s'_{NI_N}}{2b_2} \\ &\quad + d_1\left(\frac{c_\text{b} - b_{1\text{n}} + s'_{I_N}}{2b_2} + N\,\frac{c_\text{b} - b_1 + s'_{NI_N}}{2b_2}\right) \\ &\quad - d_2\left(\frac{c_\text{b} - b_{1\text{n}} + s'_{I_N}}{2b_2} + N\,\frac{c_\text{b} - b_1 + s'_{NI_N}}{2b_2}\right)^2 \end{aligned}$$

with respect to (s'_{NI_N}, s'_{I_N}) and subject to constraint (A.16) reversed with <. The socially optimal subsidy levels are given by

$$s'^*_{NI_N} = \frac{b_2 d_1 - d_2(N+1)(c_\mathrm{b} - b_1) + b_2(b_1 - b_{1\mathrm{n}})}{b_2 + d_2(N+1)}; \tag{A.18}$$

$$s'^*_{I_N} = \frac{b_2 d_1 - d_2(N+1)(c_\mathrm{b} - b_{1\mathrm{n}})}{b_2 + d_2(N+1)}. \tag{A.19}$$

The maximum welfare level to be attained is

$$W'^*(I_N) = \frac{(N+1)(c_\mathrm{b} - b_{1\mathrm{n}} + d_1)^2}{4[b_2 + d_2(N+1)]} - R(b_1 - b_{1\mathrm{n}}).$$

A simple computation shows that $W^*(I_N) > W'^*(I_N)$ for any $N > 0$. Thus, the optimal decision of the government in stage IIb is given by any combination of subsidies

$$(s^*_{NI_N}, s^*_{I_N}) = \left(s^*_{NI_N}, \frac{[2b_2 N - d_2(N+2)^2](c_\mathrm{b} - b_{1\mathrm{n}}) + 2(N+2)b_2 d_1}{d_2(N+2)^2 + 4b_2} \right),$$

where

$$s^*_{NI_N} \geq (b_1 - b_{1\mathrm{n}}) + \frac{[b_2(N-2) - d_2(N+2)^2](c_\mathrm{b} - b_{1\mathrm{n}}) + (N+2)b_2 d_1}{d_2(N+2)^2 + 4b_2}.$$

Proof of Lemma 2.1.6 Given the decision of firm 1 to innovate and offer no licenses, the government anticipates the equilibrium outcome of subgame Γ_{I_0} and maximizes the welfare function

$$\begin{aligned} W_{I_0}(s_{NI_0}, s_{I_0}) \quad = \quad & \frac{(a - c_\mathrm{b})(a + c_\mathrm{b})}{2} + \frac{(c_\mathrm{b} - b_{1\mathrm{n}} + s_{I_0})^2}{4b_2} - R(b_1 - b_{1\mathrm{n}}) + \\ & + N\frac{(c_\mathrm{b} - b_1 + s_{NI_0})^2}{4b_2} - s_{I_0}\frac{c_\mathrm{b} - b_{1\mathrm{n}} + s_{I_0}}{2b_2} - N s_{NI_0}\frac{c_\mathrm{b} - b_1 + s_{NI_0}}{2b_2} \\ & + d_1\left(\frac{c_\mathrm{b} - b_{1\mathrm{n}} + s_{I_0}}{2b_2} + N\frac{c_\mathrm{b} - b_1 + s_{NI_0}}{2b_2}\right) - \\ & - d_2\left(\frac{c_\mathrm{b} - b_{1\mathrm{n}} + s_{I_0}}{2b_2} + N\frac{c_\mathrm{b} - b_1 + s_{NI_0}}{2b_2}\right)^2 \end{aligned}$$

with respect to (s_{NI_0}, s_{I_0}). The socially optimal subsidy levels in this subgame coincide for the innovating firm and the non-innovating firms and are given by

$$s^*_{NI_0} = s^*_{I_0} = \frac{b_2 d_1 - d_2(N+1)(c_\mathrm{b} - b_1) - d_2(b_1 - b_{1\mathrm{n}})}{b_2 + d_2(N+1)}. \tag{A.20}$$

Proof of Proposition 2.1.7 In stage I, firm 1 anticipates optimal decisions of the government and other firms in the subsequent subgames and thus decides whether or not to innovate (and if so, whether to offer licenses) based on its maximum profits to be attained given the utility-maximizing decisions of other players. First of all, observe that, for any $N > 0$, $\pi_1(I_N, (s_{NI_N, s_{I_N}})) > \pi_1(I_0, (s_{NI_0}, s_{I_0}))$. Thus, firm 1 will never take the strictly dominated action I_0 in stage I. Consequently, the solution depends on the comparison of profits attained from playing NI and I_N:

$$\begin{aligned} \pi_1^*(NI) &= \frac{b_2(c_{\mathrm{b}} - b_1 + d_1)^2}{4[b_2 + d_2(N+1)]^2}; \\ \pi_1^*(I_N) &= \frac{(N+2)^3 b_2(c_{\mathrm{b}} - b_{1\mathrm{n}} + d_1)^2}{2[4b_2 + d_2(N+2)^2]^2} - r(b_1 - b_{1\mathrm{n}})^2. \end{aligned}$$

I_N is preferable if $\pi_1(I_N) \geq \pi_1(NI)$. Condition $\pi_1(I_N) \geq \pi_1(NI)$ is satisfied if

$$\frac{(N+2)^3 b_2(c_{\mathrm{b}} - b_{1\mathrm{n}} + d_1)^2}{2[4b_2 + d_2(N+2)^2]^2} - \frac{b_2(c_{\mathrm{b}} - b_1 + d_1)^2}{4[b_2 + d_2(N+1)]^2} \quad \geq \quad r(\Delta b_1)^2$$

or, equivalently, if

$$(r-1)(\Delta b_1)^2 + 2\beta \Delta b_1 - \alpha\beta^2 \quad \leq \quad 0. \tag{A.21}$$

