Title: Renewable Energy Policy Instruments and Market Power¹

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Abstract: Markets for green certificates allow generators with market power to squeeze the margins of their competitors, as a generator that is vertically integrated into network activities might do. We analyse this issue in a stylised electricity industry in which a dominant producer of both conventional and renewable energy is facing a competitive fringe of renewable-energy producers. We demonstrate that whether or not a dominant firm is vertically integrated into network activities, it can disadvantage the fringe producers by distorting certificates prices, thereby inducing cost inefficiency in the generation of renewable energy. We compare green certificates to a system of feed-in tariffs, where a similar margin squeeze is not possible.

Keywords: Green certificates, vertical relations, market power, feed-in tariff, renewable energy, network regulation

JEL Classification codes: D42, L11, L41, L42 and L94

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1 Introduction

Most electricity market reforms have included measures to increase competition and undermine market power. Paradoxically, policies to further investment in renewable electricity may re-introduce opportunities for anti-competitive practices. In particular, when renewables are supported by tradable quotas generators with market power may limit the profit margin for producers of renewable energy by acting simultaneously on electricity and quota markets. A similar opportunity for ‘margin squeeze’ is not available when renewables are supported by a tax.

Our interest in these issues is inspired by recent events in European energy policy. This policy aims at achieving competitiveness, sustainability and security of supply. Measures to increase competitiveness include unbundling, i.e., the splitting up of vertically integrated incumbent power producers, so that market participants obtain network access on fair and non-discriminatory terms. However, concentration on the wholesale markets continues to persist, albeit at different degrees across countries.² Due to limited interconnection capacities the European electricity industry is for the foreseeable future likely to continue as a series of essentially national or regional markets with a high degree of concentration.

To enhance sustainability and security of supply, the European Union has set a binding target of having 20 percent of final energy consumption met by renewable energy sources by 2020. At present, feed-in tariff schemes constitute the predominant support mechanism in Europe. In such a scheme, renewable electricity producers receive a fixed price (classical feed-in tariff) or, alternatively, a fixed premium on top of the electricity price (price premium). With progressing liberalisation of the electricity sector, quota systems with tradable green certificates are receiving increased attention as they leave price formation to markets. In such a scheme, the regulator stipulates a minimum percentage requirement of renewable energy sources (the quota) in total elec-

²For eleven Member States, the Herfindahl Hirschmann index indicates very high or high degrees of concentration for the electricity markets (EC, 2011). In Bulgaria, France, United Kingdom, Ireland, Poland, Portugal, Slovakia and Spain, market concentration has actually increased since 2008 (CEC, 2011).

tricity consumption,³ and electricity producers receive an amount of green certificates corresponding to the quantity of renewable energy they produce. The green certificates constitute a financial product that can be traded on a separate, purely financial market. Eligible renewable electricity producers thus have two revenue streams: first, they obtain the conventional electricity price for selling electricity on the electricity market; second, they generate revenue by selling green certificates on the certificates market. Demand on the certificates market is created by means of the green quota imposed on end consumers and retailers.⁴

The establishment of a green-certificates market provides generators with a new means to exercise market power. In particular, by increasing the supply of renewable electricity and driving down the certificates price a generator reduces the profitability of competitors in the renewables segment. In other words, by simultaneously playing on electricity and certificates markets - under-supplying conventional electricity and over-supplying renewable electricity - a generator can limit the market left for competing producers of renewables and shift output and profits towards itself. Such a strategy closely resembles “margin-squeezing” or the strategy of a generator that controls access to infrastructure and prices access so as to discriminate against its competitors. Margin squeezing is not possible with a feed-in tariff, since here the premium for renewables is set by the regulator rather than the market.

We analyse these issue in a stylised model that is constructed so as to highlight the underlying mechanisms. In this model, a dominant firm suppling both conventional and renewable energy faces a fringe of price takers that supply renewable energy only.⁵

³Alternatively to this downstream system, in the upstream system the obligation is put on the supply side, i.e., on electricity producers and importers. We concentrate attention on the downstream system, which is the more common; the analysis would be equivalent for an upstream system.

⁴Non-compliance with a certificates obligation is typically penalised with a fee. A fixed penalty payment in effect puts an upper bound on the green-certificates price since there will be no demand for certificates sold at a price above the level of the fee. Some Member States allow for banking of certificates, which may reduce the volatility of certificates prices (see Amundsen et al., 2006). We abstract from these issues in our analysis.

⁵Strictly speaking, the two energy types are distinguished by how they are regulated rather than by differences in source or technology. Typically, regulation to support ‘green’ energy is confined to new renewable energy sources and so excludes existing plants even if they are based on renewable resources. For example, in the Nordic region the category ‘conventional’ would include large amounts of hydro generation.

We think of the dominant firm as representing the typical market incumbent, with the main interests in conventional generation but which also partakes in the renewables segment. A typical fringe firm would be involved in a single project of distributed generation. It would be straightforward to extend our analysis to a more general set up - with more players with market power, supplying conventional and/or renewable energy - but, while this would considerably complicate the analysis, it would not alter the fundamental nature of our results. Moreover, our set up highlights the parallel between anti-competitive pricing of green certificates and network access.

In this model, we compare the outcome when renewables are regulated by green certificates and a feed-in tariff respectively. In the first part, we show that with green certificates the dominant firm obtains an additional instrument to manipulate market outcomes because it makes the two electricity sources (conventional and renewables) complementary. As the dominant firm controls the supply of conventional electricity, it also determines the total demand for renewable electricity. By over-supplying renewable electricity, the dominant firm reduces the equilibrium premium on such electricity, allowing it to charge a higher price for the complementary good, conventional electricity; the dominant firm margin squeezes the fringe. The net effect is that the dominant firm acts as if it buys all electricity from the fringe and resells it to end-users, and, as in a monopsony, extracts rents from the fringe by setting a low price. Overall, this strategy reduces efficiency because the dominant firm generates too much and the fringe too little renewable electricity. We also show that if the dominant firm were to control a second complementary good (the transmission network), the outcome would not change, as control over one complementary good is sufficient to extract all rents from the fringe.

In the second part of the paper, we show that a feed-in premium reduces the possibility of the dominant firm to manipulate support for renewable electricity as long as it is financed by a general tax. However, when support is collected from final consumers as an electricity tax, the dominant firm will restrict renewable generation to limit the electricity tax.

Our analysis is related to three strands of literature, on, respectively, instruments to

promote renewables, leverage and foreclosure, and access pricing.⁶

The early literature on green certificates concentrated on the interplay between perfectly competitive markets for certificates and electricity. Amundsen and Mortensen (2001, 2002) demonstrated that an increase in the percentage requirement of green certificates will increase the consumer price of electricity, but that the effect on the certificates price, the producer price of conventional electricity and investment in renewables is inconclusive; in particular, it is not generally true that a higher quota induces a larger capacity of renewable electricity in the long run (see also Jensen and Skytte, 2002; Unger and Ahlgren, 2005; Böhringer and Rosendahl, 2010).⁷ The more recent literature has introduced elements of imperfect competition, but has either assumed strategic behaviour in the market for electricity only (as in Tamás, Shresthab and Zhouor, 2010) or has ignored the impact of conventional generation capacity on the price of certificates (as in Amundsen and Bergman, 2012). Thereby, the literature has circumvented the knife-edge problem identified by Amundsen and Nese (2004), that if green and conventional energy are supplied by Cournot quantity setters there is no equilibrium unless one introduces an exogenous upper and lower bound on the certificates price.⁸ We solve this problem by making the realistic assumption that there exists a segment of producers who adapt their behaviour to market prices. This assumption allows us to study the behaviour of strategic agents who take account of their impact on all relevant markets. Furthermore, we contrast the performance of green certificates to that of feed-in tariffs in an otherwise symmetrical setting with imperfect competition.

The literature on leverage and foreclosure has analysed how a firm enjoying a dominant position in one market may extend that position into another market, thereby disadvantaging competitors (see Motta, 2004, for an introduction to the literature). It has been demonstrated that, under certain circumstances, tying or bundling different products may constitute an element of such a strategy. In our setting, tying is not at

⁶It is also related to the literature on market power and permit trading, in particular the analysis of Liski and Montero (2006), who consider a dominant-firm framework.

