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On the Price and Volume Effects from Green Certificates in the Energy Market

Abstract:
We present a model for an energy market that includes a green certificate for suppliers of energy from renewables and a purchaser commitment to buy these certificates. We show that price and volume effects in the energy market are ambigous under a wide range of alternative levels of the purchaser commitment. We calibrate our model to data for the Norwegian economy. Simulations shows a downward movement in energy prices as the government starts increasing the level of the purchaser commitment. This implies that the producer of ordinary energy pays for the restriction in the market while energy consumption and consumer surplus increases. When the purchaser commitment increases above a certain level, the purchaser price increases and the volume effect is negative. Although the effects are sensitive to elasticities of demand and supply of both technologies, the main results are robust against a variety of combinations of elasticities. The article discusses effects both under autarky and free trade of both energy and green certificates. The results vary denpendent upon whether only one or a majority of actual countires introduces a domestic market or allows for international trade both in energy and the green certificate instrument.

Keywords: Green certificates, energy market model, new instruments.

JEL classification: Q41, Q42, Q48, H23, H30.

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1 Introduction

In the autumn 2001 politicians agreed upon allowing a tradable quota system to deal with the country specific stated goals in the Kyoto protocol to reduce the emissions of greenhouse gases in a cost efficient way, Marracesh (2001)[1]. The market for permits sets a price on emissions of greenhouse gases, increases the cost of producing energy from fossil fuels and thereby improves the profitability of producing from renewable energy sources. Pricing emissions implies substitution from highly polluting technologies to less polluting technologies. There are some well-founded scepticism about the time frame, the pace and the possibility to have an effective introduction of such a permit market. Besides, since US hardly ratify the Kyoto protocol, a permit market solution probably realize close to zero prices in the short run, see Bøhringer (2002) and IEA World Energy Outlook 2000. Emission reduction potential is then low. Politicians then advocate additional instruments to speed up the conversion to non-fossil fuels or renewable energy to combat greenhouse gas emissions. They propose instruments that directly or indirectly stimulates and foster the expansion of renewable or so called green energy. In this paper we refer to green technologies synonymous with renewable energy[2].

There are several incentive problems with traditional instruments like price and investment support for renewable energy. Stimulating the cost minimizing green energy sources through subsidies requires information about the cost of all possible renewable energy technologies. Lack of information complicates cost minimization, increases the possibility of cost over coverage, and lack of efficiency. A political anomaly may also occur since lowering the cost of renewable energy lowers purchaser prices of energy, which implies a subsidy of energy and increased energy consumption. An obvious advantage of supporting renewable energy is the creation of possible positive externalities from research on new technologies through learning by doing, see for instance Spence (1984), Hall and Howell (1985), Joskow and Rose (1985), Romer (1986) and Schrattenholzer (2002).

A new alternative supporting instrument for renewable energy coming up in the literature, and frequently discussed among politicians, is the so called green certificate system. A green certificate is a proof of the green origin of an amount

[1]See the second addendum, The Marracesh Accords

[2]Defining the green technology is not simple, however this is not the subject in this article. For a closer discussion see Voogt et al (2000)

of energy produced. Different kinds of renewable energy sources are classified as green, see COMM(2000), Hoogland et al. (2000), Poupolo et al. (2000), Voogt et al. (2000), Voogt et al. (2001), Amundsen et al. (2001) and Jensen et al. (2002). For each unit of energy produced by renewable energy the government issues a green certificate to the producer. The consumer has to purchase a number of certificates, which is proportional to his total amount of energy. This creates a market for the green energy certificates. The green producers harvest an additional certificate price in the certificate market, which increase the profitability of producing energy from green technologies. An advantage of this green certificate instrument over a simple price and standard investment subsidy instrument is that the certificate market will contribute to a cost efficient solution in the energy market under the green energy production share constraint. The green commitment share and the definition of green technologies is a governmental issue.

Amundsen and Mortensen (2001) study the relationship between a green certificate market and a market for CO_2 permits, under the constraint of upper and lower price bounds on the green certificates. They particularly show that under certain circumstances harsher CO_2 constraints may lead to less capacity of green electricity, which at first sight may seem contra intuitive. Jensen and Skytte (2002) show that under certain premises the purchaser price effect in the electricity market may be ambiguous when introducing green certificates.