The solution of ineq. (A.21) depends on the value of concavity parameter r. In particular, if $r = 1$, condition (A.21) is satisfied for $\Delta b_1 \in (0, \alpha\beta/2)$. If $r > 1$, it is satisfied for any

$$\Delta b_1 \in \left(0, \frac{\beta}{r-1}\left(\sqrt{1+\alpha(r-1)} - 1\right)\right].$$

Finally, if $0 < r < 1$, this condition is satisfied for

$$\Delta b_1 \in \left(0, \frac{\beta}{1-r}\left(1 - \sqrt{1-\alpha(1-r)}\right)\right] \cup \left[\frac{\beta}{1-r}\left(1 + \sqrt{1-\alpha(1-r)}\right), \infty\right).$$

Thus, the equilibrium outcome depends on the R&D cost of innovation and thus on the marginal cost difference Δb_1. The subgame-perfect equilibrium action of firm 1 in stage I is given by I_N for a sufficiently low value of Δb_1 (with the notable exception of the case with $r < 1$ when sufficiently large values of r support this equilibrium, too). By way of contrast, if Δb_1 is too high, then the only action of firm 1 sustainable in a subgame-perfect equilibrium is NI.

Proof of Lemma 2.2.1 Suppose that firm 1 does not innovate in stage I by choosing action NI. The fine and the quota levels chosen by the government in stage II are f_{NI} and $\bar{x}_{NI}$. Given a competitive market in stage III, a representative power generator faces the optimization problem

$$\max_{x_{i\mathrm{b}}, x_{ig}} [p(x_{i\mathrm{b}} + x_{ig}) - f_{NI}(\bar{x}_{NI} - x_{ig}) - C_{\mathrm{b}}(x_{i\mathrm{b}}) - C_{\mathrm{g}}(x_{ig})], \tag{A.22}$$

Quantities of green electricity produced by each firm and their profits are given by

$$x_{ig}(NI, f_{NI}) = \frac{c_{\mathrm{b}} - b_1 + f_{NI}}{2b_2}; \tag{A.23}$$

$$\pi_i(NI, f_{NI}, \bar{x}_{NI}) = \frac{(c_{\mathrm{b}} - b_1 + f_{NI})^2}{4b_2} - f_{NI}\bar{x}_{NI}. \tag{A.24}$$

Proof of Lemma 2.2.2 In stage IIIb, firm 1 innovates and announces to offer N licenses in return of a royalty of υ^q per unit of green electricity. The government determines welfare-maximizing quota and fine levels $(\bar{x}_{I_N}, f_{I_N})$, $(\bar{x}_{NI_N}, f_{NI_N})$.

Subgame $\Gamma^q_{I_N,NI}$. Suppose that firms of type 2 reject firm 1's offer. Then firm 1 operates with the new cost function $C_{\text{gn}}(x_{1\text{g}})$ while firms of type 2 continue to operate with the cost function $C_{\text{g}}(x_{2\text{g}})$. Thus, firm 1's profit maximization problem is given by

$$\max_{x_{1\text{b}},x_{1\text{g}}} [p(x_{1\text{b}} + x_{1\text{g}}) - f_{I_N})(\bar{x}_{NI} - x_{1\text{g}}) - C_{\text{b}}(x_{1\text{b}}) - C_{1\text{gn}}(x_{1\text{g}}) - R(b_1 - b_{1\text{n}})], \tag{A.25}$$

while firm 2's profit maximization problem corresponds to (A.22) with $i = 2$, $f_{NI} = f_{NI_N}$, and $\bar{x}_{NI} = \bar{x}_{NI_N}$. Thus, quantities of green electricity produced by firm 1 and firms of type 2 are respectively given by

$$\begin{aligned} x_{1\text{g}}(I_N, (f_{NI_N}, f_{I_N}), \upsilon, NI) &= \frac{c_{\text{b}} - b_{1\text{n}} + f_{I_N}}{2b_2}; \\ x_{2\text{g}}(I_N, (f_{NI_N}, f_{I_N}), \upsilon, NI) &= \frac{c_{\text{b}} - b_1 + f_{NI_N}}{2b_2}, \end{aligned}$$

with profits therefore amounting to

$$\begin{aligned} \pi_1(I_N, (f_{NI_N}, f_{I_N}, \bar{x}_{I_N}), \upsilon^q, NI) &= \frac{(c_{\text{b}} - b_{1\text{n}} + f_{I_N})^2}{4b_2} - R(b_1 - b_{1\text{n}}) - f_{I_N}\bar{x}_{I_N}; \\ \pi_2(I_N, (f_{NI_N}, f_{I_N}, \bar{x}_{NI_N}), \upsilon^q, NI) &= \frac{(c_{\text{b}} - b_1 + f_{NI_N})^2}{4b_2} - f_{NI_N}\bar{x}_{NI_N}. \end{aligned}$$

Subgame $\Gamma^q_{I_N,I}$. Now suppose that firms of type 2 accept firm 1's offer and have to pay a royalty of υ^q per unit of green electricity produced. Thus, all firms operate with the new cost function $C_{\text{gn}}(x_{\text{g}})$. The profit maximization problems of firm 1 and firms of type 2 are respectively given by

$$\begin{aligned} &\max_{x_{1\text{b}},x_{1\text{g}}} [p(x_{1\text{b}} + x_{1\text{g}}) - f_{I_N})(\bar{x}_{I_N} - x_{1\text{g}}) - C_{\text{b}}(x_{1\text{b}}) - C_{\text{gn}}(x_{1\text{g}}) + N\upsilon^q x_{2\text{g}} - R(b_1 - b_{1\text{n}})]; \\ &\max_{x_{2\text{b}},x_{2\text{g}}} [p(x_{2\text{b}} + x_{2\text{g}}) - f_{I_N})(\bar{x}_{I_N} - x_{2\text{g}}) - C_{\text{b}}(x_{2\text{b}}) - C_{\text{gn}}(x_{2\text{g}}) - \upsilon x_{2\text{g}}], \end{aligned}$$

