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Authors' addresses:

Reinhard Madlener
Institute for Future Energy Consumer Needs and Behavior (FCN)
Faculty of Business and Economics / E.ON Energy Research Center
RWTH Aachen University
Templergraben 55
52056 Aachen, Germany
E-mail: rmadlener@eonerc.rwth-aachen.de

Ilja Neustadt, Peter Zweifel
Socioeconomic Institute (SOI)
Faculty of Economics
University of Zurich
Hottingerstrasse 10
8032 Zurich, Switzerland
E-mail: ilja.neustadt@soi.uzh.ch, pzweifel@soi.uzh.ch

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Chair of Energy Economics and Management
Director, Institute for Future Energy Consumer Needs and Behavior (FCN)
E.ON Energy Research Center (E.ON ERC)
RWTH Aachen University
Templergraben 55, 52056 Aachen, Germany
Phone: +49 (0) 241-80 97 162
Fax: +49 (0) 241-80 92 206
Web: www.eonerc.rwth-aachen.de/fcn
E-mail: post_fcn@eonerc.rwth-aachen.de

Promoting renewable electricity generation in imperfect markets: price vs. quantity policies

Reinhard Madlener [a], Ilja Neustadt [b], Peter Zweifel [c]

[a] *Institute for Future Energy Consumer Needs and Behavior (FCN), School of Business and Economics / E.ON Energy Research Center, RWTH Aachen University, Mathieustrasse 6, 52074 Aachen, Germany*

[b] *Economics Subject Group, LMBS, London Metropolitan University, 84 Moorgate, London EC2M 6SQ, UK*

[c] *Department of Economics, University of Zurich, Hottingerstrasse 10, 8032 Zurich, Switzerland*

Abstract

The search for economically efficient policy instruments designed to promote the diffusion of renewable energy technologies in liberalized markets has led to the introduction of quota-based tradable 'green' certificate (TGC) schemes for renewable electricity. However, there is a debate about the pros and cons of TGC, a quantity control policy, compared to guaranteed feed-in tariffs, a price control policy. This paper contributes to the discussion by contrasting these two alternatives in terms of social welfare, taking into account that electricity markets are not perfectly competitive, and shows that the price control policy dominates the quantity control policy in terms of social welfare. Further, the price control policy still dominates the quantity policy in the presence of uncertainty in the (environmental) benefits of renewables, albeit less significantly than in the certainty case, in contrast to the result of Pizer (1999b).

Key words: Green certificates, Renewable portfolio standard, Feed-in tariff

JEL classification: Q42, Q48

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* Corresponding author. E-mail: RMadlener@eonerc.rwth-aachen.de (R. Madlener); Tel. +49-241-80 49820; Fax: +49-241-80 49829

1 Introduction

Electricity generation from renewable energy sources is increasingly recognized to play an important role for the achievement of a variety of primary and secondary energy policy goals, the primary goals being such as improved diversity and security of energy supply as well as reduction of local pollutant and global greenhouse gas emissions. Furthermore, secondary goals can be achieved that, however, may be not unique to renewable energy facilities, e.g. regional and rural development and exploitation of opportunities for fostering social cohesion, value added and employment at the local and regional level.

The plan of the European Commission of the 1990s to issue an EU Directive on the promotion of electricity from renewables (CEC, 1998, 1999a,b), which eventually led to the issuance of Directive 2001/77/EC (CEC, 2001), has triggered an intensive political and intellectual debate over the pros and cons of guaranteed feed-in tariffs (FIT) versus tradable green certificate (TGC) schemes (e.g. Berry, 2002; Lauber, 2004; Palmer and Burtraw, 2005; Madlener and Stagl, 2005; Kildegaard, 2008).[1] Recently, a new and more comprehensive EU Directive for renewable energy promotion has been published (CEC, 2009a), in which no clear preference for one or another instrument is indicated. According to an accompanying Commission report (CEC, 2009b), however, and given the track record of the two instruments so far, the preference of the Commission seems to have shifted away from establishing a uniform European TGC scheme in favor of creating an investor-friendly climate and optimizing existing national systems.[2]

[1] In the literature quota-based TGC schemes are sometimes also referred to as Renewable Portfolio Standards (RPS).

[2] This apparent shift has to be seen in light of the very ambitious and binding policy

Guaranteed FIT provide certainty about the achievable per-unit revenues from selling renewable electricity to the grid. While FIT have turned out to be very effective in countries such as Austria, Denmark, Germany and Spain (e.g. Bode and Groscurth, 2006; del Río and Gual, 2007; del Río, 2008; Lipp, 2007; Lesser and Su, 2008; Couture and Gagnon, 2010; Haas et al., 2011), they cause market distortions to increase when electricity generation from renewables expands. In contrast, TGC are based on competitive market principles, typically featuring mandatory quota targets and certificate trading (e.g. Menanteau et al., 2003). Since TGC in theory promise to enhance both static and dynamic efficiency, they have attracted considerable attention. Over the years, they have been introduced in a number of countries with liberalized electricity markets, such as in Sweden, Belgium (Flanders), and the UK (e.g. Berry and Jaccard, 2001; Dinica and Arentsen, 2003; Langniss and Wiser, 2003; Lorenzoni, 2003; Nielsen and Jeppesen, 2003; Verbruggen, 2004; Fan et al., 2005; Nishio and Asano, 2006; Sáenz de Miera et al., 2008). More recently, the debate has been revolving around the interplay between TGC markets and markets for tradable CO_2 permits (e.g. Morthorst, 2001; Jensen and Skytte, 2003; Söderholm, 2008), and between TGC markets and liberalized power markets (e.g. Amundsen and Mortensen, 2001, 2002; Jensen and Skytte, 2002; Morthorst, 2003; Amundsen and Bergman, 2004), respectively. Another active strand of research concerns

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target of achieving a 20% share of renewables in energy consumption by 2020, see CEC (2009b). FIT, due to their relative simplicity in design, seem to find higher political acceptance and have become widespread in Europe and elsewhere in recent years. In CEC (2008) it is reported that by 2007, of all 27 EU member countries, 19 had a FIT (or premium/bonus) system in place, seven a quota-based TGC system, and only one a tender system (France for wind onshore, solar photovoltaic, and biomass), see CEER (2011).

financial risk of investors (Lemming, 2003; Dinica, 2006).

While FIT are similar to a subsidy for suppliers of renewables, TGC constitute an internalization mechanism in the Baumol-Oates standard-price tradition (Baumol and Oates, 1988). In fact, comparisons between taxes or subsidies and quota-based certificate schemes have so far been undertaken mainly in environmental economics, and in particular with regard to emission control. Denicolò (1999), for example, analyzes the effects of effluent charges and pollution permits when innovation is expected. Building on seminal work by Weitzman (1974, 1978), Pizer (1999a,b) studies the difference between a tax and quota policy under uncertainty, finding that uncertainty causes the optimal amount of emission reduction to increase, which justifies a preference for taxation over quantity control. In the context of renewable energy, Madlener and Neustadt (2010) assess the impact of pre-commitment by government with respect to policy targets in the presence of cost-reducing innovation. In an empirical study, Palmer and Burtraw (2005) analyze the cost-effectiveness of two different renewable electricity policies (TGC vs. tax credits for renewable power production) in the U.S., and their impact on greenhouse gas emissions. Tamas et al. (2010) contrast FIT and TGC in an oligipoly market in a formal model and, using numerical UK data, show that social welfare under TGC is consistently higher than FIT for a wide range of parameter values.

This paper is devoted to the issue of whether the diffusion of renewable power generating technologies can be better promoted by means of FIT or TGC, and in particular whether one of the schemes dominates the other in terms of cost-effectiveness and social welfare. We find that, given imperfectly competitive electricity markets, social welfare achieved under the optimal FIT policy is at least as high and likely to be strictly greater than social welfare under the optimal TGC policy, the latter importantly depending on the outcome of a strategic game in the market for tradable certificates. This is an important new insight, although it does not answer the question about the preferability of first-best instruments as such. However, in the presence of uncertainty in the environmental benefits of renewables, in contrast to Pizer (1999b), we establish a result that the preference for the FIT policy still exists but becomes less pronounced.

Our paper is organized as follows. Section 2 introduces the basic models used for contrasting effects of TGC and FIT in perfectly and imperfectly competitive markets for power. Under perfect competition, the equivalence of TGC and FIT is shown. This equivalence does not hold in a duopoly with quasi-symmetric costs, as demonstrated in section 3. Section 4 contains an evaluation of the two policies in terms of social welfare and studies the robustness of the results when there exists uncertainty about the external benefits. Section 5 discusses policy implications, and section 6 concludes.