⁷Amundsen and Nese (2009) consider similar issues for a green-certificates system that covers multiple jurisdictions.

⁸A similar knife-edge problem has been identified for access to transmission capacity, see for instance Oren (1997).

the discretion of market participants but is a result of regulation: the green-certificates policy requires consumers to buy electricity and certificates in a certain proportion. However, the resulting relation between electricity and certificates market allows the dominant firm to shift profitability from the segment where it faces competition to the segment where it does not. A similar bundling effect is not present when renewables are regulated by a feed-in tariff.

While tying is typically associated with horizontally related markets, leverage and foreclosure may be undertaken in vertically related markets also. The idea that a dominant firm may use its control over an essential input to raise rivals' costs is often associated with Salop and Scheffman (1983), but has been considered in a number of different settings, including network access (eg. Armstrong et al., 1996; Armstrong and Vickers, 1998) and market-based instruments for environmental regulation (eg. von der Fehr, 1993). We demonstrate that there is a close parallel between discriminatory access pricing and anti-competitive behaviour on the certificates market; indeed, in our setting they are equivalent.

The remainder of the paper is organised as follows. In Section 2, we present our modelling framework. This is then used in Section 3 to examine the regime of green certificates and in Section 4 to examine the regime of a feed-in tariff. Finally, Section 5 contains our conclusions.

2 The Electricity Industry Model

In this section, we present a stylised model of an electricity industry consisting of a dominant firm facing a competitive fringe. The fringe firms supply renewable electricity only and we denote total output of the fringe by q_F . The dominant firm generates conventional electricity in the amount q_M , as well as an amount q_R of renewable electricity. At equilibrium, total electricity demand, D , is equal to total electricity supply, given by the sum of renewable generation from the fringe and conventional and renew-

able generation from the dominant firm:

$$D = q_F + q_M + q_R. \quad (1)$$

Demand for electricity is a decreasing function of the price paid by consumers, p , i.e. $D = D(p)$ with $D' < 0$.

The dominant firm generates conventional electricity at increasing cost C_M , with $C'_M \geq 0$, and renewable electricity at increasing and strictly convex cost C_R , with $C'_R \geq 0$ and $C''_R > 0$. The fringe produces renewable electricity at the same total cost C_R as the dominant firm. This latter assumption is purely for simplicity and does not affect the general nature of our results; in particular, it makes the analysis of renewables generation especially transparent as any difference between the dominant firm and the fringe arises from market power rather than technology or input prices.⁹

Electricity supply requires access to the (transmission and distribution) network, which is owned by an independent entity and where access is granted on equal terms to the dominant firm and the fringe at a regulated network tariff, a . This market structure will be referred to as unbundling or vertical separation. In our analysis of green certificates in the next section we will briefly compare it to a bundled or vertically integrated set up where the network is owned and operated by the dominant firm (cf. Proposition 2 below). We let C_N denote network costs and assume that network costs are increasing in total generation, i.e. $C'_N \geq 0$.

For illustration, we will sometimes refer to numerical solutions for a parametrised example with linear demand, $D(p) = 1 - p$, constant unit cost of conventional electricity, $C_M(q) = c_M q$, linear marginal cost of renewable electricity, $C_R(q) = c_R q + \frac{1}{2} d_R q^2$, and constant unit network costs, $C_N(q) = c_N q$. The numerical illustrations are based on the following parameter values: $c_M = 0$, $c_R = 0.5$, $d_R = 1$ and $a = 0.2$. For comparison purposes we note that, without specific regulation (in which case the fringe

⁹This assumption does, however, remove a potentially interesting comparison between the two subsidy regimes when firms differ in their efficiency in the generation of renewable electricity. In particular, with green certificates inefficient generators would tend to be driven from the market by strategic behaviour, whereas a feed-in tariff will shelter such inefficient generators.

would not want to enter the market), the monopoly price of electricity would equal $\frac{1}{2}(1 + c_M + a) = 0.6$, while the competitive price would be $c_M + a = 0.2$. Details of the example are given in the Appendix.

3 Green Certificates

In this section, we analyse the regime in which renewables are supported by green certificates. In particular, we assume that consumers of electricity are obliged to hold an amount of green certificates in proportion to their level of consumption. The imposition of this regulation creates a demand for green certificates kD , where $k \in [0, 1]$ denotes the proportionality factor or quota.¹⁰ Electricity generators may sell an amount of green certificates equal to their output of renewable electricity, implying that the total supply of green certificates is given by $q_F + q_R$. At equilibrium, demand for certificates equals supply, i.e. $kD = q_F + q_R$. In other words, renewables supply is regulated so that at equilibrium it constitutes a fraction of total generation:

$$q_F + q_R = k(q_F + q_M + q_R). \quad (2)$$

It follows that the equilibrium supply of conventional electricity by the dominant firm may be expressed as a function of (the residual of) the quota and total demand:

$$q_M = (1 - k)D. \quad (3)$$

On the electricity market electricity is traded at the price p_E , and on the green-certificates market certificates are traded at the price p_C . Hence, while conventional electricity receives the electricity price only, renewable electricity is also paid the certificate price and so receives the total price $p_E + p_C$.

¹⁰We assume complete fulfilment of the quota, i.e., there is no excess or under-supply of renewable energy and certificates and no banking. These restrictions could be lifted at the cost of complicating the analysis but without altering the main results; in particular, strategic behaviour on the market for green certificates tends to reduce their price, making it less likely that a penalty for non-compliance would be binding and hence, impact on price.

We assume that the consumer price of electricity p is given by the sum of the price of conventional electricity and the certificate price weighted by the quota:

$$p = p_E + kp_C. \quad (4)$$

This assumption would be satisfied if consumers operated directly on the electricity and green-certificates markets, implying that for a unit of electricity consumers effectively pay the electricity price p_E plus the price of green certificates p_C for a proportion k of their consumption. Alternatively, the assumption may be justified by appealing to a perfectly competitive retail segment with constant unit costs normalised to zero.

The profit of the fringe is composed of revenue from electricity and certificates sales and costs of generation and network services:

$$\pi_F = (p_C + p_E) q_F - C_R(q_F) - a q_F. \quad (5)$$

The fringe maximises profits taking prices as given. The first-order condition for this problem implies that marginal costs equal the (net) price of renewable energy;¹¹ that is,

$$C'_R = p_C + p_E - a. \quad (6)$$

From this condition, we find (with slight abuse of notation) the supply function of the fringe:

$$q_F = q_F(p_C + p_E - a), \quad (7)$$

where the function q_F is the inverse of the marginal cost function C'_R . It follows that the fringe supply function is strictly increasing, i.e. $q'_F > 0$.

The revenue of the dominant firm is obtained from sale of conventional and renewable electricity (and the corresponding amount of certificates), while it incurs generation

¹¹We concentrate on the case in which there is an interior solution, i.e. the fringe supplies a positive amount of renewable electricity. There may also be cases with corner solutions (particularly for small quotas), where the dominant firm finds it optimal to set prices so as to drive the fringe out of the market.

costs as well as network costs:

$$\pi_M = p_E q_M + (p_C + p_E) q_R - C_M(q_M) - C_R(q_R) - a(q_M + q_R). \quad (8)$$

The dominant firm's profit-maximisation problem consists of maximising (8) subject to (1), (2), (4) and (7).

Using (2), (3) and (4), we may rewrite the profit of the dominant firm as follows:

$$\pi_M = pD(p) - p_a q_F(p_a) - C_M((1-k)D(p)) - C_R(kD(p) - q_F(p_a)) - aD(p). \quad (9)$$

where $p_a = p_C + p_E - a$ is the (net) price of renewable energy obtained by the fringe. It is as if the dominant firm sells all electricity to final consumers at price p , buys electricity from the fringe at a price p_a and generates the rest itself. The profit-maximisation problem of the dominant firm may then alternatively be expressed as maximising (9) by setting the monopoly output price p and the monopsony input price p_a .