The quantities of green electricity produced are

$$\begin{aligned} x_{1\text{g}}(I_N, (f_{NI_N}, f_{I_N}), \upsilon^q, I) &= \frac{c_{\text{b}} - b_{1\text{n}} + f_{I_N}}{2b_2}; \\ x_{2\text{g}}(I_N, (f_{NI_N}, f_{I_N}), \upsilon^q, I) &= \frac{c_{\text{b}} - (b_{1\text{n}} + \upsilon^q) + f_{I_N}}{2b_2}, \end{aligned}$$

with profits thus amounting to

$$\begin{aligned} \pi_1(I_N, (f_{NI_N}, f_{I_N}, \bar{x}_{I_N}), \upsilon^q, I) &= \frac{(c_{\text{b}} - b_{1\text{n}} + f_{I_N})^2}{4b_2} + N\upsilon^q \frac{c_{\text{b}} - (b_{1\text{n}} + \upsilon^q) + f_{I_N}}{2b_2} \\ &\quad - R(b_1 - b_{1\text{n}}) - f_{I_N}\bar{x}_{I_N}; \\ \pi_2(I_N, (f_{NI_N}, f_{I_N}, \bar{x}_{I_N}), \upsilon^q, I) &= \frac{(c_{\text{b}} - (b_{1\text{n}} + \upsilon^q) + f_{I_N})^2}{4b_2} - f_{I_N}\bar{x}_{I_N}. \end{aligned}$$

Firms of type 2 decide in stage IIIb either to reject (NI) or accept (I) firm 1's offer depending on which of their maximum profits attainable in subgames $\Gamma^q_{I_N,NI}$ and $\Gamma^q_{I_N,I}$ is larger. Thus, its subgame-perfect equilibrium actions with respect to the adoption of the new technology are given as follows:

$$\begin{cases} NI & \text{if} \quad \upsilon^q > \upsilon^{q\max} := \sqrt{(c_\text{b} - b_1 + f_{I_N})^2 + 4b_2(f_{NI_N}\bar{x}_{NI_N} - f_{I_N}\bar{x}_{I_N})} - (c_\text{b} - b_{1\text{n}} + f_{I_N}) \\ I & \text{if} \quad \text{otherwise.} \end{cases}$$

In other words, $\upsilon^{q\max}$ is the highest possible royalty level at which firm of type 2 innovates.

Firm 1's decision in stage IIIb is based on the maximization of its profits with respect to the royalty level υ^q. Notice that firm 1's profit if firms of type 2 accept the offer $\pi_1(I_N, (f_{NI_N}, f_{I_N}, \bar{x}_{I_N}), \upsilon^q, I)$, is always at least as high as if the offer is rejected as long as $\upsilon^q \in [0, c_\text{b} - b_{1\text{n}} + f_{I_N}]$. Moreover, the profit function $\pi_1(I_N, (f_{NI_N}, f_{I_N}, \bar{x}_{I_N}), \upsilon^q, I)$ attains its maximum w.r.t. υ^q at the royalty level $\upsilon^q = (c_\text{b} - b_{1\text{n}} + f_{I_N})/2$. Thus, firm 1's equilibrium offer υ^{q*} in stage IIIb will be given by

$$\upsilon^{*q} = \begin{cases} \upsilon^{q\max} & \text{if } \upsilon^{q\max} < \dfrac{c_\text{b} - b_{1\text{n}} + f_{I_N}}{2}; \\ \dfrac{c_\text{b} - b_{1\text{n}} + f_{I_N}}{2} & \text{otherwise.} \end{cases}$$

This offer will always be accepted by firms of type 2 in the equilibrium[10]. The quantity of green electricity produced by any firm of type 2 in the subgame starting at node G_2, $x_{2\text{g}}(I_N, (f_{NI_N}, f_{I_N}, \bar{x}_{I_N}, \bar{x}_{NI_N}), I)$, thus amounts to

$$\begin{cases} \dfrac{2(c_b - b_1 + f_{NI_N}) - \sqrt{(c_\text{b} - b_1 + f_{I_N})^2 + 4b_2(f_{NI_N}\bar{x}_{NI_N} - f_{I_N}\bar{x}_{I_N})}}{2b_2} & \text{if } \upsilon^{q\max} < \dfrac{c_\text{b} - b_{1\text{n}} + f_{I_N}}{2}; \\ \dfrac{c_\text{b} - b_{1\text{n}} + f_{I_N}}{4b_2} & \text{otherwise.} \end{cases}$$

Firms' profits in this subgame are therefore given by $\pi_1(I_N, (f_{NI_N}, f_{I_N}, \bar{x}_{I_N}, \bar{x}_{NI_N}), I) =$

$$= \begin{cases} \dfrac{(c_b - b_{1\text{n}} + f_{I_N})^2}{4b_2} - 2Nf_{NI_N}\bar{x}_{NI_N} + (2N-1)f_{I_N}\bar{x}_{I_N} - R(b_1 - b_{1\text{n}}) \\ + \frac{N\left[3(c_\text{b} - b_{1\text{n}} + f_{I_N})\sqrt{(c_\text{b} - b_1 + f_{I_N})^2 + 4b_2(f_{NI_N}\bar{x}_{NI_N} - f_{I_N}\bar{x}_{I_N})} - (c_\text{b} - b_1 + f_{I_N})^2 - 2(c_\text{b} - b_{1\text{n}} + f_{I_N})^2\right]}{b_2} \\ \text{if } \upsilon^{q\max} < \dfrac{c_\text{b} - b_{1\text{n}} + f_{I_N}}{2}; \\ \dfrac{(N+2)(c_\text{b} - b_{1\text{n}} + f_{I_N})^2}{8b_2} - R(b_1 - b_{1\text{n}}) - f_{I_N}\bar{x}_{I_N} \qquad \text{otherwise,} \end{cases}$$