2 Promoting renewable electricity in a competitive market

We start our analysis with the simplest case, assuming that in a perfectly competitive electricity market there are N firms with equal electricity generation costs. Let there be only two options to produce electricity, either from fossil/nuclear resources ('brown electricity') or renewable resources (solar, wind, hydro, biomass etc.), with the second referred to as 'green electricity'. We assume that generation costs of fossil/nuclear power are generally lower than those of green electricity, often due to economies of scale and higher energy density of the input fuel used. However, green electricity cannot only help to avoid negative externalities from fossil/nuclear power generation, but also yield positive externalities in the form of different kinds of socio-economic benefits (e.g. creation of new employment, local value-added and infrastructure, spillovers from R&D in innovative energy technologies and systems, learning-by-doing externalities that, with an increasing adoption, lead to a cost reduction for the renewable technologies).[3] The fact that these externalities are not sufficiently taken into account in decisions regarding the type and level of electricity production and consumption may motivate policy interventions such as the introduction of FIT and TGC.

2.1 FIT as a subsidy policy

The term 'subsidy' 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] Given a competitive market, a representative generator of power faces the following optimization problem:

$$\max_{x_{\mathrm{b}},x_{\mathrm{g}}} \left[p x_{\mathrm{b}} + (p+s)x_{\mathrm{g}} - C_{\mathrm{b}}(x_{\mathrm{b}}) - C_{\mathrm{g}}(x_{\mathrm{g}})\right], \tag{1}$$

where x_{b} and x_{g} denote the amounts of electricity produced from fossil/nuclear ('brown') fuels and renewable ('green') energy sources, respectively, $C_{\mathrm{b}}(x_{\mathrm{b}})$ is the cost function for electricity produced from fossil/nuclear fuel, $C_{\mathrm{g}}(x_{\mathrm{g}})$ is

[3] Note that the use of green electricity may also lead to non-negligible negative externalities (e.g. Abbasi and Abbasi, 2000; Tsoutsos et al., 2005), but we assume here that these are generally smaller than the positive ones, and that the positive externalities of green electricity are generally larger than those of brown electricity.

[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.

the cost function for green electricity, and p denotes the average market price for electricity. For an interior solution, the f.o.c. are

$$p - C'_{\mathrm{b}}[x^*_{\mathrm{b}}] = 0 \qquad (2)$$
$$p + s - C'_{\mathrm{g}}[x^*_{\mathrm{g}}] = 0. \qquad (3)$$

Inserting (2) into (3), we find that in an optimum with $x_{\mathrm{b}} > 0$ and $x_{\mathrm{g}} > 0$, the government subsidy s (or negative tax) has to be equal to the (absolute) difference between the marginal costs of green and conventional electricity evaluated at the optimum, $C'_{\mathrm{g}}[x^*_{\mathrm{g}}]$ and $C'_{\mathrm{b}}[x^*_{\mathrm{b}}]$, with $C'_{\mathrm{g}}[x^*_{\mathrm{g}}] > C'_{\mathrm{b}}[x^*_{\mathrm{b}}]$. The economic intuition behind this result is that if $s > C'_{\mathrm{g}}[x^*_{\mathrm{g}}] - C'_{\mathrm{b}}[x^*_{\mathrm{b}}]$, all generators will supply green electricity only; in contrast, if $s < C'_{\mathrm{g}}[x^*_{\mathrm{g}}] - C'_{\mathrm{b}}[x^*_{\mathrm{b}}]$, then no green electricity at all will be provided.

2.2 TGC as a quota-based policy

Rather than subsidizing green electricity, the government can also impose a green power production quota on each generator.[5] If a generator falls short of the quota, it faces a fine that increases with the shortfall. For each unit of green electricity produced, the generator obtains a certificate, providing proof of partial satisfaction of the norm.

Initially, assume that certificates are non-tradable. This assumption is natural given the assumption of identical costs across generators (no opportunity for trading). In section 3 below, the non-tradability assumption will be relaxed and a market for certificates introduced. For the situation of non-tradable certificates, the objective function that applies to a generator can be stated

[5] Note that in practice it is often the wholesalers or retailers, and sometimes even the final consumers of electricity, that are obliged to fulfil the quota.

as:

$$\max_{x_{\mathrm{b}},x_{\mathrm{g}}} \left[p \cdot (x_{\mathrm{b}} + x_{\mathrm{g}}) - f \cdot (\bar{x}_{\mathrm{g}} - x_{\mathrm{g}}) - C_{\mathrm{b}}(x_{\mathrm{b}}) - C_{\mathrm{g}}(x_{\mathrm{g}})\right], \tag{4}$$

where $\bar{x}_{\mathrm{g}}$ denotes the green electricity quota of the firm, f is the fine per unit of shortfall from the norm, and p, x_{b}, x_{g}, $C_{\mathrm{b}}(x_{\mathrm{b}})$, $C_{\mathrm{g}}(x_{\mathrm{g}})$ are the same as before. The f.o.c. with respect to x_{g} read

$$p - C'_{\mathrm{b}}[x^*_{\mathrm{b}}] = 0 \tag{5}$$
$$p + f - C'_{\mathrm{g}}[x^*_{\mathrm{g}}] = 0. \tag{6}$$

Note the similarity of (6) and (3). Although the two instruments are markedly different from each other, in fact the fine f plays the same role as the subsidy s, which therefore represents the shadow price of the quota. In an optimum, the unit price of the certificate should be equal to (slightly lower than) the value of the fine per unit.

2.3 Equivalence of FIT and TGC given identical costs

To show the equivalence of FIT and TGC, i.e. subsidy and quota-based policies, in terms of social welfare and for the case of no trading, we state the problem of a social planner as follows: [6]

$$W(Q, x_{\mathrm{g}}) = \max_{Q,x_{\mathrm{g}}} \int_0^Q p(\nu)d\nu - N \cdot C_{\mathrm{b}}\left(\frac{Q}{N} - x_{\mathrm{g}}\right) - N \cdot C_{\mathrm{g}}(x_{\mathrm{g}}) + E(Nx_{\mathrm{g}}), \tag{7}$$

where $Q = N(x_{\mathrm{b}} + x_{\mathrm{g}})$ stands for total electricity output produced by N firms, $p(\nu)$ for the inverse demand function, and $E(Nx_{\mathrm{g}})$ for the monetary value of

[6] Seminal work on the equivalence of price and quantity control was provided by Bhagwati (1969) in the context of foreign trade (tariffs vs. quotas) and by Weitzman (1974) in the context of pollutant emission control (taxes vs. quotas), respectively.

the avoided negative and achieved positive externalities associated with green electricity production. As f.o.c. one obtains

$$p[Q^*] - C_{\mathrm{b}}'[x_{\mathrm{b}}^*] = 0 \tag{8}$$
$$C_{\mathrm{b}}'[x_{\mathrm{b}}^*] = C_{\mathrm{g}}'[x_{\mathrm{g}}^*] - E'[Nx_{\mathrm{g}}^*], \tag{9}$$

which determine the social optimum values of Q^*, x_{b}^* and x_{g}^*. Eq. (9) simply says that optimal aggregate output of green electricity must be such that the difference between the marginal cost and the marginal external benefit of green electricity is equal to the marginal cost of conventional power. If these quantities are known, the quota can be set as $\bar{x}_{\mathrm{g}} = x_{\mathrm{g}}^*$. The optimal subsidy level is given by $s^* = C_{\mathrm{g}}'[x_{\mathrm{g}}^*] - C_{\mathrm{b}}'[x_{\mathrm{b}}^*]$ from (3), and the optimal fine by $f^* = C_{\mathrm{g}}'[x_{\mathrm{g}}^*] - p$ from (6).

Obviously, subsidy and quota levels that are set according to the optimal values determined by maximizing social welfare will lead to the same level of green electricity production, yielding the same welfare. In this sense, and given our assumptions, the subsidy system and quota system are equivalent. Figure 1 illustrates the basic intuition behind these results. Let S^* denote the supply schedule reflecting that green power creates an external benefit to society. Therefore, it should be used at a rate $x_{\mathrm{g}}^1 > x_{\mathrm{g}}^0$, with x_{g}^0 being the outcome of supply S_0 based on private (marginal) cost and demand D. In the presence of externalities, x_{g}^0 gives rise to the 'deadweight loss' marked as the shaded area. Clearly, the efficient quantity of green power can be attained alternatively, either by paying the optimal subsidy s^*, or imposing the optimal quota $\bar{x}_{\mathrm{g}}^*$.

