Centre for Energy Policy and Economics
Swiss Federal Institutes of Technology

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CEPE Working Paper No. 45
December 2005

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

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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 power. However, there is a debate about the pros and cons of TGC, a quantity control policy, compared to guaranteed feed-in tariffs (FIT), a price control policy. In this paper we contrast these two alternatives in terms of cost effectiveness and social welfare, taking into account that electricity markets are not perfectly competitive.

Key words: Renewable electricity, Feed-in tariffs, Tradable green certificates, Quota, Energy policy, Duopoly

JEL classification: Q42, Q48

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1 Introduction

Electricity generation from renewable energy sources is increasingly recognized to play an important role for the achievement of policy goals high on the agenda, such as reductions in local pollutant and global greenhouse gas emissions, improved diversity and security of energy supply, and exploitation of opportunities for creating local value added and employment.

The intention of the European Commission to issue a 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 debate over the pros and cons of guaranteed feed-in tariffs (FIT) versus tradable green certificate (TGC) schemes.[1] FIT provide certainty about the achievable per unit revenues from selling renewable electricity to the grid. In contrast, TGC are based on competitive market principles, typically featuring mandatory quota targets and certificate trading (see e.g. Menanteau et al., 2003). While FIT have turned out to be very effective in countries like Austria, Denmark, Germany and Spain, a problem with guaranteeing such prices is that market distortions increase with increasing shares of electricity generation from renewables. TGC, on the other hand, promising to enhance static and dynamic efficiency, have attracted considerable attention in recent years. They have been introduced in a number of countries with liberalized electricity markets (e.g. Rader and Norgaard, 1996; Espey, 2000; Berry, 2002; Nielsen and Jeppesen, 2003; Lorenzoni, 2003; Verbruggen, 2004). More recently, the debate has been revolving around the interplay between TGC markets and markets

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

for tradable CO_2 permits (e.g. Morthorst, 2001), and between TGC markets and liberalized power markets (e.g. Morthorst, 2003), respectively. Another active strand of research concerns financial risk of investors (Lemming, 2003; Dinica, 2006).

FIT is similar to a subsidy for suppliers of renewables, while TGC constitute an internalization mechanism in the Baumol-Oates (1998) standard-price tradition. 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. Based 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 preference for taxation over quantity control. In the context of renewable energy policy-making, Madlener and Gao (2005) assess the impact of pre-commitment of government with respect to policy targets in the presence of cost-reducing innovation. And in an empirical study, Palmer and Burtraw (2005) analyze the cost effectiveness of two different renewable electricity policies (TGC versus renewable energy production tax credit) targeted at the U.S. electricity sector and their impact on greenhouse gas emissions.

This paper is devoted to the issue of whether the diffusion of renewable electricity 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. The answer to this question is found to importantly depend on the structure of imperfectly competitive markets for power.

Our paper is organized as follows. Section 2 introduces the basic models that are used to contrast the 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. Section 5 discusses policy implications, and section 6 concludes.

2 Promoting renewable electricity in a perfectly competitive market

We start with the simplest case, assuming that in a perfectly competitive electricity market there are N firms with equal electricity generation costs. In terms of primary energy inputs used, let there be only two ways to produce electricity, fossil/nuclear or renewables (solar, wind, hydro, biomass etc.), with the second referred to as 'green electricity'. Generation cost associated with fossil/nuclear is assumed to be generally lower than that of green electricity. However, green electricity has positive externalities to society not only in terms of biophysical but also socio-economic benefits (e.g. additional employment, local value-added, new infrastructure).[2] The fact that these externalities are not sufficiently taken into account in decisions regarding type and level of electricity production and consumption may motivate policy interventions such as FIT and TGC.

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[2] 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).

2.1 FIT as a subsidy

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 of s per unit of green electricity.[3] Given a competitive market, a representative generator of power faces the following optimization problem,

$$\max_{x,x_{\mathrm{g}}} \left[px + (p+s)x_{\mathrm{g}} - cx - c_{\mathrm{g}}(x_{\mathrm{g}})\right], \tag{1}$$

where x and x_{g} denote the amounts of electricity produced from fossil/nuclear fuels and renewable ('green') energy sources, respectively, c refers to per unit cost of electricity produced from fossil/nuclear fuel (assumed to be constant for simplicity), $c_{\mathrm{g}}(x_{\mathrm{g}})$ is the cost function for green electricity, and p is the spot market price for electricity.