$\pi_2(I_N, (f_{NI_N}, f_{I_N}, \bar{x}_{I_N}, \bar{x}_{NI_N}), I) =$

$$= \begin{cases} \dfrac{\left[2(c_b - b_{1\text{n}} + f_{I_N}) - \sqrt{(c_\text{b} - b_1 + f_{I_N})^2 + 4b_2(f_{NI_N}\bar{x}_{NI_N} - f_{I_N}\bar{x}_{I_N})}\right]^2}{4b_2} - f_{I_N}\bar{x}_{I_N} \\ \text{if } \upsilon^{q\max} < \dfrac{c_\text{b} - b_{1\text{n}} + f_{I_N}}{2}; \\ \dfrac{(c_\text{b} - b_{1\text{n}} + f_{I_N})^2}{8b_2} - f_{I_N}\bar{x}_{I_N} \qquad \text{otherwise.} \end{cases}$$

[10]By assumption, firms of type 2 adopt the new technology if indifferent.

Proof of Lemma 2.2.3 Now suppose that firm 1 innovates but offers no licenses to its competitors by choosing I_0. In stage II, the government determines the welfare-maximizing quota and fine levels $\bar{x}_{I_0}$, f_{I_0}, $\bar{x}_{NI_0}$, f_{NI_0}. Firm 1's profit maximization problem is thus given by

$$\max_{x_{1\text{b}},x_{1\text{g}}} [p(x_{1\text{b}} + x_{1\text{g}}) - f_{I_0})(\bar{x}_{I_0} - x_{1\text{g}}) - C_\text{b}(x_{1\text{b}}) - C_\text{gn}(x_{1\text{g}}) - R(b_1 - b_{1\text{n}})], \tag{A.26}$$

while firm 2's profit maximization problem corresponds to (A.22) with $i = 2$, $f_{NI} = f_{NI_0}$, and $\bar{x}_{NI} = \bar{x}_{NI_0}$. Thus, quantities of green electricity produced by firm 1 and firms of type 2 are respectively given by

$$\begin{aligned} x_{1\text{g}}(I_0, f_{NI_0}) &= \frac{c_\text{b} - b_{1\text{n}} + f_{I_0}}{2b_2}; \\ x_{2\text{g}}(I_0, f_{NI_0}) &= \frac{c_\text{b} - b_1 + f_{NI_0}}{2b_2}. \end{aligned}$$

Firms' profits therefore amount to

$$\begin{aligned} \pi_1(I_0, (f_{I_0}, \bar{x}_{I_0})) &= \frac{(c_\text{b} - b_{1\text{n}} + f_{I_0})^2}{4b_2} - f_{I_0}\bar{x}_{I_0} - R(b_1 - b_{1\text{n}}); \\ \pi_2(I_0, (f_{NI_0}, \bar{x}_{NI_0})) &= \frac{(c_\text{b} - b_1 + f_{NI_0})^2}{4b_2} - f_{NI_0}\bar{x}_{NI_0}. \end{aligned}$$

Proof of Lemma 2.2.4 Given the decision of firm 1 not to innovate, the government anticipates all firms' optimal quantity decisions in the subgame Γ^q_{NI} and faces the social welfare function

$$\begin{aligned} W_{NI}(f_{NI}, \bar{x}_{NI}) &= Q\left(a - \frac{Q}{2}\right) + (N+1)\pi_i(NI, f_{NI}, \bar{x}_{NI}) - f_{NI}(N+1)x_\text{g}(NI, f_{NI}) + \\ &\quad + d_1(N+1)x_\text{g}(NI, f_{NI}) - d_2[(N+1)x_\text{g}(NI, f_{NI})]^2 \\ &= \frac{a^2 - c_\text{b}^2}{2} + (N+1)\left[\frac{(c_\text{b} - b_1 + f_{NI})^2}{4b_2} - f_{NI}\bar{x}_{NI}\right] \\ &\quad + (N+1)f_{NI}\left(\bar{x}_{NI} - \frac{c_\text{b} - b_1 + s_{NI}}{2b_2}\right) + \\ &\quad + (N+1)d_1\,\frac{c_\text{b} - b_1 + f_{NI}}{2b_2} - d_2(N+1)^2\frac{(c_\text{b} - b_1 + f_{NI})^2}{4b_2^2}. \end{aligned}$$

One can immediately see that both expressions containing the quota levels cancel out. Thus, this welfare function is identical with that in (A.14) with $s_{NI} = f_{NI}$. Consequently, the government maximizes the welfare function with respect to f_{NI} and sets the socially optimal fine level as

$$f^*_{NI} = \frac{b_2 d_1 - d_2(N+1)(c_\text{b} - b_1)}{b_2 + d_2(N+1)}, \tag{A.27}$$

while the quota level $\bar{x}_{NI}$ can be deliberately set by the government. The equilibrium quantities and profits are thus given by

$$\begin{aligned} x_{i\text{g}}(NI) &= \frac{c_\text{b} - b_1 + d_1}{2[b_2 + d_2(N+1)]}; \\ \pi^q_i(NI) &= \frac{b_2(c_\text{b} - b_1 + d_1)^2}{4[b_2 + d_2(N+1)]^2} - \frac{b_2 d_1 - d_2(N+1)(c_\text{b} - b_1)}{b_2 + d_2(N+1)}\bar{x}_{NI} < \pi_i(NI). \end{aligned}$$