Below we demonstrate the following result:

Proposition 1. *The dominant firm has an incentive to set a high consumer price in order to obtain high revenues from its energy sales while keeping the price received by the fringe low so as to shift output from the fringe to itself, in effect exerting a margin squeeze on the fringe. As a result, at equilibrium the dominant firm supplies more renewable electricity than the fringe, i.e. $q_R > q_F$, while the consumer price exceeds, and the certificates price falls below, competitive levels.*

The first-order conditions for the dominant firm's profit-maximising problem may be written¹²

$$p \left(1 - \frac{1}{\varepsilon_D} \right) = (1-k)C'_M + kC'_R + a, \quad (10)$$

$$p_a \left(1 + \frac{1}{\varepsilon_F} \right) = C'_R. \quad (11)$$

where $\varepsilon_D = -pD'/D > 0$ is (the absolute value of) the elasticity of demand with re-

¹²Throughout we assume that the profit-maximisation problem of the dominant firm is well-behaved; in particular, we assume the relevant second-order conditions are satisfied.

spect to the consumer price p and $\varepsilon_F = p_a q'_F / q_F > 0$ is the elasticity of the supply of the fringe with respect to the (net) energy price received by the fringe. The left-hand side of (10) is marginal revenue of supplying consumers with a unit of electricity, while the right-hand side is the corresponding marginal cost. The fact that electricity supplies must contain a fixed proportion of renewables is reflected in both price and marginal cost, where the latter is the weighted sum of the marginal cost of conventional and renewable generation, respectively, plus the incurred network cost. Similarly, (11) equates the marginal revenue and marginal cost of supplying a unit of renewable electricity, taking account of the supply response of the fringe; this corresponds to the trade-off of a monopsonist that can produce renewable electricity itself or buy such electricity from the fringe.

Compared to a perfectly competitive benchmark, there are two kinds of effects arising from the price-setting behaviour of the dominant firm. First, there is the classic monopoly effect, whereby the dominant firm induces a gap between consumer price and marginal cost:

$$p > p \left(1 - \frac{1}{\varepsilon_D} \right) = (1 - k) C'_M + k C'_R + a. \quad (12)$$

Second, there is the monopsony effect that induces cost inefficiency in the production of renewable electricity. In particular, at equilibrium the marginal cost of the dominant firm exceeds that of the fringe:

$$C'_R(q_R) = p_a \left(1 + \frac{1}{\varepsilon_F} \right) > p_a = C'_R(q_F). \quad (13)$$

From (9), we see that for the dominant firm the (net) price of renewables p_a is relevant only because it affects the supply of the rival fringe. Moreover, the dominant firm has an incentive to reduce this price, which may be done by reducing the certificates price through supplying renewables and certificates to a point where marginal cost exceeds price (cf (11)). It follows that while market power in the electricity market is exercised by under-supplying the relevant product, market power in the certificates

market is exercised by over-supplying it.

We may compare this outcome with that of vertical integration, when the dominant firm owns and operates the network and charges the fringe an access charge. In that case, the dominant firm could also exert a margin squeeze by means of the access charge, thereby raising the rival fringe's cost; in fact, the access charge and the certificates price are equivalent instruments in our setting - the dominant firm can extract the monopsony rents only once (see the Appendix for details). In other words, the certificate market enables the dominant firm to exercise market power as if it were vertically integrated. Although vertical separation hinders the dominant firm from inducing a margin squeeze by use of the network access charge, the certificates market provides it with the necessary means. Therefore, a margin squeeze on competitors in renewable generation occurs whether or not there is vertical integration.

Indeed, distortions may well be larger with vertical separation than with vertical integration. As we can see from (10), the marginal cost of the dominant firm of supplying consumers with electricity is increasing in the access charge. Moreover, it is easy to show that the consumer price of electricity is increasing in this charge.¹³ We therefore have the following result:

Proposition 2. *Unless regulation of network access is perfect (i.e. the access charge equals the marginal cost of network use), the consumer price of electricity is higher, and hence the output of conventional as well as renewable electricity is lower, with vertical separation than with vertical integration.*

While with vertical integration the monopolist faces the true cost of network use, with vertical separation the monopolist faces a higher cost unless the access charge perfectly reflects the underlying cost of the network. Hence the monopolist tends to set a higher price of electricity with vertical separation than with vertical integration. In other words, vertical separation involves a sort of double-marginalisation problem in the absence of perfect regulation.

¹³Differentiating through the set of first-order conditions (10) and (11), using that $\frac{\partial^3 \pi_M}{\partial a \partial p} = -D'$ and $\frac{\partial^3 \pi_M}{\partial a \partial p_a} = 0$ and assuming that the relevant second-order conditions are satisfied, give the result.

We conclude the analysis of green certificates by considering how equilibrium prices and quantities depend on renewable energy policy, as measured by the quota k .

It seems reasonable that an increase in the quota of green certificates raises the consumer price and the price of conventional electricity and reduces total electricity supply and the supply of conventional electricity. Intuitively, as may be seen from (10), more stringent regulation of renewable energy deployment, i.e. a larger quota, raises the marginal cost of supplying consumers. As a consequence, the dominant firm responds by raising the price of electricity. This implies that demand will fall, and with it, the total supply and the supply of conventional electricity, giving room for a higher proportion of renewable electricity. This is shown in Figure 1, which provides an illustration of the relationship between market quantities and the quota.

Figure 1: Quantities as functions of quota.

Moreover, from the equilibrium condition $q_F + q_R = kD$, it is clear that an increase in the quota has two different and opposing effects on renewable energy supply. On the one hand, a higher quota means that, for a given level of the consumer price, and hence demand, renewable output increases; on the other hand, demand falls as the consumer price goes up. For low levels of the quota, we expect the first effect to dominate and

hence that renewable output is increasing in the quota, as shown in Figure 1. However, for sufficiently large levels of the quota, the second effect may dominate, in which case renewable output is decreasing in the quota. In this case, although a higher quota induces a higher proportion of renewables in total energy supply, the absolute level of renewable energy may be lowered by an increase in quota due to a contraction in demand.

Figure 2 depicts an example in which the fringe net price, p_a , has an inverse-U shape, mirroring fringe supply in Figure 1. Here, as the quota gets higher from its starting point at zero, the dominant firm engages in margin squeezing at a diminishing rate; that is, the dominant firm allows the fringe to obtain higher profits per unit of output, until the quota rises to a critical level where the fringe price has its maximum. After this level has been reached, the dominant firm successively increases the margin squeeze again. As explained above, the consumer price of electricity is nevertheless monotonically increasing with the quota over the whole range.

Figure 2: Prices as functions of quota.

The behaviour of the composite prices $p = p_E + kp_C$ and $p_a = p_C + p_E - a$ is reflected in the underlying prices of conventional electricity, p_E , and green certificates, p_C .

We expect the impact on the price of conventional electricity by an increase in the quota to be positive, as it responds to the increase in cost of producing electricity. However, the relationship between the quota and the certificates price is more complicated, and the certificates price may be either increasing or decreasing in the quota, depending on parameter values and the size of the quota. In Figure 3 we show two examples (with, respectively, low and high marginal costs of renewables), one where the relationship between the certificates price and the quota is monotonically decreasing, and one where it is non-monotone.

Figure 3: Certificates price as a function of quota.

4 Feed-in Tariff

In this section, we consider a regime in which renewable electricity is subject to a feed-in tariff. We do so by disregarding the green-certificates market and assuming instead that renewable energy is paid a price τ per unit of output on top of the market price of electricity p_E . We could alternatively have assumed that renewable energy is paid a fixed price that is independent of the market price of electricity, but this would lead to essentially similar results. Indeed, Ropenus and Jensen (2009), who analyse cream-

skimming effects in a dominant firm-fringe set up, assume that producers of renewable energy obtain a fixed feed-in tariff; they show that a higher feed-in tariff leads to a lower electricity price.¹⁴ We demonstrate that their results are also valid when the feed-in tariff constitutes a price premium and extend the analysis to the case when the feed-in tariff is financed by a tax on electricity consumers. For comparison with the regime in which renewable energy is regulated by means of green certificates the formulation of a feed-in price premium is particularly convenient as we demonstrate below.