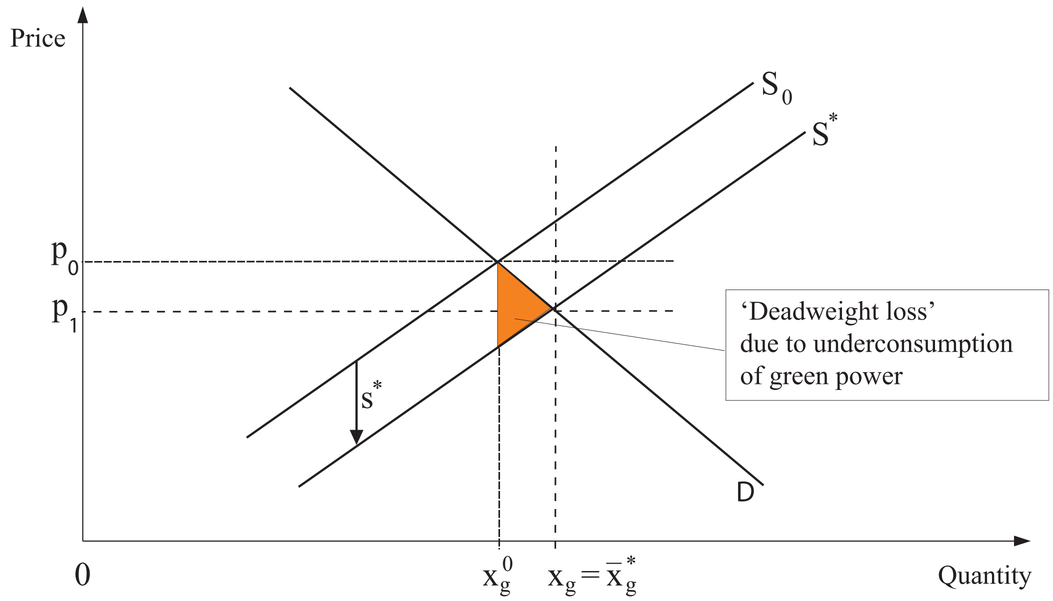

Fig. 1. Equivalence of subsidy and quota-based policy given equal costs.

3 Duopoly market and quasi-symmetric costs

Studying the case of imperfectly competitive power markets as a duopoly game under quasi-symmetric costs can be justified on the following grounds. First, power markets are dominated by a few major players. For example, EdF still has a monopoly in France, E.ON UK and RWE each have a market share of 17 percent in the UK, and the four biggest suppliers in Germany, RWE, E.ON Energie, Vattenfall Europe and EnBW, together control more than two thirds of the market (cf. Bower et al., 2001; Matthes et al., 2005; RWE, 2010). Moreover, the existence of transmission constraints that limit the spatial extent of competition in electricity markets at particular times may lead to imperfect competition. However, the extent of this effect will depend on further characteristics of these constraints, e.g. their frequency. Second, assuming the production costs of green power to be the same for all producers is not compatible with certificate trading. Therefore, we extend the basic model to the case of heterogeneous production costs in order to derive the potential for trading green certificates.

Assume there are two generators in the market, firm 1 and 2, that have identical technology and hence cost functions in using fossil/nuclear fuel but differing costs of generating renewable electricity. In this sense, the firms are 'quasi-symmetric'. The main reason to expect heterogeneous cost structures for green power is that it does not yet constitute a mature technology like that based on fossil or nuclear fuels, where competition presumably has forced operators to adopt the least-cost alternative. Therefore, producers of green power are assumed to employ different technologies, have more or less favorable siting of plants, use energy resources of different qualities, and employ different vintage mixes of a given technology.

To keep our model simple and to avoid multiple equilibria, we assume the cost function in using fossil/nuclear fuel $C_{\mathrm{b}}(x_{\mathrm{b}}) = c_{\mathrm{b}} x_{\mathrm{b}}$ to be linear and the difference of marginal cost between firm 1 and firm 2, $C'_{1\mathrm{g}}(y) - C'_{2\mathrm{g}}(y)$, to be a positive constant. Without loss of generality, we assume $C_{1\mathrm{g}}(y) > C_{2\mathrm{g}}(y)$ for any $y > 0$. Furthermore, with some loss of generality but considerable gain in simplicity, let the demand function take on the following form,

$$p(x_{1\mathrm{b}}, x_{1\mathrm{g}}, x_{2\mathrm{b}}, x_{2\mathrm{g}}) = a - x_{1\mathrm{b}} - x_{1\mathrm{g}} - x_{2\mathrm{b}} - x_{2\mathrm{g}}, \quad a > 0, \tag{10}$$

which implies that consumers' willingness to pay is the same for fossil/nuclear and green power.

We start with the subsidy policy, focusing on the Cournot solution because power markets have been characterized by an absence of the fierce price competition one would expect in a Bertrand world. Limited price competition may be the result of collusion (Newbery, 2002), a variant of which is to stick to Cournot strategies. Moreover, under certain circumstances (e.g., capacity constraints), Cournot strategies continue to be pursued even under Bertrand-type competition (Kreps and Scheinkman, 1983). Given the market structure described above, firm 1 (the leader) believes that firm 2 (the follower) will react to firm 1's choice of green power produced. Thus in equilibrium firm 1 will have chosen a higher production level than in the case of a Cournot equilibrium and, consequently, firm 2 a lower level.

3.1 Effect of subsidy on equilibrium

In this paper, we assume that the subsidy is uniform. Thus, the two firms face the optimization problem,

$$\max_{x_{i\mathrm{b}}, x_{i\mathrm{g}}} (a - x_{i\mathrm{b}} - x_{i\mathrm{g}} - x_{j\mathrm{b}} - x_{j\mathrm{g}})(x_{i\mathrm{b}} + x_{i\mathrm{g}}) + s x_{i\mathrm{g}} - c_{\mathrm{b}} x_{i\mathrm{b}} - C_{i\mathrm{g}}(x_{i\mathrm{g}}), \quad (11)$$

where $i, j = 1, 2$, and $i \neq j$.

Further, we assume that the subsidy s is exogenous and equal across firms. Generalizing condition (3), one can distinguish three different cases for the subsidy level (denoted S1–S3).

3.1.1 Case S1: $s \leq C'_{2\mathrm{g}}[x^*_{2\mathrm{g}}] - c_{\mathrm{b}} < C'_{1\mathrm{g}}[x^*_{1\mathrm{g}}] - c_{\mathrm{b}}$

If $s < C'_{2\mathrm{g}}[x^*_{2\mathrm{g}}] - c_{\mathrm{b}}$, it is obvious that no green electricity will be produced because the subsidy does not make up for the efficient producer's cost disadvantage. Accordingly, the standard Cournot solution to the game is (cf. Kreps, 1990, p. 326),

$$x^*_{1\mathrm{b}} = x^*_{2\mathrm{b}} = \frac{a - c_\mathrm{b}}{3}; \qquad x^*_{1\mathrm{g}} = x^*_{2\mathrm{g}} = 0. \tag{12}$$

If $s = C'_{2\mathrm{g}}[x^*_{2\mathrm{g}}] - c_\mathrm{b}$, then generator 2 is indifferent between producing green electricity and fossil/nuclear electricity.

3.1.2 Case S2: $C'_{2\mathrm{g}}[x^*_{2\mathrm{g}}] - c_\mathrm{b} \leq s < C'_{1\mathrm{g}}[x^*_{1\mathrm{g}}] - c_\mathrm{b}$

In this case, the subsidy makes up for the cost disadvantage of green power for generator 2, but fails to do so for the less efficient generator 1, who therefore refrains from producing green electricity. The Cournot solution remains the same (in the sense that total electricity output of each firm remains unchanged), as compared to the case of a uniform quota.

So if $s > C'_{2\mathrm{g}}[x^*_{2\mathrm{g}}] - c_\mathrm{b}$, then generator 2 switches to green electricity, i.e.,

$$x^*_{1\mathrm{b}} = \frac{a - 2c_\mathrm{b} + C'_{2\mathrm{g}}[x^*_{2\mathrm{g}}] - s}{3} \tag{13}$$

$$x^*_{2\mathrm{g}} = \frac{a - 2C'_{2\mathrm{g}}[x^*_{2\mathrm{g}}] + c_\mathrm{b} + 2s}{3} \tag{14}$$

$$x^*_{1\mathrm{g}} = x^*_{2\mathrm{b}} = 0. \tag{15}$$

Note that $x^*_{1\mathrm{b}}$ in (13) and $x^*_{2\mathrm{g}}$ in (14) are larger than in (12).

3.1.3 Case S3: $s \geq C'_{1\mathrm{g}}[x^*_{1\mathrm{g}}] - c_\mathrm{b}$

If $s > C'_{1\mathrm{g}}[x^*_{1\mathrm{g}}] - c_\mathrm{b}$, then the subsidy overcompensates the cost disadvantage of green power even for the less efficient generator 1. Therefore, both firms produce green electricity only. Accordingly, the optimal solutions are now

$$x_{1g}^* = \frac{a + C'_{2g}[x_{2g}^*] - 2C'_{1g}[x_{1g}^*] + s}{3} \tag{16}$$

$$x_{2g}^* = \frac{a + C'_{1g}[x_{1g}^*] - 2C'_{2g}[x_{2g}^*] + s}{3} \tag{17}$$

$$x_{1b}^* = x_{2b}^* = 0. \tag{18}$$

In the limiting case where $s = C'_{1g}[x_{1g}^*] - c_b$, generator 1 is indifferent between producing green and fossil/nuclear power, while generator 2, being efficient in the production of green power, supplies green electricity only.