Proof of Lemma 2.2.5 Given the decision of firm 1 to innovate and offer N licenses, the government anticipates the equilibrium outcomes of subgames $\Gamma^q_{I_N,NI}$, $\Gamma^q_{I_N,I}$, as well as that of the royalty bargaining subgame, and faces the social welfare function $W^q_{I_N}(f_{NI_N}, f_{I_N}, \bar{x}_{NI_N}, \bar{x}_{I_N})$ specified below. Since the outcome of the subsequent subgame crucially depends on whether or not condition

$$\upsilon^{q\max} \quad \geq \quad \frac{c_\mathrm{b} - b_{1\mathrm{n}} + f_{I_N}}{2} \tag{A.28}$$

is satisfied, the welfare in stage IIb is given as a piecewise defined continuous function. We distinguish two cases, depending on whether condition (A.28) is fulfilled or not.

Case 1: condition (A.28) is satisfied (the 'otherwise' case in stage IIIb). The government maximizes the welfare function

$$\begin{aligned} W^q_{I_N}(f_{NI_N}, f_{I_N}, \bar{x}_{NI_N}, \bar{x}_{I_N}) \quad = \quad & \frac{(a-c_\mathrm{b})(a+c_\mathrm{b})}{2} + 2(N+1)\,\frac{(c_\mathrm{b} - b_{1\mathrm{n}} + f_{I_N})^2}{8b_2} \\ & -R(b_1 - b_{1\mathrm{n}}) - (N+1) f_{I_N}\bar{x}_{I_N} \\ & +f_{I_N}\left(\bar{x}_{I_N} - \frac{c_\mathrm{b} - b_1 + f_{I_N}}{2b_2}\right) + N f_{I_N}\left(\bar{x}_{I_N} - \frac{c_\mathrm{b} - b_{1\mathrm{n}} + f_{I_N}}{4b_2}\right) \\ & +d_1(N+2)\frac{c_\mathrm{b} - b_{1\mathrm{n}} + f_{I_N}}{4b_2} - d_2(N+2)^2\,\frac{(c_\mathrm{b} - b_{1\mathrm{n}} + f_{I_N})^2}{16b_2^2} \end{aligned}$$

with respect to $f_{NI_N}, f_{I_N}, \bar{x}_{NI_N}, \bar{x}_{I_N}$ and subject to constraint (A.28). Again, since the quota levels can be set exogenously, the welfare function is identical with that in the subsidy case. The socially optimal fine level is given by

$$f^*_{I_N} \quad = \quad \frac{[2b_2N - d_2(N+2)^2](c_\mathrm{b} - b_{1\mathrm{n}}) + 2(N+2)b_2d_1}{d_2(N+2)^2 + 4b_2}. \tag{A.29}$$

The maximum welfare level attained in this case is therefore

$$W^{*q}(I_N) = \frac{(N+2)^2(c_\mathrm{b} - b_{1\mathrm{n}} + d_1)^2}{4[(N+2)^2 d_2 + 4b_2]} - R(b_1 - b_{1\mathrm{n}}).$$

Case 2: condition (A.28) is not satisfied. The government maximizes the welfare function

$$W'^q_{I_N}(f'_{NI_N}, f'_{I_N}, \bar{x}'_{NI_N}, \bar{x}'_{I_N}) = \frac{(c_b - b_{1n} + f'_{I_N})^2}{4b_2} - 2Nf'_{NI_N}\bar{x}'_{NI_N} + (2N-1)f'_{I_N}\bar{x}'_{I_N} - R(b_1 - b_{1n})$$
$$+\frac{N\left[3(c_b - b_{1n} + f'_{I_N})\sqrt{(c_b - b_1 + f'_{I_N})^2 + 4b_2(f'_{NI_N}\bar{x}'_{NI_N} - f'_{I_N}\bar{x}'_{I_N})} - (c_b - b_1 + f'_{I_N})^2 - 2(c_b - b_{1n} + f'_{I_N})^2\right]}{b_2}$$
$$+N\left[\frac{\left[2(c_b - b_{1n} + f'_{I_N}) - \sqrt{(c_b - b_1 + f'_{I_N})^2 + 4b_2(f'_{NI_N}\bar{x}'_{NI_N} - f'_{I_N}\bar{x}'_{I_N})}\right]^2}{4b_2} - f'_{I_N}\bar{x}'_{I_N}\right]$$
$$+f'_{I_N}\left(\bar{x}'_{I_N} - \frac{c_b - b_{1n} + f'_{I_N}}{2b_2}\right)$$
$$+Nf'_{I_N}\left(\bar{x}'_{I_N} - \frac{2(c_b - b_1 + f'_{NI_N}) - \sqrt{(c_b - b_1 + f'_{I_N})^2 + 4b_2(f'_{NI_N}\bar{x}'_{NI_N} - f'_{I_N}\bar{x}'_{I_N})}}{2b_2}\right)$$
$$+d_1\left(\frac{c_b - b_{1n} + f'_{I_N}}{2b_2} + N\frac{2(c_b - b_1 + f'_{NI_N}) - \sqrt{(c_b - b_1 + f'_{I_N})^2 + 4b_2(f'_{NI_N}\bar{x}'_{NI_N} - f'_{I_N}\bar{x}'_{I_N})}}{2b_2}\right) -$$
$$-d_2\left(\frac{c_b - b_{1n} + f'_{I_N}}{2b_2} + N\frac{2(c_b - b_1 + f'_{NI_N}) - \sqrt{(c_b - b_1 + f'_{I_N})^2 + 4b_2(f'_{NI_N}\bar{x}'_{NI_N} - f'_{I_N}\bar{x}'_{I_N})}}{2b_2}\right)^2$$