The profit of the fringe now becomes

$$\pi_F = (p_E + \tau) q_F - C_R(q_F) - a q_F, \quad (14)$$

from which we derive its supply function

$$q_F = q_F(p_E + \tau - a), \quad (15)$$

where, again, the function q_F is the inverse of the marginal cost function C'_R .

From (15), it is immediately clear that, since the feed-in tariff is exogenous, determined by the regulatory authority, the margin of the fringe can only be manipulated through the price of electricity.¹⁵ In other words, while the reward for renewables is market determined with green certificates and hence, open to manipulation, here it is exogenous and outside the reach of the dominant firm.

Proposition 3. *With a feed-in tariff, the dominant firm cannot induce a margin squeeze through the premium on renewables, as it can when renewables are regulated by green certificates. Hence, market power can only be exercised through the price of electricity.*

The profit of the dominant firm may be written

$$\pi_M = p_E q_M + (p_E + \tau) q_R - C_M(q_M) - C_R(q_R) - a(q_M + q_R), \quad (16)$$

¹⁴They also show that if the dominant firm is vertically integrated a higher feed-in tariff induces the dominant firm to raise the access charge to skim part of the fringe's additional income and reduce the fringe's output.

¹⁵In the case of vertical integration, fringe margin may be manipulated through the access charge also.

Note that, compared to (8) under the tradable green-certificates system, the only formal difference is that here the exogenous feed-in premium, τ , replaces the endogenous certificates price, p_C .

We first consider the case in which the feed-in tariff is financed in a way that is exogenous to activity in the electricity industry, say by a general tax. Then the price paid by consumers is simply equal to that received by producers, exclusive of any feed-in tariff, i.e.,

$$p = p_E. \quad (17)$$

The profit of the dominant firm may be rewritten as

$$\pi_M = (p - a)(D - q_F) + \tau q_R - C_M(D - q_F - q_R) - C_R(q_R). \quad (18)$$

where q_F is given by (15). We may think of the dominant firm's problem as setting the price of electricity, p , (taking account of how price affects demand as well as supply of the fringe) and determining the amount of renewable energy to be produced by itself, q_R .

We shall demonstrate the following proposition:

Proposition 4. *When the feed-in tariff is financed by a tax that is exogenous to activity in the electricity market, the dominant firm exercises market power by under-supplying electricity; in particular, it supplies less renewables than the fringe, i.e. $q_R < q_F$, but chooses a cost-efficient output mix, i.e. $C'_R(q_R) - \tau = C'_M(q_M)$. Supply of renewables and total supply of electricity are increasing in the tariff.*

The first-order conditions for the dominant firm's profit-maximisation problem may be written¹⁶

$$p \left(1 - \frac{1}{\varepsilon_{DF}} \right) = C'_M + a = C'_R + a - \tau, \quad (19)$$

where $\varepsilon_{DF} = -p(D' - q'_F) / (D - q_F) > 0$ is (the absolute value of) the elasticity of the residual demand curve facing the dominant firm. The first equality equates marginal

¹⁶When presenting first-order conditions we implicitly assume that the solution is interior. Below, we consider examples where corner solutions occur; these are further discussed in the Appendix.

revenue - evaluated with respect to the residual demand curve - with marginal cost of supplying electricity. Note that, unlike in the case with green certificates where the dominant firm effectively controls the output of the fringe by manipulating the net price paid for renewables, here the dominant firm must take into account the response of the fringe when setting the price of electricity. Note also that a more generous policy towards renewables - i.e. a higher feed-in tariff - tends to reduce the consumer price of electricity and increase demand.¹⁷ A decrease in the consumer price of electricity would also occur in the case of a fixed feed-in tariff system, as shown by Ropenus and Jensen (2009). In other words, feed-in systems, either in the form of a premium or a fixed tariff, have the opposite effect of green certificates on total energy consumption. As we shall see below, this result depends crucially on the assumption that the feed-in tariff is not financed by revenues raised in the electricity industry itself.

The second equality in (19) equates the marginal costs of supplying electricity from conventional and renewable sources. Irrespective of source, costs include production costs and the access charge; however, for renewables, costs are taken net of the feed-in tariff, which effectively subsidises the generation of renewable electricity. In other words, taking the subsidy to renewable electricity into account, the dominant firm balances renewable and non-renewable output so as to minimise costs.

Figure 4 shows demand and supply for different values of the feed-in tariff. For the lowest levels of the tariff ($\tau \leq 0.10$), the dominant firm sets the unconstrained monopoly price and only supplies conventional electricity. For higher values ($0.10 < \tau \leq 0.23$), the dominant firm limit-prices so as not to make it profitable for the fringe to enter. Note that for this range, although there is no supply of renewable electricity, conventional electricity supply actually increases due to the imposition of the feed-in tariff, countering the market power of the dominant firm and benefitting consumers. For yet higher values ($\tau > 0.23$), the fringe supplies, while the dominant firm only produces from renewable sources when net costs are sufficiently low compared to the cost of

¹⁷Comparative statics on the first-order conditions (19) demonstrates that a sufficient condition for $\frac{dp}{d\tau} < 0$ is that the cost of renewable electricity is increasing at a faster rate than the cost of conventional electricity over the relevant ranges, i.e. $C_R'' \geq C_M''$. The same condition ensures $\frac{dq_R}{d\tau} > 0$.

conventional electricity ($\tau > 0.5$). While total demand and supply of renewable electricity are increasing in the feed-in tariff, supply of conventional electricity is decreasing and eventually ceases for sufficiently high levels of the tariff ($\tau > 0.77$).

Figure 4: Quantities as functions of tariff - exogenous tax.

While with green certificates the fringe generates less renewable electricity than the dominant firm, here the fringe's output of renewable electricity is greater (as illustrated in Figure 4). There are two reasons for this. First, the dominant firm has a higher effective (opportunity) cost of renewable electricity than the fringe, as it balances the cost of renewables against the cost of conventional electricity. Second, being sensitive to its ability to influence the market price, *ceteris paribus* the dominant firm supplies less than the fringe.

So far we have assumed that the feed-in tariff is financed in a way that is exogenous to activity in the electricity industry. One could argue that, since with green certificates electricity consumers finance the cost of the subsidy for renewables, a more relevant comparison with this regime would be when the feed-in tariff is financed in a similar manner. We now turn to this case.

Suppose the feed-tariff is financed by a tax on electricity consumption:

$$p = p_E + t, \quad (20)$$

where t is the tax rate. We assume that the tax rate is set so as to exactly cover the cost of the feed-in tariff, i.e.,

$$\tau(q_F + q_R) = tD(p). \quad (21)$$

Note that, while the feed-in tariff τ corresponds to the price of green certificates p_C , the tax rate t corresponds to the premium paid by consumers to cover the costs of green certificates kp_C . We return to this correspondence in the comparison of the two regimes below.

The dominant firm's profit may now be written

$$\pi_M = (p - t - a)(D - q_F) + \tau q_R - C_M(D - q_R - q_F) - C_R(q_R), \quad (22)$$

where $D = D(p)$ and $q_F = q_F(p - t + \tau - a)$.

Again the problem of the dominant firm may be viewed as setting the price of electricity and the amount of renewable output, i.e. maximising (22) with respect to p and q_R given (21). So, now the dominant firm must not only take account of the supply of the fringe but also the fact that the consumer tax will be set so as to cover the cost of the feed-in tariff. We have:

Proposition 5. *When the feed-in tariff is financed by a tax on electricity consumption, under reasonable assumptions the dominant firm exercises market power by both under-supplying electricity, i.e. $p_E > C'_M + a$, and over-supplying conventional electricity relative to renewable electricity, i.e. $C'_M(q_M) > C'_R(q_R) - \tau$. For a sufficiently high tariff, total supply of electricity is decreasing in the tariff.*

From (21), we find the following partial relationships

$$\frac{dt}{dp} = \frac{\tau q'_F - tD'}{\tau q'_F + D} > 0, \quad (23)$$

$$\frac{dt}{dq_R} = \frac{\tau}{\tau q'_F + D} > 0. \quad (24)$$

The first relationship is derived by holding the dominant firm's supply of renewables

fixed; then a higher price of electricity reduces demand and increases the fringe's supply of renewables, necessitating a rise in the tax to finance the cost of the feed-in tariff. The second relationship is derived by holding the price of electricity fixed; then a larger supply of renewables by the dominant firm necessitates an increase in the tax to cover the feed-in tariff.