3.1.4 Optimal subsidy level

The results derived in the previous subsection show that the equilibrium solutions to the Cournot game strongly depend upon the level of the subsidy. This raises the issue of determining the optimal subsidy level. In analogy to (7), let social welfare be given by

$$\begin{aligned} W^j(Q, x_{1g}, x_{2g}; s) = &\int_0^Q p(\nu)d\nu - c_b(Q - x_{1g} - x_{1g}) \\ &- C_{1g}(x_{1g}) - C_{2g}(x_{2g}) + E(x_g), \end{aligned} \tag{19}$$

with W^j denoting the social welfare gains associated with case j (j = 1, 2, and 3) of sections 3.1.1–3.1.3. We assume that in case S2, s is slightly greater than $C'_{2g}[x_{2g}^*] - c_b$, and in case S3 slightly greater than $C'_{1g}[x_{1g}^*] - c_b$, in order to avoid ambiguity.

To facilitate comparison between the cases, the externality function [7] associ-

[7] 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

ated with green electricity takes the form $E(x_{\mathrm{g}}) = \beta x_{\mathrm{g}}$, $\beta > 0$. While it would certainly be interesting to elaborate on possible alternative functional forms of $E(x_{\mathrm{g}})$, and consequences for the outcome, such an analysis is beyond the scope of this paper and saved for future research.

The parameter β (called 'welfare parameter' henceforth) implies a constant marginal social benefit from producing green electricity. Using the equilibrium values given in (11) to (17), the welfare associated with the three cases can be written as follows:

$$W^1 = \left(a - \frac{Q}{2}\right) Q - c_{\mathrm{b}} Q \tag{20}$$

$$W^2 = \left(a - \frac{Q}{2}\right) Q + \beta x_{2\mathrm{g}} - c_{\mathrm{b}}(Q - x_{2\mathrm{g}}) - C_{2\mathrm{g}}(x_{2\mathrm{g}}) \tag{21}$$

$$W^3 = \left(a - \frac{Q}{2}\right) Q + \beta Q - C_{1\mathrm{g}}(x_{1\mathrm{g}}) - C_{2\mathrm{g}}(x_{2\mathrm{g}}). \tag{22}$$

As is to be expected, whether or not the welfare parameter β exceeds the marginal cost parameters is of crucial importance. For $\beta > C'_{1\mathrm{g}}[x^*_{1\mathrm{g}}] - c_{\mathrm{b}}$, the welfare parameter is larger than the additional costs incurred by firm 1, so that it is optimal if both firms produce green electricity. Conversely, if the positive externality $\beta x_{2\mathrm{b}}$ exceeds the extra costs of producing green electricity for firm 2, it is optimal if firm 2 produces green instead of brown electricity.

More specifically, we can distinguish the following situations:

(A) if $\beta > C'_{1\mathrm{g}}[x^*_{1\mathrm{g}}] - c_{\mathrm{b}}$, then $W^3 > W^2 > W^1$. Hence the optimal subsidy is the lower bound of the subsidy interval in case 3, i.e., $s^*_{\mathrm{A}} = C'_{1\mathrm{g}}[x^*_{1\mathrm{g}}] - c_{\mathrm{b}}$.

(B) if $\beta = C'_{1\mathrm{g}}[x^*_{1\mathrm{g}}] - c_{\mathrm{b}}$, then $W^3 = W^2 > W^1$. The welfare gains remain the

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to produce electricity, and thus also the amount of the brown electricity actually displaced and the (environmental) benefits incurred.

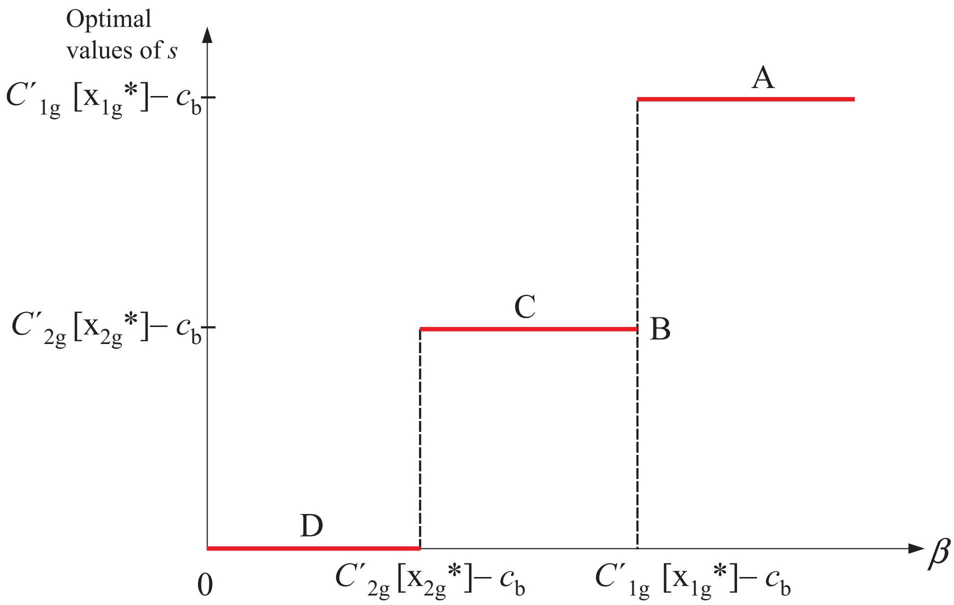

Fig. 2. Optimal subsidy levels vs welfare parameter β of green electricity, cases A through D.

same for $s^*_{\mathrm{B}} = C'_{1\mathrm{g}}[x^*_{1\mathrm{g}}] - c_{\mathrm{b}}$ and $s^{**}_{\mathrm{B}} = C'_{2\mathrm{g}}[x^*_{2\mathrm{g}}] - c_{\mathrm{b}}$, though the amounts of green electricity produced are different.

(C) if $C'_{2\mathrm{g}}[x^*_{2\mathrm{g}}] - c_{\mathrm{b}} \leq \beta < C'_{1\mathrm{g}}[x^*_{1\mathrm{g}}] - c_{\mathrm{b}}$, then $W^2 > W^3$ and $W^2 \geq W^1$. The optimal subsidy is thus equal to the lower bound of the subsidy interval in case 2, i.e., $s^*_{\mathrm{C}} = C'_{2\mathrm{g}}[x^*_{2\mathrm{g}}] - c_{\mathrm{b}}$.

(D) if $\beta < C'_{2\mathrm{g}}[x^*_{2\mathrm{g}}] - c_{\mathrm{b}}$, then $W^1 > W^2 > W^3$. Therefore, the optimal subsidy is zero, because none of the rates s are effective in promoting green power.

Figure 2 summarizes the optimal subsidy schedule for different values of the welfare parameter β.

3.2 Quota-based policy

Building on (4) of section 2.2, the decision problem faced by the two firms in a duopoly market can be written as

$$\begin{aligned} \max_{x_{i\mathrm{b}},x_{i\mathrm{g}}} & [(a - x_{i\mathrm{b}} - x_{i\mathrm{g}} - x_{j\mathrm{b}} - x_{j\mathrm{g}})(x_{i\mathrm{b}} + x_{i\mathrm{g}}) + z(\tilde{x}_{i\mathrm{g}} - \tilde{x}_{j\mathrm{g}}) \\ & - f(\bar{x}_{\mathrm{g}} - x_{i\mathrm{g}} - \tilde{x}_{i\mathrm{g}}) - c_{\mathrm{b}}x_{i\mathrm{b}} - C_{i\mathrm{g}}(x_{i\mathrm{g}})], \qquad (23) \\ \text{s.t.} \quad & x_{i\mathrm{g}} + x_{j\mathrm{g}} = 2\bar{x}, \end{aligned}$$

with $\tilde{x}_{i\mathrm{g}}$ ($\tilde{x}_{j\mathrm{g}}$) denoting the amount of certificates sold (purchased), respectively, $i, j = 1$ or 2, and $i \neq j$, f denoting the fine per unit as in (4), and z denoting the certificate price[8]. Note that the constraint implies that the amount of green certificates produced by the two firms must not exceed the industry quota – i.e. we assume that once the quota is satisfied the certificate price drops to zero. Thus, there is no incentive to produce more green electricity than is required by the quota target.

In the above model, each firm has two choice variables. However, given the assumption that the difference $C'_{1\mathrm{g}}(y) - C'_{2\mathrm{g}}(y)$ is a positive constant for any $y > 0$, generator 1's choice of $x_{1\mathrm{g}}$ boils down to a choice between 0 and $\bar{x}_{\mathrm{g}}$, depending on the ordering of f, z, and the level of the difference in marginal costs of producing green and brown electricity (cf. figure 3). If it is in the interest of generator 1 to purchase green electricity certificates at all, it must

[8] 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. Nilsson and Sundqvist, 2007; Söderholm, 2008; Bergek and Jacobsson, 2010; Wood and Dow, 2011). Yet, there is a need for more research on markets for tradable green certificates with perfect competition.