with respect to $(f'_{NI_N}, f'_{I_N}, \bar{x}'_{NI_N}, \bar{x}'_{I_N})$ and subject to constraint (A.28) reversed with $<$. It can be shown that, as in the subsidy case, $W^{*q}(I_N) > W'^{q*}(I_N)$ for any $N > 0$. Thus, the optimal decision of the government in stage IIb is given by any combination of fines

$$(f^*_{NI_N}, f^*_{I_N}) = \left(f^*_{NI_N}, \frac{[2b_2N - d_2(N+2)^2](c_b - b_{1n}) + 2(N+2)b_2d_1}{d_2(N+2)^2 + 4b_2}\right)$$

where $f^*_{NI_N}$ satisfies inequality

$$\sqrt{(c_b - b_1 + f^*_{I_N})^2 + 4b_2(f^*_{NI_N}\bar{x}_{NI_N} - f^*_{I_N}\bar{x}_{I_N})} \quad \geq \quad \frac{3}{2}(c_b - b_{1n} + f^*_{I_N}). \tag{A.30}$$

In this case, the government's choice of the quotas $\bar{x}_{NI_N}, \bar{x}_{I_N}$ is constrained by inequality (A.30).

Proof of Lemma 2.2.6 Given the decision of firm 1 to innovate and offer no licenses, the government anticipates the equilibrium outcome of subgame $\Gamma^q_{I_0}$. As in other subgames, welfare maximization is equivalent to the subsidy case. Here we simply state the socially optimal fine level, which is given by

$$f^*_{NI_0} = f^*_{I_0} \quad = \quad \frac{b_2d_1 - d_2(N+1)(c_b - b_1) - d_2(b_1 - b_{1n})}{b_2 + d_2(N+1)}, \tag{A.31}$$

which is identical for the innovating and non-innovating firms as in the subsidy case.

Proof of Proposition 2.2.7 Firm 1 anticipates optimal decisions of the government and its competitors in the subsequent stages and thus decides whether or not to innovate (and if so, whether or not to offer licenses), based on the comparison of its maximum attainable profits given the utility-maximizing decisions of other players. In contrast to the subsidy case, the profit functions in the quota case depend on the quotas set by the government. However, as shown above, the quota levels are not determined from welfare maximization but set exogenously[11].

Here, we assume that the quota level $\bar{x}_I$ set for any innovating firm is equal irrespective of its decision about licenses, $\bar{x}_I := \bar{x}_{I_N} = \bar{x}_{I_0}$. Then we can observe that, for any $N > 0$ and any fine level,

$$\pi_1(I_N, (f_{NI_N}, f_{I_N})) > \pi_1(I_0, (f_{NI_0}, f_{I_0})).$$

Thus, firm 1 will never take action I_0 in stage I. The optimal decision of firm 1 depends on the comparison of maximum attainable profits from choosing NI and I_N, respectively:

$$\begin{aligned}
\pi_1^*(NI) &= \frac{b_2(c_\mathrm{b} - b_1 + d_1)^2}{4[b_2 + d_2(N+1)]^2} - f^*_{NI}\bar{x}_{NI}; \\
\pi_1^*(I_N) &= \frac{(N+2)^3 b_2(c_\mathrm{b} - b_{1\mathrm{n}} + d_1)^2}{2[4b_2 + d_2(N+2)^2]^2} - r(b_1 - b_{1\mathrm{n}})^2 - f^*_{I_N}\bar{x}_{I_N}.
\end{aligned}$$

I_N is preferable if $\pi_1^*(I_N) \geq \pi_1^*(NI)$. As in the subsidy case, I_N constitutes a subgame-perfect equilibrium strategy for sufficiently low values of Δb_1, namely when the following inequality is satisfied:

$$A(\Delta b_1)^2 + B\Delta b_1 - C \quad \leq \quad 0,$$

or, equivalently, for any

$$\Delta b_1 \in \left(0, \frac{\sqrt{B^2 - 4AC} - B}{2A}\right]. \tag{A.32}$$

By way of contrast, if Δb_1 exceeds the threshold value of $\frac{\sqrt{B^2-4AC}-B}{2A}$, then the only subgame-perfect equilibrium action of firm 1 is NI (Not Innovate). Note, however, that under the quota policy the threshold level of Δb_1 can be influenced by the government as the quota levels are set exogenously.

Proof of Proposition 3.1.1 In stage III, competition takes place given firm 1's decision in stage I and the government's decisions in stage II. Notice that subgame $\tilde{\Gamma}_{NI}$ is equivalent to Γ_{NI} with $s_{NI} = \tilde{s}_{NI}$, subgames $\tilde{\Gamma}_{I,NI}$ and $\tilde{\Gamma}_{I,I}$, respectively, to $\Gamma_{I,NI}$ and $\Gamma_{I,I}$ with $(s_{NI_N}, s_{I_N}) = (\tilde{s}_{NI}, \tilde{s}_I)$, and subgame $\tilde{\Gamma}_{I_0}$, to Γ_{I_0} with $(s_{NI_0}, s_{I_0}) = (\tilde{s}_{NI}, \tilde{s}_I)$. The maximum profit levels of firm 1 in these subgames are therefore given by:

$$\begin{aligned}
\pi_1(NI, (\tilde{s}_{NI}, \tilde{s}_I)) &= \frac{(c_\mathrm{b} - b_1 + \tilde{s}_{NI})^2}{4b_2}; \\
\pi_1(I_0, (\tilde{s}_{NI}, \tilde{s}_I)) &= \frac{(c_\mathrm{b} - b_{1\mathrm{n}} + \tilde{s}_I)^2}{4b_2} - R(b_1 - b_{1\mathrm{n}}); \\
\pi_1(I_N, (\tilde{s}_{NI}, \tilde{s}_I)) &=
\end{aligned}$$