Using the above partial relationships, we find that the first-order conditions for the dominant firm's problem may be written

$$(p - t) \left(1 - \frac{\varepsilon_{P_E}}{\varepsilon_{DFt}} \right) = C'_M + a, \quad (25)$$

$$C'_M = C'_R - \tau \left(1 - \frac{q_M + q_R}{D} \right) \left(1 + \frac{p_a - C'_R}{p_a} \varepsilon_F \right), \quad (26)$$

where $\varepsilon_{DFt} = -p \left(D' - q'_F \frac{dp_a}{dp} \right) / (D - q_F) > 0$ is (the absolute value of) the elasticity of the residual demand curve facing the dominant firm with respect to the consumer price, $\varepsilon_{P_E} = (dp_E/dp) / (p/p_E)$ is the elasticity of the producer price with respect to the consumer price, $\varepsilon_F = p_a q'_F / q_F > 0$ is the elasticity of fringe supply and $p_a = p - t + \tau - a$ is the (net) price of renewable electricity.

Condition (25) equates the marginal revenue of increasing the supply of conventional energy with the corresponding marginal cost. Comparing (25) with (19), we find three differences. First, the producer price of electricity is different from, and smaller than, the consumer price of electricity, i.e. $p_E = p - t < p$, when the feed-in tariff is financed by a tax on electricity consumption.

Second, a change in the consumer price affects the producer price directly as well as indirectly through the tax rate; this effect is captured by the elasticity of the producer price with respect to the consumer price, ε_{P_E} . Note that $\varepsilon_{P_E} = \left(1 - \frac{dt}{dp} \right) / \left(1 - \frac{t}{p} \right)$, where dt/dp is the derivate of the consumer tax with respect to the consumer price of electricity. It follows that $\varepsilon_{P_E} > 1$ if $dt/dp < t/p$ - or $(dt/dp) / (p/t) < 1$, i.e. the elasticity of the tax with respect to the consumer price is greater than one - and so an increase in the consumer price reduces the producer price. Taken in isolation, this effect tends to increase the incentive to exercise market power when $\varepsilon_{P_E} > 1$ or $dt/dp < t/p$,

and vice versa.

Third, the induced change in the tax rate affects the supply of the fringe; this effect is captured by the elasticity of the residual demand curve facing the dominant firm with respect to the consumer price, ε_{DFt} , and, in particular, the element dp_a/dp , the derivative of the price received by the fringe with respect to the consumer price. We have $dp_a/dp = 1 - dt/dp$. Therefore, since an increase in the consumer price increases the tax rate, i.e. $dt/dp > 0$, $dp_a/dp = 1 - dt/dp < 1$, and so the response of the fringe is smaller than if the tax was exogenous. Taken in isolation, this effect tends to increase the incentive to exercise market power.

Overall, we find that the endogeneity of the tax rate has potentially conflicting effects on the incentive to exercise market power in the electricity market. If the elasticity of consumer demand is sufficiently small, it follows from (23) that $dt/dp < t/p$; in this case, the endogeneity of the tax rate tends to increase the incentive to exercise market power.

Condition (26) equates the marginal cost of conventional and renewable energy, respectively. Comparing (26) with (19), we find two differences. The first, captured by the term $(q_M + q_R)/D$, i.e. the share of the dominant firm in overall supply, reflects the fact that an increase in the supply of renewable energy raises the cost of the feed-in tariff, inducing an increase in the tax rate and a corresponding reduction in the producer price of electricity. This effect, which tends to reduce the profitability of increasing the supply of renewable energy, depends on the market share of the dominant firm.

The second difference, captured by the term $[(p_a - C'_R)/p_a] \varepsilon_F$, reflects the fact that the induced increase in the tax rate reduces fringe supply. This effect, which tends to increase the profitability of increasing supply of renewable electricity, depends on the profit margin for renewable electricity, $(p_a - C'_R)/p_a$, as well as the elasticity of fringe supply, ε_F .

Overall, we find again that the endogeneity of the tax rate has conflicting effects; the smaller is the market share of the fringe, the dominant firm's profit margin for renewables and the elasticity of fringe supply, the more likely it is that the dominant firm's

incentive to supply renewables is smaller when the tax rate is endogenous than when it is exogenous.

Figure 5 shows demand and supply quantities for different values of the feed-in tariff, as in Figure 4 above. Qualitatively, we have the same picture: for the lowest levels of the tariff, the dominant firm operates as an unconstrained monopolist; then there is a region where the dominant firm limit-prices; for yet higher tariff levels, the higher the tariff, the more the fringe enters and supplies, while the dominant firm reduces output of conventional electricity, then starts supplying renewable electricity and finally concentrates on renewables only.

Figure 5: Quantities as functions of tariff - endogenous tax.

An obvious difference from the case when subsidies for renewables are financed by a general tax is that here the renewables tax on electricity consumers tends to reduce demand for electricity: this effect is small for low levels of the feed-in tariff where the boost to supply of renewables drives down the electricity price and increases demand; however, for higher levels of the tariff the cost of financing increases with the penetration of renewables and reduces overall demand; when the tariff becomes so high that conventional electricity is driven out entirely, tax and tariff become identical and outweigh each other so that demand and supply of electricity become independent of the level of the tariff. Due to the downward pressure on demand from the tax on consump-

tion, the point at which conventional electricity is driven out occurs earlier than when the feed-in tariff is externally financed (at $\tau = 0.72$ instead of at $\tau = 0.77$).

The endogenous tax strengthens the incentive of the dominant firm to exercise market power. The region where the dominant firm limit-prices increases (from $0.10 < \tau \leq 0.23$ to $0.10 < \tau \leq 0.27$). Also, the dominant firm requires a higher tariff level to supply any renewables at all ($\tau > 0.64$ as opposed to $\tau > 0.5$) and supplies less for any level of the tariff; supplying renewables tends to increase the tax on consumption and hence to reduce demand, while supplying conventional electricity has the opposite effect.

We end by comparing the feed-in tariff and green-certificates regimes when both are financed in the electricity market. It is easy to demonstrate that in the absence of market power market performance would be identical; in particular, with price-taking behaviour by all participants, setting $\tau = p_C$ and $t = kp_C$ (where p_C refers to the equilibrium value of the quota price for a quota equal to k) would implement the same outcome in both cases.

Based on the analysis in this and the previous sections, we would expect market power to increase consumer price more, and hence reduce demand and overall supply more, in the green-certificates regime, as there the dominant firm is able to contain the response of the fringe by manipulating the premium on renewable electricity. For the same reason, we would expect the dominant firm to have both a larger market share and a larger share of the supply of renewable electricity with green certificates than with a feed-in tariff.

We have not been able to prove these conjectures analytically, but they do hold in our parametrised example, as illustrated in Figure 6. This figure builds on Figure 5 above, where we have restricted attention to the region in which the renewables policy is effective (i.e. $0.27 \leq \tau \leq 0.72$). For each value of the feed-in tariff we have calculated the share of renewables in total supply, $(q_F + q_R) / (q_F + q_R + q_M)$, and presented the corresponding variables for the green-certificates regime for this value of k (accordingly, the horizontal axis measures the value of $k = (q_F + q_R) / (q_F + q_R + q_M)$). In other words, we compare outcomes across the two regimes for identical shares of re-

newables in total electricity output. This seems a natural comparison given that goals for renewables are often stated in terms of their share in total output, cf the 20-20-20 goals of the European Union.

Figure 6: Comparison of tariff and quota (endogenous tax).

The two solid lines show that total demand (and supply) is greater in the feed-in tariff regime. This reflects the weaker market power of the dominant firm in the tariff regime; whereas with green certificates the dominant firm is able to influence the margin for renewables separately, with a feed-in tariff the firm is only able to exercise market power through the price of electricity. Consequently, the dominant firm supplies more, or sets a lower price on electricity, in the tariff regime than in the green-certificates regime.