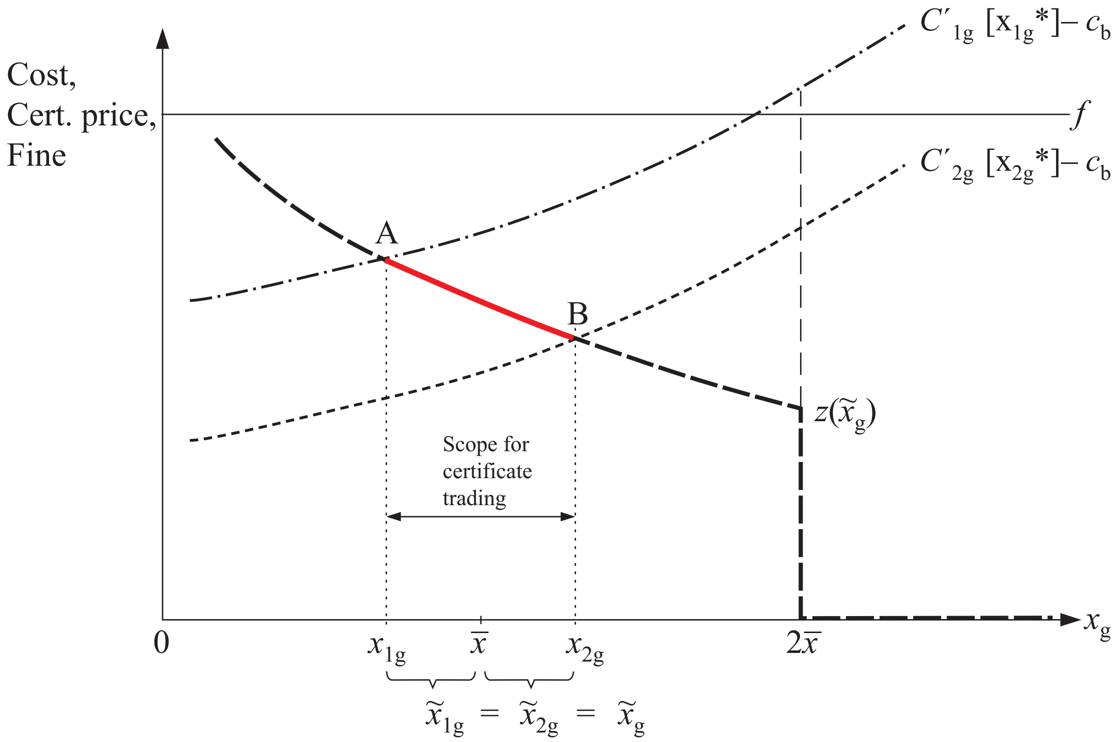

Fig. 3. Effects of the TGC policy in a duopoly game

also be (at least weakly) in its interest to go all the way. Therefore, we can find a Nash equilibrium by comparing the firms' payoffs for $x^*_{1g} \in \{0, \bar{x}_g\}$, which will be determined in the following section. Before turning to the Nash equilibrium, however, we briefly discuss the different possible cases, of which we will examine the ones that are desirable from a social welfare point of view.

Case I: The fine could fall short of the difference in marginal costs for firms 1 and 2, in which both firms prefer to pay the fine and produce conventional electricity only.

Case II: If the fine is larger than the cost difference for firm 2 but lower than the marginal cost difference for firm 1 of producing green instead of brown electricity, then we can distinguish two sub-cases: either the certificate price is larger or smaller than the fine. In the former case, firm 1 prefers to pay the fine, rather than buying certificates from firm 2, while in the latter case it would buy certificates from firm 2 up to its quota (provided, of course, that trading is possible).

Case III: The fine may be set at a higher level than the difference in the marginal costs of producing green instead of conventional electricity for both generators. In this case we can again distinguish two sub-cases, one where z is lower than the cost difference for firm 1 (so that it has an incentive to buy certificates up to $\bar{x}$ from generator 2) and a situation where it is higher (in which case generator 1 would self-generate green electricity up to its quota[9]).

In the following, we consider the two cases where certificate trading occurs (case I) and the case where firm 1 self-produces green certificates (case II).

3.3 Nash equilibrium under the quota-based policy

We now elaborate the Nash equilibrium for the quota-based policy, by comparing the firms' payoffs under the two socially desirable strategies stated at the end of the previous section 3.2. Hence, in the discussion below, we distinguish the two cases I and II.

[9] Note that in this situation generator 1 would possibly be forced at some point to leave the market, as its costs of producing green electricity are too high.

3.3.1 *Case I: $x_{1\mathrm{g}}^* = 0$*

Case I refers to a situation where the cost difference for firm 1 of producing green instead of brown electricity is lower than the fine f but higher than the certificate price z. Therefore, it is cheaper for firm 1 to buy certificates from firm 2. Given that $x_{1\mathrm{g}}^* = 0$, generator 2 is required to produce at least $2\bar{x}_{\mathrm{g}}$ units of green electricity in order to satisfy the industry quota. This can be summarized as follows,

$$x_{1\mathrm{g}}^* = 0 \Leftrightarrow f > C_{1\mathrm{g}}'[x_{1\mathrm{g}}^*] - c_{\mathrm{b}} > z > C_{2\mathrm{g}}'[x_{2\mathrm{g}}^*] - c_{\mathrm{b}} \tag{24}$$

or as

$$C_{1\mathrm{g}}'[x_{1\mathrm{g}}^*] - c_{\mathrm{b}} > f > z > C_{2\mathrm{g}}'[x_{2\mathrm{g}}^*] - c_{\mathrm{b}}.$$

Firm 1 solves the problem

$$\max_{x_{1\mathrm{b}}, x_{1\mathrm{g}}} \Pi_1 = (a - x_{1\mathrm{b}} - x_{2\mathrm{b}} - x_{2\mathrm{g}})x_{1\mathrm{b}} - c_{\mathrm{b}}x_{1\mathrm{b}} - z\tilde{x}_{\mathrm{g}} - \max\{0, f(\bar{x}_{\mathrm{g}} - \tilde{x}_{1\mathrm{g}})\}, \tag{25}$$

with f.o.c.:

$$\frac{\partial \Pi_1}{\partial x_{1\mathrm{b}}} = a - 2x_{1\mathrm{b}}^* - x_{2\mathrm{b}}^* - x_{2\mathrm{g}}^* - c_{\mathrm{b}} = 0. \tag{26}$$

Observing the constraint $x_{2\mathrm{g}} \geq 2\bar{x}_{\mathrm{g}}$, firm 2 solves

$$\begin{aligned}\max_{x_{2\mathrm{b}}, x_{2\mathrm{g}}} L(x_{2\mathrm{b}}, x_{2\mathrm{g}}, \lambda) = {} & (a - x_{1\mathrm{b}} - x_{2\mathrm{b}} - x_{2\mathrm{g}})(x_{2\mathrm{b}} + x_{2\mathrm{g}}) - c_{\mathrm{b}}x_{2\mathrm{b}} + z\tilde{x}_{\mathrm{g}} \\ & - \max\{0, f(\bar{x}_{\mathrm{g}} - x_{2\mathrm{g}} + \tilde{x}_{\mathrm{g}})\} - C_{2\mathrm{g}}(x_{2\mathrm{g}}) + \lambda(2\bar{x}_{\mathrm{g}} - x_{2\mathrm{g}}),\end{aligned}$$

with $\lambda \geq 0$ denoting the Lagrange multiplier. The f.o.c. read,

$$\frac{\partial L}{\partial x_{2\mathrm{b}}} = a - x_{1\mathrm{b}}^* - 2x_{2\mathrm{b}}^* - 2x_{2\mathrm{g}}^* - c_{\mathrm{b}} = 0 \tag{27}$$

$$\frac{\partial L}{\partial x_{2\mathrm{g}}} = a - x_{1\mathrm{b}}^* - 2x_{2\mathrm{b}}^* - 2x_{2\mathrm{g}}^* - c_{\mathrm{b}} - C_{2\mathrm{g}}'(x_{2\mathrm{g}}^*) + f + \lambda = 0. \tag{28}$$

From (26) and (27) we get $x_{1\mathrm{b}}^* = (a - c_{\mathrm{b}})/3$, and from (27) and (28) we obtain $x_{2\mathrm{b}}^* + x_{2\mathrm{g}}^* = (a - c_{\mathrm{b}})/3$.

Given that firm 1 does not produce any green electricity, we need to distinguish two subcases. In the first subcase (Ia, Appendix A), firm 2 self-generates its own quota, while in the second subcase (Ib, Appendix A) it produces twice the individual firm's quota (and hence is able to sell the excess certificates to firm 1, which faces higher production costs).