[11] With the notable exception of stage IIb, in which constraint (5) must be satisfied. However, this is the only constraint for the choice of three variables, $f^*_{NI_N}$, $\bar{x}_{NI_N}$, and $\bar{x}_{I_N}$. In other words, for any free choice of both quota levels, there exists a lower bound for $f^*_{NI_N}$

$$= \begin{cases} \dfrac{(c_b - b_{1n} + \tilde{s}_I)^2}{4b_2} - R(b_1 - b_{1n}) + \\ +N[(b_1 - b_{1n}) - (\tilde{s}_{NI} - \tilde{s}_I)] \frac{c_b - b_1 + \tilde{s}_{NI}}{2b_2} & \text{if } (b_1 - b_{1n}) - (\tilde{s}_{NI} - \tilde{s}_I) < \dfrac{c_b - b_{1n} + \tilde{s}_I}{2}; \\ \dfrac{(N+2)(c_b - b_{1n} + \tilde{s}_I)^2}{8b_2} - R(b_1 - b_{1n}) & \text{otherwise.} \end{cases}$$

Under the pre-commitment regime, the government (G) sets the subsidies without any information about the innovation decision of firm 1. Moreover, firm 1 makes its decision whether to innovate or not (and if so, whether to offer licenses) prior to the announcement of the subsidy levels set by the government. Therefore, both decisions can be considered to be made simultaneously and can be modeled as a normal-form game taking place in stages I and II. In this game, firm 1 chooses one of three actions $\{NI, I_N, I_0\}$, while the government determines a pair of subsidies (s_{NI}, s_I).

In a Nash equilibrium of this normal-form game, any equilibrium strategy of a player must belong to the set of best responses to an equilibrium strategy of the other player. The government's best responses (BR_G) to firm 1's actions are equivalent to its actions in stage II in the no pre-commitment case:

$$\begin{aligned} s^1 &= (s^1_{NI}, s^1_I) := BR_G(NI) = \left\{ \left(\frac{b_2 d_1 - d_2(N+1)(c_b - b_1)}{b_2 + d_2(N+1)}, s_I \right) : \ s_I \in \mathbb{R} \right\}; \\ s^2 &= (s^2_{NI}, s^2_I) := BR_G(I_N) = \left\{ \left(s_{NI}, \frac{[2b_2 N - d_2(N+2)^2](c_b - b_{1n}) + 2(N+2)b_2 d_1}{d_2(N+2)^2 + 4b_2} \right) : \right. \\ &\qquad \left. s_{NI} \leq \frac{4b_2(b_1 - b_{1n}) - d_2(N+2)^2(c_b - b_1) + b_2(N-2)(c_b - b_{1n}) + (N+2)b_2 d_1}{4b_2 + d_2(N+2)^2} \right\}; \\ s^3 &= (s^3_{NI}, s^3_I) := BR_G(I_0) = \\ &= \left(\frac{b_2 d_1 - d_2(N+1)(c_b - b_1) - d_2(b_1 - b_{1n})}{b_2 + d_2(N+1)}, \frac{b_2 d_1 - d_2(N+1)(c_b - b_1) - d_2(b_1 - b_{1n})}{b_2 + d_2(N+1)} \right). \end{aligned}$$

Firm 1's best responses (BR_1) to s^1, s^2, and s^3 can be derived by observing its profits as functions of subsidy levels given in (A.5), (A.9), and (A.11). Notice that, since the government's best response to I_N is given by $s^2 = (s^2_{NI}, s^2_I)$ as shown above, condition (A.16) cannot be violated in a Nash equilibrium. Therefore, if firm 1 chooses action I_N in stage I it faces the profit function

$$\pi_1(I_N, (\tilde{s}_{NI}, \tilde{s}_I)) = \frac{(N+2)(c_b - b_{1n} + \tilde{s}_I)^2}{8b_2} - R(b_1 - b_{1n}).$$

Moreover, since $\pi_1(I_N, (\tilde{s}_{NI}, \tilde{s}_I)) > \pi_1(I_0, (\tilde{s}_{NI}, \tilde{s}_I))$ for any $(\tilde{s}_{NI}, \tilde{s}_I))$, action I_0 is strictly dominated and thus cannot be played in a Nash equilibrium. Hence, action $s^3 = (s^3_{NI}, s^3_I)$ of the government cannot be supported in an equilibrium since it constitutes a best response to the strictly dominated action I_0 only. Action NI is a best response of firm 1 to (s^1_{NI}, s^1_I) if $\pi_1(NI, (s^1_{NI}, s^1_I)) \geq \pi_1(I_N, (s^1_{NI}, s^1_I))$. A rearrangement shows that this condition is satisfied if

$$s^1_I \in \left[-(c_b - b_{1n}) \pm \sqrt{\frac{2b_2}{N+2} \left(\frac{b_2(c_b - b_1 + d_1)^2}{[b_2 + d_2(N+1)]^2} + 4r(\Delta b_1)^2 \right)} \right], \tag{A.33}$$

where $\Delta b_1 = b_1 - b_{1\mathrm{n}}$. Therefore, the first set of Nash equilibria is given if player 1 does not innovate and the government chooses (s^1_{NI}, s^1_I) with s^1_{NI} given above and s^1_I satisfying condition (A.33). By an appropriate choice of s^1_I, the government is able to prevent or allow for the occurrence of this equilibrium. Action I_N is a best response of firm 1 to (s^2_{NI}, s^2_I) if $\pi_1(I_N, (s^2_{NI}, s^2_I)) \geq \pi_1(NI, (s^2_{NI}, s^2_I))$. After solving for s^2_{NI}, we obtain the following condition:

$$s^2_{NI} \in \left[-(c_\mathrm{b} - b_1) \pm \sqrt{b_2 \left(\frac{b_2(N+2)^3(c_\mathrm{b} - b_{1\mathrm{n}} + d_1)^2}{[4b_2 + d_2(N+2)^2]^2} - 4r(\Delta b_1)^2 \right)} \right]. \tag{A.34}$$

The second set of Nash equilibria is given if player 1 innovates and announces to offer N licenses, while the government chooses (s^2_{NI}, s^2_I) with s^2_I given above and s^2_{NI} satisfying condition (A.34).