The two dashed lines show that, although total supply is smaller, the market share of the dominant firm is higher with green certificates than with a feed-in tariff. In the green-certificates regime, by simultaneously withholding supply and squeezing the margin for renewables, the dominant firm is able to both raise prices and shift supply towards itself; in the tariff regime, withholding supply and raising the electricity price encourages the fringe to supply more.

Finally, the dotted lines show that the dominant firm's share of renewables is greater in the green-certificates regime than in the feed-in tariff regime. With green certificates,

the dominant firm over-supplies renewable electricity to drive down the price received by the fringe. By contrast, with a feed-in tariff the dominant firm under-supplies renewable electricity to limit the tax on consumers, and hence the price they pay and their demand for electricity.

The fact that, for a given share of renewables, total supply is lower with green certificates than with a feed-in tariff - and so, of course, is the supply of both conventional and renewable generation - indicates that market power has a greater impact on overall supply with a certificates regime than with a tariff regime. In other words, the deviation from the outcome without market power is greater with green certificates than with a feed-in tariff. Taken in isolation this result would tend to favour green certificates over a feed-in tariff if, for other reasons, negative externalities from conventional generation are relatively important (eg. due to carbon emissions that are not properly accounted for by other policies). If, on the other hand, positive externalities from renewables are relatively important (eg. due to innovation spillovers), a feed-in tariff regime would tend to be better than a green-certificates regime since the former leads to a larger output of renewables. Specifically, if negative externalities from conventional generation are properly accounted for (so that c_M reflects true, economy-wide costs) then a feed-in tariff is preferable because it does not allow the dominant firm to manipulate the premium on renewables and tend to undermine the dominant firm's market power in the electricity market.

The latter point is illustrated in Figure 7, which shows net surplus for different shares of renewables in total supply for the two regulatory regimes as well as for a model in which all firms act as price takers. Net surplus is given by total willingness to pay less total costs pluss the positive externality of renewables, which is assumed to be proportional to the volume of renewables with a proportionality factor equal to 1 (i.e. we model the externality as $\delta(q_F + q_R)$ and set $\delta = 1$ in the numerical example). In this case (which is exactly when a subsidy for renewables is the economically relevant policy), the tariff regime dominates the quota regime for all renewable shares due to the higher levels of supply. The surplus-maximising policy is $\tau = 0.55$ in the feed-in

tariff regime - which corresponds to a share of renewables equal to 0.28 - and $k = 0.09$ in the green-certificates regime; by comparison, the optimal policy with price taking behaviour is $\tau = 0.51$ or $k = 0.24$.¹⁸ In other words, the optimal policy is stronger in the tariff regime (a higher tariff), but weaker in the quota regime (a lower quota), compared to the case with no market power.¹⁹

Figure 7: Net surplus

5 Conclusion

In this paper, we have considered a set up in which a dominant electricity producer that operates in both the conventional and renewables segments faces a fringe of price-taking producers of renewable energy. The analysis leads to a number of insights.

First, we have found that when renewable energy is regulated by green certificates the dominant firm will find it optimal to impose a margin squeeze on its rivals by over-supplying renewable energy in order to drive down the price of certificates. This demonstrates that the establishment of a market for green certificates introduces a new

¹⁸Since the subsidy for renewables is paid for by electricity consumers - and hence introduces a distortion in the electricity market - the optimal tariff is smaller than the marginal value of the externality even with price-taking behaviour.

¹⁹These results are robust for alternative values of the externality δ .

opportunity for strategic price manipulation by agents with market power, which may not only distort the certificates market but also impact the performance of the electricity market and the efficiency in generation.

Second, we have seen that the market outcome is the same whether or not the dominant firm is vertically integrated into the network business, so long as the network access price is perfectly regulated in the case of vertical separation; if regulation is imperfect, distortions are smaller under vertical integration than under vertical separation.²⁰ The main insight from this result is not that vertical separation or unbundling is a bad idea (our simple model does not account for a number of important aspects of this issue), but rather that the establishment of a green-certificates market may undermine the pro-competitive effects of unbundling by re-introducing means for predation and foreclosure. In particular, the margin squeeze that may be imposed through the certificates market parallels that which may be imposed through the pricing of access to networks or other essential facilities; in fact, in our set up the two sets of strategies are equivalent.

Third, we have found that feed-in tariffs do not provide a similar opportunity for manipulating the support for renewable energy. The difference between feed-in tariffs and green certificates is especially pronounced when the tariff is financed by a general tax, since the whole support system is then essentially exogenous to participants in the electricity industry.²¹ However, if the tariff is financed by a tax on electricity consumers, the tax affects the dominant firm's incentive to exercise market power on the electricity market, as well as the incentive to balance conventional and renewable energy. Under reasonable assumptions, the dominant firm has a stronger incentive to exercise market power and to produce conventional energy when the tax is financed by the industry itself than when it is not. However, the incentive and ability to exercise market power is nevertheless smaller in the feed-in tariff regime than in the green-certificates regime.

Admittedly, our set up is simple and abstracts from a number of real-world charac-

²⁰We are not the first to point to the possibility of such 'double marginalisation' when regulation is imperfect; see for instance Cremer, Cremer and De Donder (2007), who also provides a more general discussion of the merits of vertical separation.

²¹Ropenus and Jensen (2009) show that the tariff may affect the incentive of a vertically integrated dominant firm to distort the access charge.

teristics of electricity markets and renewables policies. In particular, market structures are more heterogeneous than our extreme dominant firm-fringe dichotomy suggests, and green-certificates markets often contain additional elements such as penalties for non-compliance and opportunities for banking. While it would be interesting to extend the analysis to such more realistic settings, we believe the fundamental insights of our analysis are robust.

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A Green Certificates with Vertical Integration

In this appendix we briefly outline the analysis of green certificates in a market structure with vertical integration, where the dominant firm owns the network. Irrespective of its empirical relevance, this market structure allows us to highlight the parallel between dominant-firm strategies that may be pursued when controlling access to infrastructure and those made possible by the presence of a green-certificates market; as we shall see, in our setting these strategic opportunities are in fact equivalent and hence only one is necessary for the firm to achieve its preferred outcome.

For the competitive fringe, the analysis is exactly as with vertical separation; profits are given by (5), which, when maximised, results in fringe supply as described in (7), where a now denotes the per unit access fee a for transmission services charged by the dominant firm.

The revenue of the vertically integrated dominant firm is obtained from the sale of conventional and renewable energy (and the corresponding amount of certificates) and network services. The dominant firm incurs generation costs as well as network costs. Hence, the profit of the dominant firm is

$$\pi_M = p_E q_M + [p_C + p_E] q_R + a q_F - C_M(q_M) - C_R(q_R) - C_N(q_F + q_M + q_R). \quad (\text{A.1})$$

Comparing (A.1) with (8), we note that here the dominant firm earns revenues from access payments by the fringe. Furthermore, rather than incurring the network tariff contribution for transmission of its own electricity, here the dominant firm pays the full cost for the transmission of electricity.

Analogous to the case of vertical separation, we can express the dominant firm's profit in terms of the consumer price and the fringe price:

$$\pi_M = [p_E + k p_C] [q_F + q_M + q_R] - [p_C + p_E - a] q_F - C_M(\cdot) - C_R(\cdot) - C_N(\cdot) \quad (\text{A.2})$$

or, alternatively,

$$\pi_M = pD(p) - p_a q_F(p_a) - C_M([1 - k]D(p)) - C_R(kD(p) - q_F(p_a)) - C_N(D(p)). \quad (\text{A.3})$$

Formally, the difference between the cases of vertical separation and vertical integration is that here the term $C_N(D)$ takes the place of aD in the case of vertical separation. It follows that if network regulation is perfect, i.e., $aD \equiv C_N(D)$, then profit expressions, and hence market outcomes, would be equivalent.