Eqs. (A.1) and (A.2) say that the two firms will produce the same total quantity of electricity, determined by the maximum possible market demand and the cost of producing electricity from fossil/nuclear fuel. From (27) and (28) we obtain

$$\lambda = C'_{2\mathrm{g}}[x^*_{2\mathrm{g}}] - c_\mathrm{b} - f. \tag{29}$$

Eq. (29) indicates that if $C'_{2\mathrm{g}}[x^*_{2\mathrm{g}}] - c_\mathrm{b} > f$, such that $\lambda > 0$, generator 2 will only produce green electricity up to the industry quota as required by our assumptions, due to the Kuhn–Tucker condition. Note that trading of certificates is also possible as long as $C'_{1\mathrm{g}}[x^*_{1\mathrm{g}}] - c_\mathrm{b} \geq f$. However, if $C'_{2\mathrm{g}}[x^*_{2\mathrm{g}}] - c_\mathrm{b} = f$ (and hence $\lambda = 0$), generator 2 has an incentive to produce at least the quota required from the industry. Also note that different values of $f \in [C'_{2\mathrm{g}}[x^*_{2\mathrm{g}}] - c_\mathrm{b}, C'_{1\mathrm{g}}[x^*_{1\mathrm{g}}] - c_\mathrm{b}]$ only affect the distribution of profits between the two firms, with no impact on the amount of certificate trading and social welfare. Therefore, we first focus on the case $C'_{2\mathrm{g}}[x^*_{2\mathrm{g}}] - c_\mathrm{b} = f$ as a benchmark.

The optimal quota continues to be determined as in eqs. (7)–(9), except that $C'_\mathrm{b}[x^*_\mathrm{b}] = c_\mathrm{b}$. Hence $\bar{x}_\mathrm{g} = x^*_\mathrm{g}/2$ still holds. As long as $2\bar{x}_\mathrm{g} \leq (a - c_\mathrm{b})/3$ (see eq. (A.2)), generator 2 produces $(a - c_\mathrm{b})/3 - 2\bar{x}_\mathrm{g}$ units of electricity using fossil/nuclear fuel and $2\bar{x}_\mathrm{g}$ units of green electricity. As to $2\bar{x}_\mathrm{g} > (a - c_\mathrm{b})/3$, recall that a denotes the willingness to pay for the first marginal unit of electricity, while c_b symbolizes the (constant) marginal cost of fossil/nuclear power, which makes $a - c_b$ a very large number. It is unlikely for $\bar{x}_g$ to exceed one sixth of that number, justifying that this case is neglected.

So far, we have assumed that generator 1 is the only buyer of generator 2's extra certificates. However, there may be another agent willing to purchase the certificates at the market price, for example, an environmental protection agency or a foundation promoting renewable energy. Since the equilibrium price of certificates is determined in such a manner that generator 2 is indifferent between producing green or fossil/nuclear fuel electricity, the presence of an additional bidder might cause generator 2 to produce green electricity in excess of the quota. However, this would make the system a combination of quantity and price policies. The reason is that these extra purchases, resulting in an increase of the value of the certificates, can be viewed as a subsidy. It is possible that such a policy mix is more effective in promoting green power than either one of the two policy instruments individually. However, a detailed analysis of such a mixed policy is beyond the scope of this paper.

3.3.2 Case II: $x^*_{1g} = \bar{x}_g$

We now turn to the case of generator 1 producing green electricity to satisfy the quota. This is possible if the difference in the marginal cost of producing green and brown electricity is strictly lower than the certificate price (and the fine), or formally,

$$x^*_{1g} = \bar{x}_g \Leftrightarrow f > z > C'_{1g}[x_{1g}] - c_b. \tag{30}$$

With no agent external to the TGC market purchasing, the condition $x_{1\mathrm{g}} = \bar{x}_\mathrm{g}$ or $x_{2\mathrm{g}} = \bar{x}_\mathrm{g}$ continues to hold. Firm 1's optimization problem now reads,

$$\max_{x_{1\mathrm{b}}, x_{1\mathrm{g}}} \Pi_1 = (a - x_{1\mathrm{b}} - x_{2\mathrm{b}} - \bar{x}_\mathrm{g} - x_{2\mathrm{g}})(x_{1\mathrm{b}} + \bar{x}_\mathrm{g}) - c_\mathrm{b} x_{1\mathrm{b}} - C_{1\mathrm{g}}(\bar{x}_\mathrm{g}),$$

with f.o.c.,

$$\frac{\partial \Pi_1}{\partial x_{1\mathrm{b}}} = a - 2x_{1\mathrm{b}}^* - 2\bar{x}_\mathrm{g} - x_{2\mathrm{b}}^* - x_{2\mathrm{g}} - c_\mathrm{b} = 0; \tag{31}$$

while firm 2 solves the problem

$$\begin{aligned} \max_{x_{2\mathrm{b}}, x_{2\mathrm{g}}} \Pi_2 = {} & (a - x_{1\mathrm{b}} - x_{2\mathrm{b}} - \bar{x}_\mathrm{g} - x_{2\mathrm{g}})(x_{2\mathrm{b}} + x_{2\mathrm{g}}) - c_\mathrm{b} x_{2\mathrm{b}} - C_{2\mathrm{g}}(x_{2\mathrm{g}}) \\ & - \max\{0, f(\bar{x}_\mathrm{g} - x_{2\mathrm{g}})\}. \end{aligned} \tag{32}$$

Since $x_{2\mathrm{g}}^*$ can only take on $\bar{x}_\mathrm{g}$ or $2\bar{x}_\mathrm{g}$ as optimal values, we concentrate on $x_{2\mathrm{g}}^* \geq \bar{x}_\mathrm{g}$ and only consider the first-order condition concerning variable $x_{2\mathrm{b}}$, which reads:

$$\frac{\partial \Pi_2}{\partial x_{2\mathrm{b}}} = a - 2x_{2\mathrm{b}}^* - 2x_{2\mathrm{g}} - x_{1\mathrm{b}}^* - \bar{x}_\mathrm{g} - c_\mathrm{b} = 0. \tag{33}$$

From (31) and (33) we get $x_{1\mathrm{b}}^* = (a - c)/3 - \bar{x}_\mathrm{g}$ and $x_{2\mathrm{b}}^* = (a - c)/3 - x_{2\mathrm{g}}$.

As before, we have to distinguish two subcases (IIa and IIb in Appendix A), in both of which firm 1 self-generates green electricity up to its individual quota, while firm 2 either produces $\bar{x}_\mathrm{g}$ or twice $\bar{x}_\mathrm{g}$.

		Firm 2: $\bar{x}_\mathrm{g}$	Firm 2: $2\bar{x}_\mathrm{g}$
Firm 1	0	$-f\bar{x}_\mathrm{g},\ -c_\mathrm{b}\bar{x}_\mathrm{g} - C_{2\mathrm{g}}(\bar{x}_\mathrm{g})$	$-z\bar{x}_\mathrm{g},\ (z - 2c_\mathrm{b})\bar{x}_\mathrm{g} - C_{2\mathrm{g}}(2\bar{x}_\mathrm{g})$
Firm 1	$\bar{x}_\mathrm{g}$	$c_\mathrm{b}\bar{x}_\mathrm{g} - C_{1\mathrm{g}}(\bar{x}_\mathrm{g}),\ c_\mathrm{b}\bar{x}_\mathrm{g} - C_{2\mathrm{g}}(\bar{x}_\mathrm{g})$	$c_\mathrm{b}\bar{x}_\mathrm{g} - C_{1\mathrm{g}}(\bar{x}_\mathrm{g}),\ 2c_\mathrm{b}\bar{x}_\mathrm{g} - C_{2\mathrm{g}}(2\bar{x}_\mathrm{g})$

Fig. 4. Payoffs to producers of green electricity under the TGC policy

If firm 2's strategy is to produce the minimal quota, then firm 1's best response is $x_{1g} = \bar{x}_g$ if $C_{1g}(\bar{x}_g) - c_b\bar{x}_g \leq f\bar{x}_g$. However, if firm 2's strategy is to produce twice the quota, then firm 1's best response is $x_{1g} = 0$ if $C_{1g}(\bar{x}_g) - c_b\bar{x}_g \geq z\bar{x}_g$. If firm 1's strategy is to produce 0, then firm 2's best response is $2\bar{x}_g$, provided the following condition holds: $C_{2g}(2\bar{x}_g) - C_{2g}(\bar{x}_g) \leq (z - c_b)\bar{x}_g$. This condition holds due to the assumptions made in this paper. If firm 1's strategy is to produce the minimal quota, then firm 2's best response is $\bar{x}_g$, provided that the following condition is satisfied: $C_{2g}(2\bar{x}_g) - C_{2g}(\bar{x}_g) \geq c_b\bar{x}_g$. This condition again holds due to the assumptions made. Therefore, if the condition $z\bar{x}_g \leq C_{1g}(\bar{x}_g) - c_b\bar{x}_g \leq f\bar{x}_g$ is satisfied, this game has two Nash equilibria in pure strategies: $(0, 2\bar{x}_g)$ and $(\bar{x}_g, \bar{x}_g)$.

4 Welfare comparison between subsidy and quota-based policies

In spite of the simplifying assumptions made, a welfare comparison between a price-subsidy and a quota policy may be worthwhile because it promises to provide some guidance to policy-makers regarding the choice of instruments for promoting renewable energy use.