For an interior solution, the f.o.c. are

$$p - c = 0 \tag{2}$$

$$p + s - c'_{\mathrm{g}}[x^*_{\mathrm{g}}] = 0. \tag{3}$$

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

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[3] 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 for simplicity.

2.2 TGC as a quota-based policy

Rather than subsidizing green electricity, the government can also impose a quota of green power on each generator.[4] 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 (no opportunity for trading). In section 3, the non-tradability assumption will be relaxed and a market for certificates introduced. Then, the following objective function applies to a generator,

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

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

$$p - c = 0 \tag{5}$$
$$p + f - c_{\mathrm{g}}'[x_{\mathrm{g}}^*] = 0. \tag{6}$$

Note the similarity of (6) and (3). In fact the fine f plays the same role as the subsidy s, which therefore represents the shadow price of the quota.[5] In an optimum, the unit price of the certificate should be equal to (slightly lower than) the value of the fine per unit.

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[4] 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.

[5] f can be viewed as a Lagrangian multiplier for the (inequality) constraint $x_{\mathrm{g}} \geq \bar{x}_{\mathrm{g}}$.

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, we state the problem of a social planner as follows:[6]

$$W(Q, x_{\mathrm{g}}) = \max_{Q, x_{\mathrm{g}}} \int_0^Q p(s)ds - c(Q - Nx_{\mathrm{g}}) - Nc_{\mathrm{g}}(x_{\mathrm{g}}) + D(Nx_{\mathrm{g}}), \tag{7}$$

where $Q = N(x + x_{\mathrm{g}})$ stands for total electricity output, $p(s)$ for the inverse demand function, and $D(Nx_{\mathrm{g}})$ for the monetary value of the avoided negative and achieved positive externalities associated with green electricity production. As f.o.c. one obtains

$$p[Q] - c = 0 \tag{8}$$
$$Nc - Nc'_{\mathrm{g}}[x^*_{\mathrm{g}}] + ND'[Nx^*_{\mathrm{g}}] = 0, \tag{9}$$

which determine the social optimum values of Q^* 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 price-cost margin 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 $s^* = (c'_{\mathrm{g}}[x^*_{\mathrm{g}}] - c)$ from eq.(3), and the fine, by $f^* = (c'_{\mathrm{g}}[x^*_{\mathrm{g}}] - p)$ from eq. (6).

It is obvious that, given the subsidy and quota levels are set according to the optimal values determined by maximizing the social welfare, they will lead

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[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.