In this article we show that the results shown in Amundsen et al. (2001) and Jensen et al (2002) are more complex as the effect on prices of volumes changes sign as the government increases the imposed share of green certificates. We establish a model that includes two different energy technologies, that are referred to as traditional environmentally damaging technology and a green technology (environmentally friendly and renewable). Both compete in the same market. The green technology is not profitable in an ordinary market. However, a green certificate instrument is introduced as described to help the penetration of green technologies. We formally derive what happens to energy prices, purchaser prices, certificate prices and energy demand by source as the government increases the committed green energy share. The theoretical model produces ambiguous price and volume effects under a wide range of assumptions about the committed green shares, elasticities, etc. The sign of the price and volume effect also changes as the share increases. We show that the purchaser obligation introduces a "tax" effect in the traditional energy market (demand tax) and a "subsidy" effect in the green energy market (producer subsidy).We also perform numerical simulations of the model under increasing impositions of the green technology market share, under different assumption on elasticities etc. Provided increasing marginal cost of expansion for both traditional and green technologies (elasticities are varied), we show that the purchaser price effect is negative and the volume effect is positive when increasing the imposed green share, even if the production cost of green energy is very high. Increasing marginal cost in the traditional energy supply sector and equilibrium effects imply that the producer of traditional energy pays more than the incremental total cost for the green technology and thereby allows consumer surplus to increase. For strict environmental conditions, i.e. large quantities of green technology commitments, the price and volume effects changes sign.

This applies for electricity or energy markets in one isolated country (autarky). Deregulation of international electricity markets implies price taker behavior as long as transmission capacity is idle. Under these conditions an increasing commitment of domestic green energy shares does not influence equilibrium energy prices, and conventional results prevail, i.e. purchaser prices increase as the commitment increase. Most European countries want to introduce green certificate markets. Deregulation makes Europe one single energy market (except when transmission capacity constraints are effective). In this market producers face increasing marginal costs of expanding energy production capacity. Again, increased green commitment shares reduce traditional energy production, which will reduce both producer and purchaser prices of energy.

The rest of the article is organized as follows; In chapter 2 we establish a formal market model under autarky and derive the theoretical results for what will happen to prices and demand as the government increases the committed amount of certificates. We assume perfect competition in both the ordinary and the renewable energy market, however restricted by the imposed green certificate rule. We also discuss modifications of the results when opening the market for trade of energy. In chapter 3 we calibrate and simulate a numerical version of the model and compare the theoretical results derived in chapter 2.Chapter 4 concludes. Theoretical derivation and numerical model presentation is presented in the Appendix A and Appendix B.

2 An autarky market model including green certificates

We define a market for two kinds of energy: green energy and traditional energy. Green energy is based on renewable energy sources and thereby environmentally friendly[3]. Traditional energy is environmental damaging of some kind, such as for instance pollution from coal fired electricity producing plants.

For simplicity we assume one consumer and one producer of energy[4]. The producer generates secondary energy (for instance electricity) based on a primary energy source (water, oil, coal etc) and a technology either classified as traditional or green. The producer may choose one or a mix of technologies. The maximization problem for the producer is

$$\max \pi(x_g, x_v) = px_v + p_g x_g - C(x_v, x_g) \tag{1}$$

subject to a positive constraint on the output, $x_i \geq 0$,of energy produced with technology $i = g, v$ (g=green, v=traditional). Here π is profit from the mixed production, p is the seller price of ordinary energy, p_g is the seller price for green energy, and $C(x_v, x_g)$ is the mixed technology cost function for the producer. Also for the consumer both types of energy are perfect substitutes and green production is therefore excluded if $p_g > p$. Since $C'_v < C'_g$ no production of green energy takes place.

The first condition necessary to establish a market for the green energy is that the government issues a green certificate for each unit of green energy produced. The producer then sells the homogenous energy product to the market clearing price p. In addition they want to sell green certificates at a price that secures $p + p_c = C'_g$, p_c being the certificate price. Equation (1) then may be written as

$$\max \pi(x_g, x_v) = px_v + (p + p_c)x_g - C(x_v, x_g) \tag{2}$$

We assume that the cost function is additively separable with respect to x_v and x_g as the two technologies are distinct and implies different investments. We also assume increasing long term marginal cost in both technologies

[3]Defining the green technology is not simple, and this is not the subject in this article. For further discussion of this subject see for instance Voogt et al. (2000).