4.1 Welfare gains under the subsidy policy

Since our main interest is to discuss how to efficiently promote green power, case S1 (section 3.1.1) can be disregarded since it is fossil/nuclear only. In addition, case S3 (section 3.1.3) is not realistic because it predicts that all firms exclusively produce green power, which would presuppose extremely high green electricity quota. Therefore, we only examine the case associated with condition $C'_{2g}[x^*_{2g}] - c_b \leq \beta < C'_{1g}[x^*_{1g}] - c_b$, i.e. case S2 of section 3.1.2. The pertinent welfare function is repeated from (21) for convenience,

$$W^s = \left(a - \frac{Q}{2}\right) Q - c_b(Q - x_{2g}) - C_{2g}(x_{2g}) + \beta x_{2g}, \tag{34}$$

where Q continues to be total production of both types of electricity. Remember that in case S2 we have $x^*_{1g} = x^*_{2b} = 0$ and the optimal subsidy is given by $s^* = C'_{2g}[x^*_{2g}] - c_b$, thus the total production given the optimal subsidy scheme can be determined as $Q^s = x^s_{1b} + x^s_{2g} = 2(a - c_b)/3$, with $x^s_{2g} = (a - c_b)/3$ denoting the amount of green energy produced by firm 2. Therefore, social welfare achieved by the optimal subsidy scheme is

$$W^s = (Q^s)^2 - C_{2g}\left(\frac{Q^s}{2}\right) + (c_b + \beta)\frac{Q^s}{2}. \tag{35}$$

4.2 Welfare gains under the quota-based policy

If marginal costs of green power are increasing, the optimal quota cannot be determined directly. To match the production of green electricity in the subsidy case, we simply assume that $\bar{x}_g$ is equal to $(a - c_b)/6$, which may constitute a rather frequent solution (see the discussion after eq. (29) in section 3.3.1). The welfare function for the quota-based certificate system can then be specified as

$$W^q = \left(a - \frac{Q}{2}\right) Q - c_b(Q - x_{2g}) - C_{2g}(x_{2g}) + \beta x_{2g}. \tag{36}$$

The total amount of energy $Q^q = 2(a - c_b)/3$ produced given the quota-based policy is identical with Q^s. However, w.r.t. to x_{2g}, we have to distinguish the following two possible pure Nash equilibrium outcomes of the game described in section 3.3.2:

(i) Welfare achieved in the Nash equilibrium $(x_{1\mathrm{g}}^{\mathrm{q1}}, x_{2\mathrm{g}}^{\mathrm{q1}}) = (0, 2\bar{x}_{\mathrm{g}})$,

$$W^{\mathrm{q1}} = (Q^{\mathrm{q}})^2 - C_{2\mathrm{g}}\left(\frac{Q^{\mathrm{q}}}{2}\right) + (c_{\mathrm{b}} + \beta)\,\frac{Q^{\mathrm{q}}}{2}. \tag{37}$$

Since $Q^{\mathrm{q}} = Q^{\mathrm{s}}$, the welfare under the quota-based policy realized in this Nash equilibrium is equal to the welfare under the optimal subsidy policy ($W^{\mathrm{q1}} = W^{\mathrm{s}}$).

(ii) Welfare achieved in the Nash equilibrium $(x_{1\mathrm{g}}^{\mathrm{q2}}, x_{2\mathrm{g}}^{\mathrm{q2}}) = (\bar{x}_{\mathrm{g}}, \bar{x}_{\mathrm{g}})$,

$$W^{\mathrm{q2}} = (Q^{\mathrm{q}})^2 - C_{2\mathrm{g}}\left(\frac{Q^{\mathrm{q}}}{4}\right) + (c_{\mathrm{b}} + \beta)\,\frac{Q^{\mathrm{q}}}{4}. \tag{38}$$

Note that the welfare level W^{q2} is lower than $W^{\mathrm{q1}} = W^{\mathrm{s}}$ if

$$C_{2\mathrm{g}}(2\bar{x}_{\mathrm{g}}) - C_{2\mathrm{g}}(\bar{x}_{\mathrm{g}}) < (c_b + \beta)\bar{x}_{\mathrm{g}}.$$

This condition is satisfied if the level of marginal social benefit of green electricity β is sufficiently high and exceeds the level

$$\beta_{\mathrm{min}} = \frac{C'_{2\mathrm{g}}(\bar{x}_{\mathrm{g}})}{c_{\mathrm{b}}}.$$

Hence, the subsidy policy guarantees a welfare level which might not be achieved with the quota policy if the Nash equilibrium $(\bar{x}_{\mathrm{g}}, \bar{x}_{\mathrm{g}})$ is played. A comparison of both firms' profits as well as of their sum shows that only firm 1 is better off in the socially efficient equilibrium $(0, 2\bar{x}_{\mathrm{g}})$. Under our assumptions, both firm 2's profit and total producer surplus are likely to be higher in the socially less desirable equilibrium $(\bar{x}_{\mathrm{g}}, \bar{x}_{\mathrm{g}})$. Therefore, even if the Cournot game were repeated an infinite number of times, no cooperative equilibrium would occur with both firms choosing the socially desirable strategies.

4.3 Uncertainty about external benefits

An interesting question in this context is whether our results change when there is uncertainty about the external benefits arising from adopting renewables. We address this question by providing a simple example. Suppose that the externality function associated with green energy is modified to read, $E(x_{\mathrm{g}}) = (\beta + \varepsilon)x_{\mathrm{g}}$, where ε denotes a stochastic part of the marginal social benefit with

$$\varepsilon = \begin{cases} k & \text{prob. } 0.5 \\ \\ -k & \text{prob. } 0.5 \end{cases}$$

As in the certainty case, the welfare level W^{q2} is lower than $W^{\mathrm{q1}} = W^{\mathrm{s}}$ if the social benefit is higher than expected. However, this comparison becomes ambiguous in the case $\varepsilon = -k$. Here, the welfare level W^{q2} might exceed W^{s} if the uncertainty associated with the marginal social benefits is too high, i.e. if k exceeds the threshold level $\hat{k}$ that can be approximated as

$$\hat{k} = \frac{c_{\mathrm{b}} + \beta}{C'_{2\mathrm{g}}(\bar{x}_{\mathrm{g}})}.$$

Yet, since this threshold level is significantly higher than $\beta_{\min}$ and thus requires the stochastic part of the marginal social benefit to exceed the deterministic one, it is highly unlikely for the Nash equilibrium $(\bar{x}_{\mathrm{g}}, \bar{x}_{\mathrm{g}})$ to become socially desirable even ex-post.

4.4 Welfare of subsidy and quota-based policies in a quasi-symmetric duopoly

Comparing welfare levels given in (35), (37), and (38), one sees that, for sufficiently high marginal social benefits of green energy, $W^{\mathrm{s}} = W^{\mathrm{q1}} > W^{\mathrm{q2}}$. This result implies that even with imperfect competition and quasi-heterogeneous costs, subsidies should be preferred to tradable certificates. It is still robust under the assumption of uncertainty about the level of external benefits of renewables. This is intuitive, since outcomes in a duopoly crucially depend on whether firms pursue price- or quantity-oriented strategies and FIT could be said to be price-oriented whereas TGC is quantity-oriented. One of the issues for suppliers of green energy under a certificate trading system is the uncertainty about what the value of TGCs will be whereas this uncertainty is usually not present for a predetermined subsidy (although unexpected adjustments of FITs cannot be ruled out completely [10]. Therefore, from this perspective the subsidy policy constitutes less risk to the investor.

Note, however, the results established above given imperfectly competitive markets seem to hinge on two crucial assumptions. The first is that TGC are tradable. This means that price is the signal to competitors, precisely as the subsidy under FIT. And since the quota and the subsidy are set as to optimally internalize the externalities present, the information content of price is the same under both regimes. Second, competitors pursue optimal duopoly strategies regardless of the choice of internalization policy adopted by the government.

In addition to these two basic premises, there are simplifying assumptions that should be kept in mind. Specifically, the cost of administering subsidies and/or quota are neglected and therefore assumed equal. However, when it comes to start-up costs, a certificate system may require more resources than a subsidy system, especially for establishing appropriate regulation and regulatory con-

[10] We are gratefully to one of the reviewers for this important comment.

trol. Also, information regarding cost and marginal revenues on the part of competitors as well as marginal positive externalities of green power on the part of government was assumed perfect. Yet due to cost heterogeneity, the amount of information required for calculating the optimal subsidy typically increases with a growing number of firms. Although the setting of the optimal quota requires similar information, the heterogeneity of firms does not enter their determination, causing it to be relatively straightforward and hence probably less costly than a subsidy system. These considerations also suggest that a generalization from duopoly to oligopoly would be straightforward.

Further, we found that subsidies provide more incentives for green power precisely when its marginal social benefits are high (as in case S3 of section 3.1.3). A pure quota-based TGC system lacks this feature.

5 Policy implications

Based on several models incorporating imperfect competitiveness of power markets for added realism, we find that the subsidy (FIT) approach, when implemented at its socially optimal value, leads to a welfare gain which is not necessarily achieved with the quota-based (TGC) policy. In the presence of uncertainty about the level of external benefits of renewables, the preference for subsidies over quotas still persists, albeit less pronounced than under certainty, the latter result being in contrast with Pizer (1999b). Furthermore, the subsidy policy is generally preferred by energy providers, likely because it does not call into question their right to cause a certain amount of pollution when usingfossil/nuclear fuel input, as it is in the case with a carbon tax. At the same time, subsidies do provide stronger incentives for pollution-abating innovation than quotas by directly favoring production of green electricity.