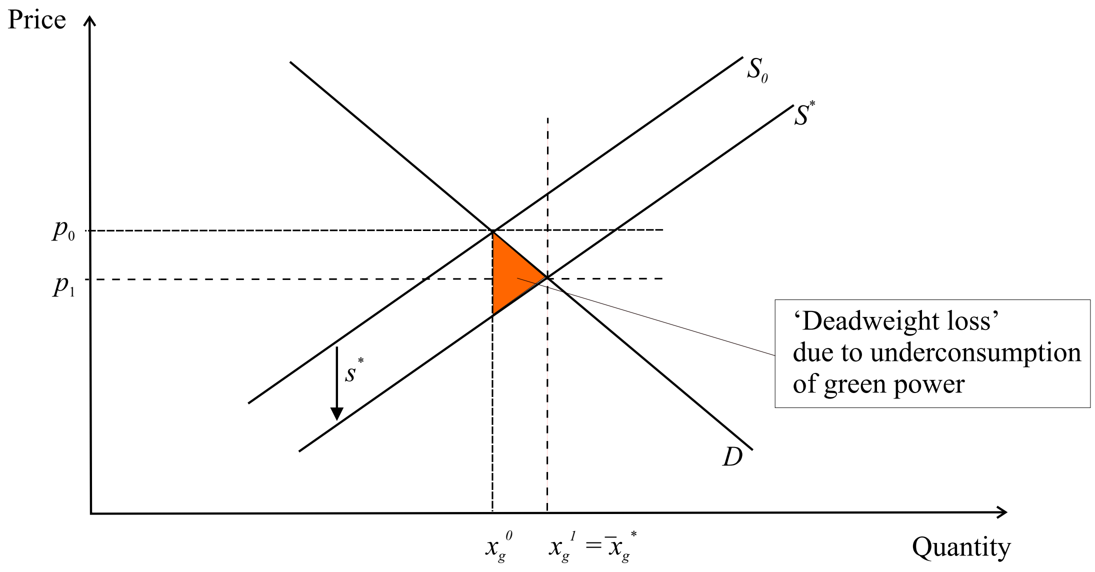

Fig. 1. Equivalence of subsidy and quota-based policy under equal costs.

to the same level of green electricity production and yield equivalent welfare results. 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 that reflects the fact 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. Clearly, the efficient quantity of green power can be attained by paying the (optimal) subsidy s^* or imposing the (optimal) standard $\bar{x}_\mathrm{g}^*$.

3 Duopoly market and quasi-symmetric costs

Studying the problem as a duopoly game under quasi-symmetric costs can be justified as follows. First, a perfectly competitive market as assumed in the basic model does not well describe a market for power dominated by a few major players. For example, EdF still has a monopoly in France, PowerGen has a market share of about 22% in the UK, while the first four suppliers in Germany, RWE, E.ON Energie, Vattenfall Europe, and EnBW together control some 80% of the market (cf. Bower et al., 2001; Matthes et al., 2005). 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 trade of green certificates.

Assume there are two generators in the market, 1 and 2, that have identical technology and hence cost function in using fossil/nuclear fuel but different costs of generating renewable electricity. This is why the firms are 'quasi-symmetric'. There are many reasons to expect heterogeneous cost structures for green power, such as different operational use of different technologies, and use of different vintages of a given technology. After all, green power is not yet a mature technology like fossil or nuclear, where competition presumably has forced operators to adopt the least-cost alternative. To keep our model simple and avoid multiple equilibria, we assume c, $c_{1\mathrm{g}}$ and $c_{2\mathrm{g}}$ to be constant, where the latter two symbols refer to the per-unit costs of green power of generators 1 and 2, respectively. Without loss of generality, we assume that $c_{1\mathrm{g}} > c_{2\mathrm{g}}$. With some loss of generality (but considerable gain in simplicity), let the demand function take on the following form,

$$p(x_1, x_{1\mathrm{g}}, x_2, x_{2\mathrm{g}}) = a - x_1 - x_{1\mathrm{g}} - x_2 - x_{2\mathrm{g}}, \quad a > 0, \tag{10}$$

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

We start with the subsidy policy, focussing 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. This may have been 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).

3.1 Effect of subsidy on equilibrium

In this section, we assume that the subsidy is uniform, failing to take the difference in cost into account; the case of a non-uniform subsidy is discussed in section 3.2 below. Here, the two firms face the following decision problem,

$$\max_{x_i, x_{ig}} \left[(a - x_i - x_{i\mathrm{g}} - x_j - x_{j\mathrm{g}})(x_i + x_{i\mathrm{g}}) + s x_{i\mathrm{g}} - c x_i - c_{i\mathrm{g}} x_{i\mathrm{g}}\right], \tag{11}$$

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

We assume that the subsidy is exogenous to and equal across firms. Generalizing condition (3), one can distinguish four different cases.

3.1.1 Case 1: $s < (c_{2\mathrm{g}} - c) < (c_{1\mathrm{g}} - c)$

If $s < (c_{2\mathrm{g}} - c)$, it is obvious that no green electricity will be produced because the subsidy does not make up for the efficient producer's cost disadvantage. The standard Cournot solution to the game accordingly is (cf. Kreps, 1990, Ch.10, p.326),

$$x_1 = x_2 = \frac{a - c}{3} \tag{12}$$

$$x_{1\mathrm{g}} = x_{2\mathrm{g}} = 0. \tag{13}$$

3.1.2 Case 2: $(c_{2\mathrm{g}} - c) \leq s < (c_{1\mathrm{g}} - c)$

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.