[4]This simplification do not matter for the results.

$$\frac{\partial C}{\partial x_v} > 0 \text{ and } \frac{\partial C}{\partial x_g} > 0 \ . \tag{3}$$

The supply of energy x^S now is

$$x^S = g(p) + h(p_g) = g(p) + h(p + p_c) \tag{4}$$

where $g(p)$ is the supply of ordinary energy and $h(p + p_c)$ is the supply of green energy.

The consumer normally maximize utility[5] $U(x^D)$ of energy demand x^D net of purchaser cost px^D

$$\max U(x^D) - px^D. \tag{5}$$

The second necessary condition to establish a market for green energy is to make sure that consumers actually purchase the green certificates. The government then imposes on the consumer to purchase an amount α of certificates x^c proportional to the amount of his energy demand x^D

$$x^c = \alpha x^D \ . \tag{6}$$

The purchaser price for energy (including certificates), p_x, may then be formulated as a weighted sum of the energy and the certificate price

$$p_x = \frac{px^D + p_c x^c}{x^D} = p + \alpha p_c \ . \tag{7}$$

Inserting (7) into (5) yields energy demand as a function of the energy price, the certificate price and the imposed share of green consumption

$$x^D = f(p + \alpha p_c) \ .$$

By assumption then the price of the certificate and the price of energy is high enough to make it profitable to produce energy from green technologies

$$p_g = p + p_c = C'_g \ . \tag{8}$$

In equilibrium a $(1 - \alpha)$ share of demand equals the supply of traditional energy and an α share of demand equals the supply of green energy

[5] We assume continuity and divisibility.

$$(1-\alpha)f(p+\alpha p_c) = g(p) \ , \tag{9}$$
$$\alpha f(p+\alpha p_c) = h(p+p_c) \tag{10}$$

which determines p and $p_c$as a function of the exogenous α. An alternative specification of (10) is

$$\alpha f(p_g-(1-\alpha)p_c) = h(p_g) \tag{11}$$

Equation (9) and (11) shows that the green certificate system turns out to be a combination of a tax on energy by an endogenous energy tax rate of αp_c and a subsidy of the green energy by an endogenous subsidy rate of $(1-\alpha)p_c$, i.e. two traditional instruments turned into one.

In most discussions about the introduction of green certificates, see for example Hoogland et al. (2000), Poupolo et al. (2000), and Voogt et al. (2001) a stepwise introduction of the green technologies is proposed. What happens to the equilibrium prices and volumes as the green share α increases, that is, as the government increases the environmental imposition of the amount of green energy, i.e. increases α?

Proposition 1. The energy price p will go down as the imposed α share increases, i.e. $\frac{\partial p}{\partial \alpha} < 0$

Proof: We find the first order derivative of both relations in the equilibrium conditions (9) and (10) with respect to α, which gives us two equations

$$[(1-\alpha)f'-g']\frac{\partial p}{\partial \alpha} + (1-\alpha)\alpha f'\frac{\partial p_c}{\partial \alpha} = f-(1-\alpha)f'p_c. \tag{12}$$

$$(\alpha f'-h')\frac{\partial p}{\partial \alpha} + (\alpha^2 f'-h')\frac{\partial p_c}{\partial \alpha} = -f-\alpha f'p_c. \tag{13}$$

where the arguments are omitted in the functions $f(p+\alpha p_c)$ etc, see appendix A. The solution for $\frac{\partial p}{\partial \alpha}$becomes (see appendix A for a formal derivation)

$$\frac{\partial p}{\partial \alpha} = \frac{-f'(\alpha f+(1-\alpha)h'p_c)+h'f}{f'((1-\alpha)^2h'+\alpha^2 g')-h'g'} < 0 \tag{14}$$

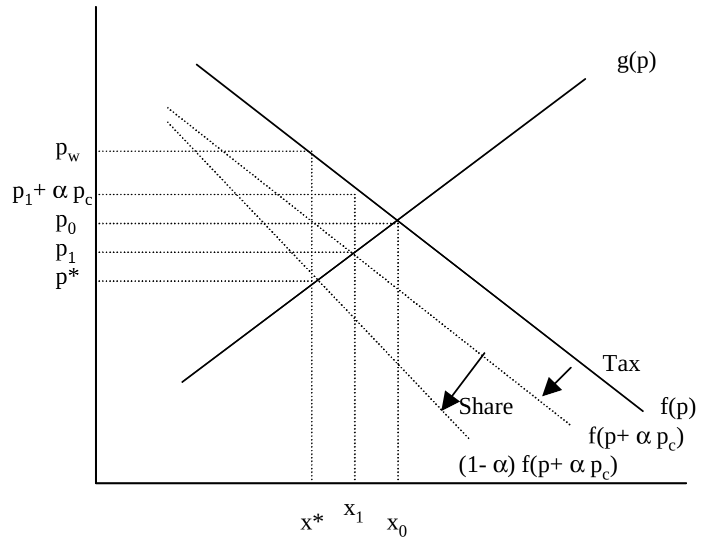
i.e. less than zero since the numerator is positive and the denominator is negative[6]. The producer price in the ordinary energy market decreases as the government