On the other hand, the financing of subsidies requires revenues from taxes or levies. When the (economic or political) cost of additional taxation is high, like in the United States (but also e.g. in Scandinavian countries), the quota-based approach may provide a viable alternative. As found in the present analysis, tradable green certificates are more efficient than non-tradable ones regardless of market structure. Trade in certificates is likely to develop because green power does not yet rely on mature cost-minimizing technologies, contrary to fossil/nuclear generation so that technological diversity is expectedly larger. Moreover, since the cost of running a market for certificates is lower once the market is established, the disadvantage of the quota-based policy will gradually wane, but without reaching the dynamic efficiency of the subsidy approach.

6 Conclusions

This paper starts from the suspicion that the conventional wisdom, claiming a tax/subsidy (FIT) and a quota/certificate (TGC) policy scheme to be equivalent in terms of static efficiency, might not hold if markets for power are imperfectly competitive. Based on a duopoly model in which the two competitors differ in terms of their marginal cost of producing 'green' power, we show that, if both schemes are implemented at their respective socially optimal values, the subsidy policy is at least equivalent, but can be superior to the quota policy depending on the outcome of the game in the market for green certificates. This result is still generally valid in the presence of uncertainty about the level of external benefits of renewables. The subsidy and the tradable certificate contain the same (correct) price information entering competitors' strategy choices, which are of the Cournot type regardless of the scheme considered. Interestingly, however, only one of two pure-strategy Nash equilibria under the quota-based policy corresponds to the unique equilibrium outcome under the subsidy policy, whereas the other Nash equilibrium (in which both firms produce green energy) leads to a lower (unless the external benefits of renewables are extremely low) welfare level. In view of the technological heterogeneity of green power generation, it is important that certificates are tradable. Thus, the subsidy is the preferable approach on the one hand; on the other hand, its financing may meet with a high marginal cost of taxation (or the imposition of levies, respectively).

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A Appendix

Subcase Ia: $x^*_{1\mathrm{b}} = \frac{a - c_\mathrm{b}}{3}$; $x^*_{1\mathrm{g}} = 0$; $x^*_{2\mathrm{b}} = \frac{a - c_\mathrm{b}}{3} - \bar{x}_\mathrm{g}$; $x^*_{2\mathrm{g}} = \bar{x}_\mathrm{g}$

Market demand:

$$a - x_{1\mathrm{b}} - x_{2\mathrm{b}} - x_{2\mathrm{g}} = \frac{a + 2c_\mathrm{b}}{3} \tag{A.1}$$

Firms' profits:

$$\Pi_1 = \frac{a + 2c_\mathrm{b}}{3}\,\frac{a - c_\mathrm{b}}{3} - c_\mathrm{b} \cdot \frac{a - c_\mathrm{b}}{3} - f\bar{x}_\mathrm{g} \;=\; \frac{(a - c_\mathrm{b})^2}{9} - f\bar{x}_\mathrm{g};$$

$$\begin{aligned}\Pi_2 &= \frac{a + 2c_\mathrm{b}}{3}\,\frac{a - c_\mathrm{b}}{3} - c_\mathrm{b} \cdot \left(\frac{a - c_\mathrm{b}}{3} - \bar{x}_\mathrm{g}\right) + z\bar{x}_\mathrm{g} - C_{2\mathrm{g}}(\bar{x}_\mathrm{g}) - f\bar{x}_\mathrm{g} \\ &= \frac{(a - c_\mathrm{b})^2}{9} - c_\mathrm{b}\bar{x}_\mathrm{g} - C_{2\mathrm{g}}(\bar{x}_\mathrm{g})\end{aligned}$$

Subcase Ib: $x^*_{1\mathrm{b}} = \frac{a - c_\mathrm{b}}{3}$; $x^*_{1\mathrm{g}} = 0$; $x^*_{2\mathrm{b}} = \frac{a - c_\mathrm{b}}{3} - 2\bar{x}_\mathrm{g}$; $x^*_{2\mathrm{g}} = 2\bar{x}_\mathrm{g}$

Market demand:

$$a - x_{1\mathrm{b}} - x_{2\mathrm{b}} - x_{2\mathrm{g}} = \frac{a + 2c_\mathrm{b}}{3} \tag{A.2}$$

Firms' profits:

$$\Pi_1 = \frac{a + 2c_\mathrm{b}}{3}\,\frac{a - c_\mathrm{b}}{3} - c_\mathrm{b}\frac{a - c_\mathrm{b}}{3} - z\bar{x}_\mathrm{g} \;=\; \frac{(a - c_\mathrm{b})^2}{9} - z\bar{x}_\mathrm{g};$$

$$\begin{aligned}\Pi_2 &= \frac{a + 2c_\mathrm{b}}{3}\,\frac{a - c_\mathrm{b}}{3} - c_\mathrm{b}\left(\frac{a - c_\mathrm{b}}{3} - 2\bar{x}_\mathrm{g}\right) + z\bar{x}_\mathrm{g} - C_{2\mathrm{g}}(2\bar{x}_\mathrm{g}) - f\bar{x}_\mathrm{g} \\ &= \frac{(a - c_\mathrm{b})^2}{9} + (z - 2c_\mathrm{b})\bar{x}_\mathrm{g} - C_{2\mathrm{g}}(2\bar{x}_\mathrm{g})\end{aligned}$$

Subcase IIa (symmetry): $x^*_{1\mathrm{b}} = x^*_{2\mathrm{b}} = \frac{a - c_\mathrm{b}}{3} - \bar{x}_\mathrm{g}$; $x^*_{1\mathrm{g}} = x^*_{2\mathrm{g}} = \bar{x}_\mathrm{g}$

Market demand:

$$a - x_{1\mathrm{b}} - x_{1\mathrm{g}} - x_{2\mathrm{b}} - x_{2\mathrm{g}} = \frac{a + 2c_\mathrm{b}}{3} \tag{A.3}$$

Firms' profits:

$$\Pi_1 = \frac{a+2c_\mathrm{b}}{3}\,\frac{a-c_\mathrm{b}}{3} - c_\mathrm{b}\left(\frac{a-c_\mathrm{b}}{3} - \bar{x}_g\right) - C_{1\mathrm{g}}(\bar{x}_\mathrm{g}) \;=\; \frac{(a-c_\mathrm{b})^2}{9} + c_\mathrm{b}\bar{x}_\mathrm{g} - C_{1\mathrm{g}}(\bar{x}_\mathrm{g});$$

$$\Pi_2 = \frac{a+2c_\mathrm{b}}{3}\,\frac{a-c_\mathrm{b}}{3} - c_\mathrm{b}\left(\frac{a-c_\mathrm{b}}{3} - \bar{x}_\mathrm{g}\right) - C_{2\mathrm{g}}(\bar{x}_\mathrm{g}) \;=\; \frac{(a-c_\mathrm{b})^2}{9} + c_\mathrm{b}\bar{x}_\mathrm{g} - C_{2\mathrm{g}}(\bar{x}_\mathrm{g})$$

Subcase IIb: $x^*_{1\mathrm{b}} = \dfrac{a-c_\mathrm{b}}{3} - \bar{x}_\mathrm{g}$; $x^*_{1\mathrm{g}} = \bar{x}_\mathrm{g}$; $x^*_{2\mathrm{b}} = \dfrac{a-c_\mathrm{b}}{3} - 2\bar{x}_\mathrm{g}$; $x^*_{2\mathrm{g}} = 2\bar{x}_\mathrm{g}$

Market demand:

$$a - x_{1\mathrm{b}} - x_{1\mathrm{g}} - x_{2\mathrm{b}} - x_{2\mathrm{g}} = \frac{a+2c_\mathrm{b}}{3} \tag{A.4}$$

Firms' profits:

$$\Pi_1 = \frac{a+2c_\mathrm{b}}{3}\,\frac{a-c_\mathrm{b}}{3} - c_\mathrm{b}\left(\frac{a-c_\mathrm{b}}{3} - \bar{x}_\mathrm{g}\right) - C_{1\mathrm{g}}(\bar{x}_\mathrm{g}) \;=\; \frac{(a-c_\mathrm{b})^2}{9} + c_\mathrm{b}\bar{x}_\mathrm{g} - C_{1\mathrm{g}}(\bar{x}_\mathrm{g});$$

$$\Pi_2 = \frac{a+2c_\mathrm{b}}{3}\,\frac{a-c_\mathrm{b}}{3} - c_\mathrm{b}\left(\frac{a-c_\mathrm{b}}{3} - 2\bar{x}_\mathrm{g}\right) - C_{2\mathrm{g}}(2\bar{x}_\mathrm{g}) \;=\; \frac{(a-c_\mathrm{b})^2}{9} + 2c_\mathrm{b}\bar{x}_\mathrm{g} - C_{2\mathrm{g}}(2\bar{x}_\mathrm{g})$$

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