Proof of Proposition 3.2.1 We have shown in section 2.2 that, due to perfect competition, the optimal decisions of the agents in all subgames are equivalent under subsidy and quota-based policies. Therefore, we derive the solution by considering the normal-form game obtained after the truncation of all subgames following the decisions of the government.

In a Nash equilibrium of this normal-form game, any equilibrium strategy of a player must belong to the set of best responses to an equilibrium strategy of the other player. As in the subsidy case, the government's best responses (BR_G) to firm 1's actions are equivalent to its actions in stage II in the no pre-commitment case:

$$\begin{aligned}
f^1 &= (f^1_{NI}, f^1_I) := BR_G(NI) = \left\{ \left(\frac{b_2 d_1 - d_2(N+1)(c_\mathrm{b} - b_1)}{b_2 + d_2(N+1)}, f_I \right) : \ f_I \in \mathbb{R} \right\}; \\
f^2 &= (f^2_{NI}, f^2_I) := BR_G(I_N) = \left\{ \left(f_{NI}, \frac{[2b_2 N - d_2(N+2)^2](c_\mathrm{b} - b_{1\mathrm{n}}) + 2(N+2)b_2 d_1}{d_2(N+2)^2 + 4b_2} \right) : \right. \\
&\qquad \left. f_{NI} \leq \frac{4b_2(b_1 - b_{1\mathrm{n}}) - d_2(N+2)^2(c_\mathrm{b} - b_1) + b_2(N-2)(c_\mathrm{b} - b_{1\mathrm{n}}) + (N+2)b_2 d_1}{4b_2 + d_2(N+2)^2} \right\}; \\
f^3 &= (f^3_{NI}, f^3_I) := BR_G(I_0) = \\
&= \left(\frac{b_2 d_1 - d_2(N+1)(c_\mathrm{b} - b_1) - d_2(b_1 - b_{1\mathrm{n}})}{b_2 + d_2(N+1)}, \frac{b_2 d_1 - d_2(N+1)(c_\mathrm{b} - b_1) - d_2(b_1 - b_{1\mathrm{n}})}{b_2 + d_2(N+1)} \right).
\end{aligned}$$

Firm 1's best responses (BR_1) to f^1, f^2, and f^3 can be derived by observing its profits as functions of the fine levels. First notice that, since the government's best response to I_N is given by $f^2 = (f^2_{NI}, f^2_I)$ as above, condition (A.16) cannot be violated in a Nash equilibrium. Therefore, if firm 1 chooses action I_N in stage I it faces the profit function

$$\pi_1(I_N, (\tilde{f}_{NI}, \tilde{f}_I)) \quad = \quad \frac{(N+2)(c_\mathrm{b} - b_{1\mathrm{n}} + \tilde{f}_I)^2}{8b_2} - R(b_1 - b_{1\mathrm{n}}).$$

Moreover, since $\pi_1(I_N, (\tilde{f}_{NI}, \tilde{f}_I)) > \pi_1(I_0, (\tilde{f}_{NI}, \tilde{f}_I))$ for any $(\tilde{f}_{NI}, \tilde{f}_I))$, action I_0 is strictly dominated and thus cannot be played in a Nash equilibrium. Consequently, action $f^3 = (f^3_{NI}, f^3_I)$ of the government cannot be supported in an equilibrium since it constitutes a best response to the strictly dominated action I_0 only.

Action NI is a best response of firm 1 to (f^1_{NI}, f^1_I) if $\pi_1(NI, (f^1_{NI}, f^1_I)) \geq \pi_1(I_N, (f^1_{NI}, f^1_I))$. A rearrangement shows that this condition is satisfied if

$$f^1_I \in \left[-(c_{\rm b} - b_{1{\rm n}}) + 4b_2\bar{x}_I \pm \frac{\xi\sqrt{2b_2}}{(N+2)[b_2 + (N+1)d_2]} \right]. \tag{A.35}$$

The first set of Nash equilibria is therefore given if firm 1 does not innovate and the government chooses (f^1_{NI}, f^1_I) with f^1_{NI} given above and f^1_I satisfying condition (A.35). By an appropriate choice of f^1_I, $\bar{x}_{NI}$, and $\bar{x}_I$, the government is able to prevent or allow for the occurrence of this equilibrium.

Action I_N is a best response of firm 1 to (f^2_{NI}, f^2_I) if $\pi_1(I_N, (f^2_{NI}, f^2_I)) \geq \pi_1(NI, (f^2_{NI}, f^2_I))$. After solving for f^2_{NI}, we obtain the following condition:

$$f^2_{NI} \in \left[-(c_{\rm b} - b_{1{\rm n}}) + 2b_2\bar{x}_{NI} - \frac{\psi\sqrt{2b_2}}{4b_2 + (N+2)^2 d_2}, -(c_{\rm b} - b_{1{\rm n}}) + 2b_2\bar{x}_{NI} + \frac{\psi\sqrt{2b_2}}{4b_2 + (N+2)^2 d_2} \right]. \tag{A.36}$$

The second set of Nash equilibria is given if firm 1 innovates and announces to offer N licenses, while the government chooses (f^2_{NI}, f^2_I) with f^2_I given above and f^2_{NI} satisfying condition (A.36).

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