If $s = (c_{2\mathrm{g}} - c)$, then generator 2 is indifferent between producing green electricity and fossil/nuclear electricity. The solution now is,

$$x_1 = (x_2 + x_{2\mathrm{g}}) = \frac{a-c}{3} \tag{14}$$

$$x_{1\mathrm{g}} = 0. \tag{15}$$

On the other hand, if $s > (c_{2\mathrm{g}} - c)$, then generator 2 switches to green electricity, i.e.,

$$x_1 = x_{2\mathrm{g}} = \frac{a-c}{3} \tag{16}$$

$$x_{1\mathrm{g}} = x_2 = 0. \tag{17}$$

3.1.3 Case 3: $s \geq (c_{1\mathrm{g}} - c)$

If $s > (c_{1\mathrm{g}} - c)$, then the subsidy overcompensates the cost disadvantage of green power even for the less efficient generator no. 1. Therefore, both firms produce green electricity only. Accordingly, the optimal solutions are now

$$x_{1\mathrm{g}} = x_{2\mathrm{g}} = \frac{a-c}{3} \tag{18}$$

$$x_1 = x_2 = 0. \tag{19}$$

In the limiting case where $s = (c_{1\mathrm{g}} - c)$, 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. Consequently, the solution is

$$(x_1 + x_{1\mathrm{g}}) = x_{2\mathrm{g}} = \frac{a-c}{3} \tag{20}$$

$$x_2 = 0. \tag{21}$$

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

$$W^j(Q, x_g) = \int_0^Q p(s)ds - c(Q - x_\mathrm{g}) - c_\mathrm{g} x_\mathrm{g} + D(x_\mathrm{g}), \tag{22}$$

with W^j denoting the social welfare gains associated with case j ($j = 1$, 2, and 3) of section 3.1.3. We assume that in case 2 s is slightly greater than $(c_{2\mathrm{g}} - c)$, and in case 3 slightly greater than $(c_{1\mathrm{g}} - c)$, in order to avoid ambiguity.

To facilitate comparisons between the cases, the externality function associated with green electricity takes the form

$$D(x_\mathrm{g}) = \beta x_\mathrm{g}, \quad \beta > 0. \tag{23}$$

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 (19), the welfare associated with the three cases can be written,

$$W^1 = \left(a - \frac{Q}{2}\right) Q - cQ \tag{24}$$

$$W^2 = \left(a - \frac{Q}{2}\right) Q + \beta\frac{Q}{2} - (c + c_{2\mathrm{g}})\frac{Q}{2} \tag{25}$$

$$W^3 = \left(a - \frac{Q}{2}\right) Q + \beta Q - (c_{1\mathrm{g}} + c_{2\mathrm{g}})\frac{Q}{2}. \tag{26}$$

As is to be expected, whether or not the welfare parameter β exceeds the marginal cost parameters is of crucial importance. Specifically,

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

(B) if $\beta = (c_{1\mathrm{g}} - c)$, then $W^3 = W^2 > W^1$. The welfare gains remain the same for $s^*_{\mathrm{B}} = (c_{1\mathrm{g}} - c)$ and $s^{**}_{\mathrm{B}} = (c_{2\mathrm{g}} - c)$, though the amounts of green electricity produced are different.

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

(D) if $\beta < (c_{2\mathrm{g}} - c)$, then $W^1 > W^2 > W^3$. Therefore, the optimal subsidy is zero, because none of the rates are effective in promoting green power. Figure 2 summarizes the optimal subsidy schedule for different values of β.

3.2 Quota-based policy

Building on (4) of section 2.2, the decision problem facing the two firms can be written,

$$\max_{x_i, x_{i\mathrm{g}}} [a - x_i - x_{i\mathrm{g}} - x_j - x_{j\mathrm{g}})(x_i + x_{i\mathrm{g}}) - f(\bar{x}_{\mathrm{g}} - x_{i\mathrm{g}}) - cx_i - c_{i\mathrm{g}} x_{i\mathrm{g}}], \tag{27}$$

with $i, j = 1$ or 2, and $i \neq j$.