[6] Recall that the first order derivative of the demand function $f' < 0$ and the first order derivative of both supply functions $g' > 0$ and $h' > 0$.

imposes a higher green energy α share. The introduction of green certificates becomes a strain on the traditional energy market, and the traditional energy producers lose profit.

Figure (1) describes the market for traditional energy. The market equilibrium before the introduction of the certificate market is (p_0, x_0). The green certificate purchaser requirement shifts the demand curve inwards in two steps; First from $f(p)$ to $f(p + \alpha p_c)$. This first step is related to the increased effective purchaser price, which is equivalent to the effect of introducing a tax on energy (αp_c). This would create a new equilibrium in (p_1, x_1) where the purchaser price equals $(p_1 + \alpha p_c)$.

Figure 1: Certificate commitment and effects in the ordinary market.



However, only a fraction $(1 - \alpha)$ of total demand may be satisfied by traditional energy. In the second step the demand curve twists downwards to the left, $(1 - \alpha)f(p + \alpha p_c)$. The new equilibrium price and volume is (p^*, x^*). Depending upon the shift and the twist of the demand curve, the imposed α share have impact on both the price and volume. The difference between the energy price and the willingness to pay, $(p_w - p^*)$, where $p_w = U'_{x*}$,may be large. Then $\frac{\partial p}{\partial \alpha} < 0$ since the introduction of green energy will displace traditional energy that faces an upward sloping supply curve. The effect comes both through an implicit taxing of traditional energy and a sharing restriction in the market.

Proposition 2. The certificate price p_c will increase, i.e. $\frac{\partial p_c}{\partial \alpha} > 0$, as the

imposed α share increases and if $\frac{h'}{g'} > \frac{\alpha}{1-\alpha}$ or else the sign is undefined

Proof: The nominator in

$$\frac{\partial P_c}{\partial \alpha} = \frac{ff' - f(h' + g') + f'p_c((1-\alpha)h' - \alpha g')}{f'((1-\alpha)^2 h' + \alpha^2 g') - h'g'} \tag{15}$$

is at first sight apparently undetermined. The first term is negative since $f > 0$ and $f' < 0$, so is the second term as both $h' > 0$ and $g' > 0$. The last term is negative if $(1-\alpha)h' > \alpha g'$, i.e. if $\frac{h'}{g'} > \frac{\alpha}{1-\alpha}$, that is if the relation between the derivative of supply of green energy to the derivative of the supply of normal energy is higher than the relation between the green and the traditional energy shares $\frac{h'}{g'} > \frac{\alpha}{1-\alpha}$. If the derivatives are equal negativity happens when the green share is less than the traditional energy share, i.e. if the green share α is less than 50 per cent. However, this is not a necessary condition for negativity. The nominator .$|f'p_c((1-\alpha)h' - \alpha g')| < |ff' - f(h' + g')|$. Intuitively the certificate price increases as the mandatory green share increases. The increasing marginal cost curve in (**??**),however, is not sufficient for concluding that $\partial 0 P_c / \partial \alpha > 0$ as the share α could increase by a reduction in the volume of traditional energy ($h(p)$).

Proposition 3. The purchaser price of energy including certificates p_x could both increase and decrease as the imposed α share increases, i.e. $0 \geq \frac{\partial p_x}{\partial \alpha} \geq 0$. The sign is ambiguous.