We see from this last expression that the dominant firm's profit depends on the composite prices p and p_a only. This implies that the original problem of maximising (A.1) subject to (1), (2), (4) and (7) is indeterminate. In other words, as long as the three component prices p_C , p_E and a satisfy the relations $p = p_E + kp_C$ and $p_a = p_C + p_E - a$, the dominant firm can implement its optimal solution in an infinity of different ways. In particular, for any given value of one of the component prices, the dominant firm can always find values for the two other components that implement the profit-maximising solution.

The result is general, in the sense that it does not depend on functional forms or any other technical assumption. It is related to the fact that profits of the dominant firm are influenced by two endogenous entities - total demand for electricity and renewables supply from the fringe - and only two instruments are required to control these entities - the consumer price of electricity and the price of electricity obtained by the fringe. Since the dominant firm has three instruments at its disposal, but requires only two, it has one degree of freedom in how it implements the solution.

Note that this result implies that as long as the dominant firm owns the network, it does not matter whether it is free to set the access charge or not. More specifically, for any given access charge, the dominant firm will be able to implement its preferred market outcome. It follows that if the access charge were regulated, the market power of the dominant firm would not be affected.

The profit-maximisation problem of the dominant firm may alternatively be ex-

pressed as maximising (A.3) with respect to p and p_a . The first-order conditions for this problem are

$$p \left[1 - \frac{1}{\varepsilon_D} \right] = [1 - k] C'_M + k C'_R + C'_N, \quad (\text{A.4})$$

$$p_a \left[1 + \frac{1}{\varepsilon_F} \right] = C'_R. \quad (\text{A.5})$$

The margin squeeze may be obtained by different combinations of the three component prices that constitute the composite price, $p_a = p_C + p_E - a$. As pointed out above, whereas the composite prices p and p_a are determined by profit-maximisation of the dominant firm, the component prices a , p_C and p_E are not. However, given the composite prices a particular relationship exists between the component prices. For example, we may write the profit-maximising values of the price of conventional electricity, p_E , and the certificate price, p_C , as functions of the access charge:

$$p_E = \frac{1}{1 - k} [p - k p_a - k a], \quad (\text{A.6})$$

$$p_C = \frac{1}{1 - k} [p_a - p + a]. \quad (\text{A.7})$$

We observe that while the equilibrium price of conventional electricity is decreasing, the equilibrium certificate price is increasing in the access charge. It follows that there is a negative relation between the equilibrium values of the price of conventional electricity and the certificate price.

B A Parametrised Example

In this appendix, we consider the parametrised example of the general model that forms the basis for the illustrations in the main text. We also derive closed-form solutions and further characterise results.

In this example, demand is linear with coefficients normalised to 1:

$$D(p) = 1 - p. \quad (\text{B.1})$$

The renewable generation costs are quadratic in output,

$$C_R(q) = c_R q + \frac{1}{2} d_R q^2, \quad (\text{B.2})$$

while conventional generation costs are linear,

$$C_M(q) = c_M q, \quad (\text{B.3})$$

and so are network costs,

$$C_N(q) = c_N q, \quad (\text{B.4})$$

where c_M , c_N and c_R are non-negative constants and d_R is strictly positive.

In order to ensure that supply of conventional and renewable electricity are non-negative at market equilibrium, we require that for both technologies marginal cost at zero output falls below the maximum price, or

$$1 - c_M - c_N > 0, \quad (\text{B.5})$$

$$1 - c_R - c_N > 0. \quad (\text{B.6})$$

We further assume that, disregarding costs of emissions, conventional energy is always cheaper than renewable energy, i.e.

$$c_M \leq c_R. \quad (\text{B.7})$$

Moreover, we assume that the fringe would not want to enter the renewables business in the absence of specific regulations; in particular, we assume that when the dominant firm maximises profits supplying conventional electricity only, price does not exceed marginal cost of the fringe at zero output:

$$\frac{1}{2} (1 + c_M + a) \leq c_R + a,$$

where the left-hand side is the price that maximises total industry revenue minus costs of supplying conventional electricity (including the network access fee) and the right-hand side is the marginal cost of supplying renewables at zero output.

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Consumer price and the fringe price are given by

$$p = 1 - \frac{3}{2[3 + k^2 d_R]} \{1 - c_M - a - k[c_R - c_M]\}, \quad (\text{B.8})$$

$$p_a = c_R + \frac{k d_R}{2[3 + k^2 d_R]} \{1 - c_M - a - k[c_R - c_M]\}. \quad (\text{B.9})$$

From the assumptions that $1 - c_N - c_R > 0$ and $c_R \geq c_M$, and since $k \leq 1$, we have $1 - c_M - c_N - k[c_R - c_M] > 1 - c_M - c_N - c_R + c_M = 1 - c_N - c_R > 0$, from which it follows that $p < 1$ and $p_a > c_R$ at $a = c_N$.

Outputs are given by:

$$q_F = \frac{k}{2[3 + k^2 d_R]} \{1 - c_M - a - k[c_R - c_M]\}, \quad (\text{B.10})$$

$$q_M = \frac{3[1 - k]}{2[3 + k^2 d_R]} \{1 - c_M - a - k[c_R - c_M]\}, \quad (\text{B.11})$$

$$q_R = \frac{k}{3 + k^2 d_R} \{1 - c_M - a - k[c_R - c_M]\}, \quad (\text{B.12})$$

where we note that the equilibrium supply of renewable electricity by the dominant firm is twice that of the fringe:

$$q_R = 2q_F. \quad (\text{B.13})$$

We conclude the analysis of green certificates by considering how equilibrium prices and quantities depend on renewable energy policy, as measured by the quota k , assuming that the access charge is set equal to marginal network costs, i.e. $a = c_N$.²²

²²All arguments go through so long as a is sufficiently close to c_N .

For the electricity price paid by consumers, we obtain

$$\frac{dp}{dk} = \frac{3[c_R - c_M] + 3kd_R\{2[1 - c_M - a] - k[c_R - c_M]\}}{2[3 + k^2d_R]}. \quad (\text{B.14})$$

Since $c_R \geq c_M$ and $1 - c_M - c_N - k[c_R - c_M] > 0$, we find

$$\frac{dp}{dk} > \frac{3[c_R - c_M]}{2[3 + k^2d_R]} > 0. \quad (\text{B.15})$$

Furthermore, we find

$$\frac{dp_a}{dk} = \frac{3d_R[1 - c_M - a] - kd_R\{kd_R[1 - c_M - a] + 6[c_R - c_M]\}}{2[3 + k^2d_R]}. \quad (\text{B.16})$$

As is easily seen, dp_a/dk is decreasing in k ; that is, the fringe price is concave in the quota. Furthermore, at $k = 0$, $dp_a/dk > 0$. This means that the fringe price is increasing at no (or, by continuity, small) quota. By contrast, at $k = (1 - c_M - a)/(c_R - c_M)$, we have $dp_a/dk < 0$. It follows that there exists some $\hat{k} \in (0, (1 - c_M - a)/(c_R - c_M))$, for which $dp_a/dk = 0$.

Since $(1 - c_M - c_N)/(c_R - c_M) > 1$, it is not clear that $\hat{k} < 1$ (the maximum quota); indeed, depending on parameter values, we may have either $\hat{k} > 1$ or $\hat{k} < 1$. In the former case, the fringe price is always increasing in the quota, whereas in the latter case, the fringe price is first increasing and subsequently decreasing in the quota.

The behaviour of the composite prices is reflected in the underlying prices of conventional electricity and green certificates. The marginal impact on the price of conventional electricity by an increase in the quota is unambiguously positive:

$$\frac{dp_E}{dk} = \frac{1 - c_R - a}{2[1 - k]^2} > 0. \quad (\text{B.17})$$

However, the relation between the quota and the certificates price is more complicated, and the certificates price may be both increasing or decreasing in the quota, depending on parameter values and the size of the quota.

In order to shed some further light on the relationship between prices and the quota,

let us now investigate the impact of the quota on outputs. From the first-order condition for the profit maximisation of the fringe (7), we have

$$q_F = \frac{1}{d_R} [p_a - c_R]. \quad (\text{B.18})$$

It follows that the relationship between q_F and k has the same shape as that between p_a and k ; more specifically, q_F is increasing in k whenever p_a is, and vice versa. Moreover, since the renewables supply of the dominant firm is proportional to that of the fringe, the same is true for the dominant firm's renewable supply.