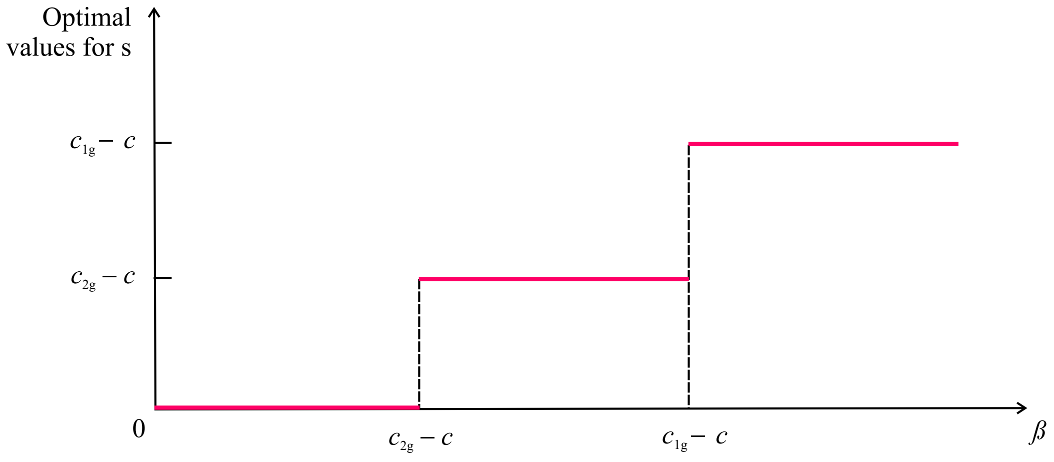

Fig. 2. Optimal subsidy levels vs welfare parameter of green electricity.

In the above model, each firm has two choice variables. However, given the assumptions that marginal costs are constant and differ such that $c_{1g} > c_{2g}$, generator 1's choice of x_{1g} boils down to a choice between 0 and $\bar{x}_g$. If it is in the interest of generator 1 to purchase green electricity certificates at all, it must 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 $x^*_{1g} = \{0, \bar{x}_g\}$.

3.3 Nash equilibrium under the quota-based policy

In the following, we elaborate the Nash equilibrium for the quota-based policy, by comparing the firms' payoffs under the two strategies stated at the end of section 3.2.

3.3.1 Case (a): $x^*_{1g} = 0$

Given that $x^*_{1g} = 0$, then generator 2 is required to produce at least $2\bar{x}_g$ units of green electricity in order to satisfy the industry quota. The profit functions

Π_i are therefore given by

$$\Pi_1 = (a - x_1 - x_2 - x_{2\mathrm{g}})x_1 - cx_1 - f\bar{x}_{\mathrm{g}} \tag{28}$$

and

$$\begin{aligned} \Pi_2 = {} & (a - x_1 - x_2 - x_{2\mathrm{g}})(x_2 + x_{2\mathrm{g}}) - f(\bar{x}_{\mathrm{g}} - x_{2\mathrm{g}}) \\ & - \lambda(x_{2\mathrm{g}} - 2\bar{x}_{\mathrm{g}}) - cx_2 - c_{2\mathrm{g}}x_{2\mathrm{g}}, \end{aligned} \tag{29}$$

where λ is a Lagrangian multiplier.

The f.o.c. for generator 1 is given by

$$a - 2x_1 - x_2 - x_{2\mathrm{g}} - c = 0, \tag{30}$$

while the f.o.c. for firm 2 are

$$a - x_1 - 2x_2 - 2x_{2\mathrm{g}} - c = 0 \tag{31}$$
$$a - x_1 - 2x_2 - 2x_{2\mathrm{g}} - c_{2\mathrm{g}} + f + \lambda = 0. \tag{32}$$

From (30) and (31) we get

$$x_1^* = (x_2^* + x_{2\mathrm{g}}^*) = \frac{a - c}{3}. \tag{33}$$

Eq. (33) simply says 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 (31) and (32) we obtain

$$\lambda = c_{2\mathrm{g}} - c - f. \tag{34}$$

Eq. (34) indicates that if $(c_{2\mathrm{g}} - c) > f$, 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 $(c_{1\mathrm{g}} - c) \geq f$. However, if $(c_{2\mathrm{g}} - c) = f$ (and hence $\lambda = 0$), generator 2 has an incentive to produce at least the quota required from the industry. Also note that given constant marginal costs, different values of $f \in [c_{2\mathrm{g}} - c, c_{1\mathrm{g}} - c]$ 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 $(c_{2\mathrm{g}} - c) = f$ as a benchmark.