Using (2), we may alternatively state the supplies of renewable electricity as

$$q_F = \frac{k}{3} [1 - p], \quad (\text{B.19})$$

$$q_R = \frac{2k}{3} [1 - p]. \quad (\text{B.20})$$

Moreover, from (3), we find that

$$q_M = [1 - k] [1 - p]. \quad (\text{B.21})$$

Feed-In Tariff - Exogenous Tax

Under the assumption that parameters are such that the fringe would produce nothing absent a specific renewables policy, it follows that the dominant firm, for sufficiently low values of the feed-in tariff, is unconstrained and can act as a monopolist supplying only conventional electricity. The dominant firm's problem is then to maximise

$$\pi_M = (p - a) D + C_M(D), \quad (\text{B.22})$$

which, in the example, has the solution

$$p = \frac{1}{2} (1 + c_M + a). \quad (\text{B.23})$$

The dominant firm is unconstrained so long as the monopoly price is at or below the net marginal cost of the fringe at zero output, i.e. $p \leq c_R + a - \tau$, which yields the first critical value for the feed-in tariff:

$$\tau_1 = c_R - c_M - \frac{1}{2}(1 - c_M - a). \quad (\text{B.24})$$

For higher values of the feed-in tariff, the unconstrained monopoly price will be sufficiently attractive to induce entry by the fringe; however, it may then be in the interest of the dominant firm to supply more to drive down the electricity price to the limit price $p = c_R + a - \tau$ and forestall entry. A necessary condition for it to be optimal for the dominant firm to hold the price at this level is that the marginal profit from raising the price, taking account of the response of the fringe, is non-positive. Taking the derivative of (18) with respect to p , substituting the limit price for p , setting the result equal to zero and solving, yields the next critical value for feed-in tariff:

$$\tau_2 = c_R - c_M - \frac{d_R}{2d_R + 1}(1 - c_M - a). \quad (\text{B.25})$$

For still higher values of the feed-in tariff, it is optimal for the dominant firm to set a price so high that the fringe supplies renewable electricity. Here, we find from (19) the following solutions for the electricity price

$$p = 1 - \frac{1}{2[1 + d_R]} \{ [2 + d_R][1 - c_M - a] + c_M - c_R + \tau \}, \quad (\text{B.26})$$

However, it is only when the tariff is high enough that the net cost of renewable electricity falls below the cost of conventional electricity that the dominant firm, which chooses the cost-minimising combination of renewable and conventional electricity, itself produces renewable electricity; the third critical value for the feed-in tariff therefore becomes

$$\tau_3 = c_R - c_M. \quad (\text{B.27})$$

Here, we find from (19) the following solutions for the dominant firm's output of

renewable electricity

$$q_R = \frac{1}{d_R} [c_M - c_R + \tau]. \quad (\text{B.28})$$

Finally, for sufficiently high values of the feed-in tariff, the dominant firm will find it most profitable not to produce any conventional electricity, in which case the dominant firm maximises the following expression:

$$\pi_M = (p - a + \tau)(D - q_F) - C_R(D - q_F), \quad (\text{B.29})$$

which has the solution

$$p = \frac{1}{(3 + d_R)(1 + d_R)} [(2 + d_R)d_R - (3 + 2d_R)(\tau - c_R - a)]. \quad (\text{B.30})$$

Using this and the condition that, at optimum, net marginal cost of renewable electricity is lower than the marginal cost of conventional electricity, which in the example may be written $c_R + d_R(D - q_F) - \tau \leq c_M$, we find the fourth and final critical value for the feed-in tariff:

$$\tau_4 = c_R - c_M + \frac{d_R}{3}(1 - c_M - a). \quad (\text{B.31})$$

In order to compare the policies of feed-in tariffs and green certificates with respect to the composition of electricity generation, we consider the case when the respective policies are set such that the share of renewables in total electricity output is the same, i.e. such that

$$\frac{q_F + q_R}{q_F + q_M + q_R} = k. \quad (\text{B.32})$$

From (B.28)-(B.32), we find the feed-in tariff that corresponds to a particular share of renewables:

$$\tau = \frac{d_R \{k[2 + d_R] - 1\}}{3 + [4 - k]d_R} [1 - c_M - a] + c_R - c_M \quad (\text{B.33})$$

Substituting (B.33) in (15) and (B.28), we find

$$\frac{q_F}{q_R} = \frac{2[1 + d_R] \{k[1 + 2d_R] - 1\} + [2 - k][2 + d_R] + d_R}{2[1 + d_R] \{k[1 + 2d_R] - 1\}} > 1. \quad (\text{B.34})$$

Feed-In Tariff - Endogenous Tax

The characterisation of equilibrium for the endogenous-tax case follows the same line as for the case of an exogenous tax. In particular, the range for which the dominant firm is unconstrained is the same in both cases and so the first critical value for the feed-in tariff is again

$$\tau_1 = c_R - c_M - \frac{1}{2}(1 - c_M - a). \quad (\text{B.35})$$

The limit price is also the same and equals $p = c_R + a - \tau$ (note that $t = 0$ when there is no supply of renewable electricity), but the second critical value for the feed-in tariff differs, since the impact on the price received by the fringe, and hence its response, is different when the tax rate is endogenous. Taking the derivative of (18) with respect to p , substituting the limit price for p , setting the result equal to zero and solving, yields the next critical value for the feed-in tariff

$$\begin{aligned} \tau_2 = & \frac{1}{4(1 + d_R)} \left\{ (2 + d_R)(c_R - c_M) - (1 + 3d_R)(1 - c_R - a) \right. \\ & \left. + \sqrt{[(2 + d_R)(c_R - c_M) + (1 - d_R)(1 - c_R - a)]^2 + 4d_R(1 + d_R)(c_R - c_M)(1 - c_R - a)} \right\}. \end{aligned} \quad (\text{B.36})$$

For yet higher values of the feed-in tariff, it is optimal for the dominant firm to set a price so high that the fringe supplies renewable electricity. For this range we have not been able to find closed-form solutions, but have had to rely on numerical simulations. The first-order condition (26) may be written as

$$q_R = \frac{1}{d_R(1 + 2A^2)} \left\{ 2(1 - A)A + [1 + (1 - 2A)A](\tau + c_M - c_R) - d_RA(1 - p) \right\}, \quad (\text{B.37})$$

where $A = \tau / [\tau + d_R(1 - p)]$ and we have used the following expressions derived from (21) and (15):

$$t = A(p + \tau - a - c_R + d_R q_R), \quad (\text{B.38})$$

$$q_F = \frac{1}{d_R}(1 - A)(p + \tau - a - c_R) - A q_R. \quad (\text{B.39})$$

This gives us a recursive system with q_R , q_F and t as functions of p that allows us to find the p that maximises profits for any given τ .

The critical value of the feed-in tariff, τ_3 , at which the dominant firm starts to produce not only conventional but also renewable electricity, is found where the solution to (B.37) equals exactly 0 for the optimal value of p (at lower tariff levels, the solution to (B.37) is negative and so we set $q_R = 0$).

Similarly, the critical value of the feed-in tariff, τ_4 , at which the dominant firm stops producing conventional electricity, is found where the solution to (B.37) equals exactly $D - q_F$ (and so the supply of renewable electricity equals total demand). For higher levels of the tariff, when the dominant firm finds it most profitable not to produce any conventional electricity, it follows from (21) that $t = \tau$. We find the profit-maximising price in the same manner as in the case of an exogenous tax:

$$p = \frac{1}{(3 + d_R)(1 + d_R)} [(2 + d_R)d_R + (3 + 2d_R)(c_R + a)]. \quad (\text{B.40})$$

Note that, for $\tau \geq \tau_4$, the market outcome is independent of the level of the feed-in tariff; a higher tariff requires a correspondingly higher tax, but since the producer price, $p_E + \tau$, and the consumer price, $p_E + t$, remain identical, the market price of electricity, p_E , simply adjusts accordingly.