The optimal quota continues to be determined as in eqs. (7)–(9), except that $c_{\mathrm{g}}(x_{\mathrm{g}}) = c_{2\mathrm{g}}$. Hence $\bar{x}_{\mathrm{g}} = x^*_{\mathrm{g}}/2$ still holds. As long as $2\bar{x}_{\mathrm{g}} \leq (a - c)/3$ [see eq. (33)], generator 2 produces $(a - c)/3 - 2\bar{x}_{\mathrm{g}}$ units of electricity using fossil/nuclear fuel and $2\bar{x}_{\mathrm{g}}$ units of green electricity. As to $2\bar{x}_{\mathrm{g}} > (a - c)/3$, recall that a denotes the willingness to pay for the first kWh of electricity, and c symbolizes the (constant) marginal cost of fossil/nuclear power, which makes $(a - c)$ a very large number. It is unlikely for $\bar{x}_{\mathrm{g}}$ to exceed one sixth of that number, justifying this case to be 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 more green electricity than the required quota. However, this would make the system a combination of quantity and price policies because 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 (b):* $x_{1\mathrm{g}} = \bar{x}_{\mathrm{g}}$

We now turn to the case of generator 1 producing green electricity to satisfy the quota. With no external agent purchasing, the condition $x_{1\mathrm{g}} = \bar{x}_{\mathrm{g}}$ or $x_{2\mathrm{g}} = \bar{x}_{\mathrm{g}}$ continues to hold. The firms' optimization problem thus reads,

$$\max_{x_i, x_{i\mathrm{g}}} \Pi_1 = (a - x_1 - x_2 - 2\bar{x}_{\mathrm{g}})(x_1 + \bar{x}_{\mathrm{g}}) - cx_1 - c_{1\mathrm{g}}\bar{x}_{\mathrm{g}} \tag{35}$$

$$\max_{x_i, x_{i\mathrm{g}}} \Pi_2 = (a - x_1 - x_2 - 2\bar{x}_{\mathrm{g}})(x_2 + \bar{x}_{\mathrm{g}}) - cx_2 - c_{2\mathrm{g}}\bar{x}_{\mathrm{g}}. \tag{36}$$

The solution to this game is the standard Cournot solution,

$$x_1^* = x_2^* = \frac{a - 3\bar{x}_{\mathrm{g}} - c}{3}. \tag{37}$$

Notice that, in equilibrium, total electricity production of each generator is the same as in case (a) of section 3.3.1. Also, the total amount of green electricity available on the market remains the same. However, the two firms now produce different amounts of green electricity, depending on the strategy chosen by generator 1, viz. do not produce green electricity but purchase certificates from generator 2, or generate green electricity up to the quota. This choice of course influences the decision of generator 2.

3.3.3 *Comparison of cases (a) and (b)*

We want to find the Nash equilibria associated with cases (a) and (b). Note that the players take the green power quota as pre-determined. The results are presented below.

Case I: The firms' profit functions are described in (28) and (29), and the optimal values for x_1 and x_2 are derived in (33). Therefore, we have

$$\Pi_1^* = \frac{(a-c)^2}{9} - \bar{x}_{\mathrm{g}}(c_{2\mathrm{g}}^* - c), \tag{38}$$

where $\bar{x}_{\mathrm{g}}$ denotes the quota. Similarly, we get

$$\Pi_2^* = \frac{(a-c)^2}{9} - \bar{x}_{\mathrm{g}}(c_{2\mathrm{g}}^* - c). \tag{39}$$

Case II: The firms' profit functions are described in (35) and (36), respectively, and the optimal values for x_1 and x_2 are derived in (37). The profit of generator 1 turns out to be

$$\Pi_1^{**} = \frac{(a-c)^2}{9} - \bar{x}_{\mathrm{g}}(c_{1\mathrm{g}}^{**} - c). \tag{40}$$

Similarly, generator 2's profit amounts to

$$\Pi_2^{**} = \frac{(a-c)^2}{9} - \bar{x}_{\mathrm{g}}(c_{2\mathrm{g}}^{**} - c). \tag{41}$$

Given $c_{1\mathrm{g}} > c_{2\mathrm{g}}$, comparison of (38) and (40) shows that generator 1 makes more profit in case I and hence prefers its strategy associated with case (b). In contrast, generator 2 is indifferent between the results associated with the two cases. This is simply because in case I, the price of certificates generator 2 receives by selling certificates to generator 1 exactly compensates it for the additional costs that arise from producing green electricity in excess of its own quota. Therefore, the Nash equilibrium solution to this duopoly game is the same as the solution in case I. That is, generator 1 produces no green electricity but purchases certificates from generator 2, and generator 2 produces double the amount of green electricity required by the quota, selling the excess over the quota to generator 1. In equilibrium, both firms' total production of electricity and their revenues are the same, and no firm has an incentive to deviate from the equilibrium once achieved.

These results are predicated on the assumption $f = (c_{2\mathrm{g}} - c)$. As pointed out above, values of $f \in [c_{2\mathrm{g}} - c, c_{1\mathrm{g}} - c]$ would not change the Cournot solution and hence leave social welfare unaffected. For example, if $(c_{1\mathrm{g}} - c) > f > (c_{2\mathrm{g}} - c)$, then generator 2 makes more profit in case I than in case II, and 1 still makes more profit in case I than in case II, but the amount of profit will be less than the amount defined in (38). Thus, it is the distribution of profits that depends upon the level of the fine set by the government.

Since total electricity production is determined for each firm as shown in eq. (33), the choices of total output amount to choices of green electricity output. Therefore, the solutions derived above can also be shown in normal form (see table 1).

In sum, we have demonstrated that in a duopolistic market for power, the two firms may have an interest in certificate trading, which results in a welfare gain for society if it occurs. Evidently, this result may depend on assumptions concerning demand and cost functions but not on the number of firms, which could be more than two.

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[6] In this case generator 1 has to pay a fine which is equal to (or slightly higher than) the price of the certificate.

Table 1

Asymmetric Cournot game under a quota-based system

		Firm 1	
		0	$\bar{x}_{\mathrm{g}}$
Firm 2	$\bar{x}_{\mathrm{g}}$	$\frac{(a-c)^2}{9} - \bar{x}_{\mathrm{g}}(c_{1\mathrm{g}} - c)$, $\frac{(a-c)^2}{9} - \bar{x}_{\mathrm{g}}(c_{2\mathrm{g}} - c)$ [a]	$\frac{(a-c)^2}{9} - \bar{x}_{\mathrm{g}}(c_{1\mathrm{g}} - c)$, $\frac{(a-c)^2}{9} - \bar{x}_{\mathrm{g}}(c_{2\mathrm{g}} - c)$
	$2\bar{x}_{\mathrm{g}}$	$\frac{(a-c)^2}{9} - \bar{x}_{\mathrm{g}}(c_{1\mathrm{g}} - c)$, $\frac{(a-c)^2}{9} - \bar{x}_{\mathrm{g}}(c_{2\mathrm{g}} - c)$	$\frac{(a-c)^2}{9} - \bar{x}_{\mathrm{g}}(c_{1\mathrm{g}} - c)$, $\frac{(a-c)^2}{9} - 2\bar{x}_{\mathrm{g}}(c_{2\mathrm{g}} - c)$

[a] Note that in this outcome generator 1 has to pay a fine that equals (or is slightly higher than) the certificate price.

4 Welfare comparison between subsidy and quota-based policies

In spite of the simplifying assumptions made in the previous section, a comparison of a price/subsidy policy with its quantity quota alternative 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 given the subsidy scheme

Since our main interest is to discuss how to efficiently promote green power, case 1 (section 3.1.1) can be disregarded since it is fossil/nuclear only. In addition, case 3 (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 $(c_{2\mathrm{g}} - c) \leq \beta < (c_{1\mathrm{g}} - c)$, i.e. case 2 of section 3.1.2. The pertinent welfare function is repeated from (26) for convenience,

$$W_s = Q\left[\left(a - \frac{Q}{2}\right) - \frac{c + c_{2\mathrm{g}}}{2} + \frac{\beta}{2}\right], \tag{42}$$

where Q continues to be the total production of both types of electricity. Derivation shows $Q_s^* = 2(a - c)/3$ to be the socially optimal quantity.

4.2 Welfare gains given the quota-based policy

Provided marginal costs and marginal externalities of green power are constant, the optimal quota cannot be identified directly. To match the production of green electricity in the subsidy case, we simply assume that $\bar{x}_{\mathrm{g}}$ is equal to $(a - c)/6$, which may constitute a rather frequent solution, see the discussion below eq. (34) in section 3.3.1. The welfare function for the quota-based certificate system can then be specified as

$$W_q = Q\left[\left(a - \frac{Q}{2}\right) - \frac{c + c_{2\mathrm{g}}}{2} + \frac{\beta}{2}\right] \tag{43}$$

with $Q_q^* = 2(a-c)/3 = Q_s^*$. These values are identical with those of section 4.1 above.

4.3 Equivalence of subsidy and quota-based policies in a quasi-symmetric duopoly

It is obvious that $W_s = W_q$. This result implies that even with imperfect competition and quasi-heterogeneous costs, subsidies may still be equivalent to tradable certificates. Because certificates with trading dominate certificates without trading, subsidies are also preferable over a pure quantity system. Therefore, this model suggests that if a market for certificates does not exist or takes time to become operational, subsidies may be the preferred solution.

Although our results confirm the equivalence of price and quantity instruments in the context of internalization of externalities given imperfectly competitive markets, the simplifying assumptions made should be kept in mind. For example, the cost of administering subsidies and/or quota are neglected in our study. 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 control.

The crucial assumption made throughout, however, is that of perfect information regarding both the marginal costs and benefits of green power. And with 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.

On the other hand, we found that subsidies provide more incentives for green power precisely when its marginal social benefits are high (as in case 3 of section 3.1.3). A pure quota-based system lacks this feature.

5 Policy implications

Based on several models incorporating imperfect competitiveness of markets for power, we find that subsidy and quota-based approaches usually lead to the same social welfare gains when operated at their socially optimal values. However, the subsidy policy is generally preferred by electricity producers, likely because it does not call into question their right to cause a certain amount of pollution when using fossil/nuclear as input. At the same time, subsidies do provide stronger incentives for technical innovation than quota because they directly favor production of green electricity. Since the future of the green electricity industry is, at least partly, dependent on future technological progress in order to lower its cost of production, subsidies are also more efficient dynamically.

On the other hand, subsidies require tax revenue to finance them. When the (economic or political) cost of additional taxation is high (like in the United States, but also the Scandinavian countries e.g.), quota may provide an alternative. As could be expected in the presence of heterogeneous costs, tradable certificates turn out to be preferable to non-tradable ones. Because the cost structure of green electricity typically differs between firms (which is much less likely of fossil/nuclear operators, who use the same mature technology to minimize cost), tradable certificates clearly constitute the preferred option if a quota policy is chosen for political reasons. Moreover, since the cost of running a market for certificates will decrease once established, the operational advantage of the subsidy policy will gradually wane, though its dynamic efficiency advantage in terms of promoting innovation may persist.

6 Conclusions

This paper starts from the notion that the conventional wisdom concerning the equivalence of a tax/subsidy and a quota/certificate scheme in terms of static efficiency may not hold if markets for power are imperfectly competitive. Introducing a duopoly model in which the two competitors differ in terms of their marginal cost of producing 'green' power, we find that the two schemes generally continue to be equivalent in terms of social welfare, but non-equivalent in terms of their incentives for innovation. The basic recommendation is to rely on the more targeted subsidies. If the quota system is preferred due to notably a high marginal cost of taxation to generate the finance for a subsidy, then tradable certificates clearly dominate non-tradable ones in view of the heterogeneity of cost between the producers of green power. However, because both alternatives have their advantages and disadvantages, a mix of the two may prove to be more efficient, a possibility deserving further investigation. As always, actual policy choice is likely to depend not only on economic but also on political considerations.

7 Acknowledgements

The authors acknowledge comments received from Michael Kuenzle and Kaushik Deb from CEPE, ETH Zurich, on an earlier version of the manuscript.

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