Proof: The purchaser price (10) is a weighted average of the change in the producer price, the change in the certificate price and the absolute value of the certificate price.

$$\frac{\partial p_x}{\partial \alpha} = \frac{\partial p}{\partial \alpha} + \alpha \frac{\partial p_c}{\partial \alpha} + p_c \tag{16}$$

The first increases, see proposition 1, and the second may decrease, see proposition 2. Manipulating (16), (14), and (15)

$$\frac{\partial p_x}{\partial \alpha} = \frac{1}{|A|} \begin{bmatrix} (1-\alpha)fh' - \alpha f g' - (1-\alpha)^2 f'h'p_c - \\ \alpha^2 f'g'p_c + (1-\alpha)^2 f'h'p_c + \alpha^2 f'g'p_c - p_c h'g' \end{bmatrix}, \tag{17}$$

where $|A| < 0$, is the determinant of the equation set (12) and (13). This reduces to

$$\frac{\partial p_x}{\partial \alpha} = \frac{1}{|A|} \{ f'((1-\alpha)h' - \alpha g') - h'g'p_c \} \tag{18}$$

The last term in the nominator $(-h'g'p_c)$ is negative since both supply's derivative and the equilibrium price of certificates have to be positive. If the relation between the supply derivative for green and ordinary energy, $\frac{h'}{g'} > \frac{\alpha}{1-\alpha}$, then $f'((1-\alpha)h' - \alpha g') < 0$ and $\frac{\partial p_x}{\partial \alpha} > 0$. The purchaser price increases as the green share increases. When the supply derivative of green energy is zero purchaser prices always increase.

When the supply derivative of green technology is infinitely large (cfr. a backstop technology) then this term is positive if $f(1-\alpha) > g'p_c$, and purchaser prices decrease as the green share increases. When the derivatives for both supply's are equal $f((1-\alpha)h' - \alpha g') > 0$ for shares of α less than 0.5, then $\frac{\partial p_x}{\partial \alpha} < 0$ might be the outcome if $f((1-\alpha)h' - \alpha g') > h'g'p_c$. Purchaser prices may well decrease as the α share increases. As the α share increases even more, the sign typically changes, i.e. $\frac{\partial p_x}{\partial \alpha} > 0$. If the derivatives are at equal sizes then small shares increases the possibility that $f((1-\alpha)h' - \alpha g') > h'g'P_c$, i.e. that purchaser prices decrease as the α share increases.

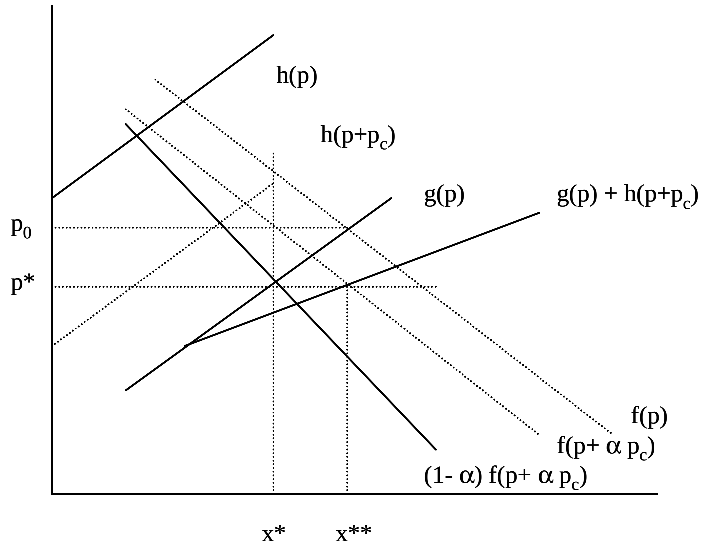
Figure (2) illustrates what happens. The supply of green energy $h(p)$ is too costly to penetrate the market at an initial price of p_0. However, the supply of green technologies shifts to the right $h(p + p_c)$ as the certificate price works as a subsidy in the market. The aggregate supply is $g(p) + h(p + p_c)$. The equilibrium point is the crossing of the total "taxed" demand $f(p+\alpha p_c)$ and the total aggregate supply, i.e. (p^*, x^{**}).

We notice that $p^* < p_0$. As discussed above, whether the purchaser price is higher or lower than the former equilibrium price, p_0, is depending upon the α share, the elasticity of supply for traditional energy (moving down the marginal cost curve) and the elasticity of supply for green energy .

3 International trade

So far we have discussed possible price and volume effects of green certificate introduction under autarky. In Northern Europe, however, the electricity markets are

Figure 2: Green and traditional energy



deregulated and trade is fluent. Most of the domestic actors are small and thereby price takers in a larger international market. Then equation (14) reduces to

$$\frac{\partial p}{\alpha} = 0, \tag{19}$$

since the domestic green production anyway will be to small to influence European market prices. In this case, cfr.(15) we found that $\partial p_c / \partial \alpha > 0$. Therefore according to (16) ,

$$\frac{\partial p_x}{\alpha} > 0. \tag{20}$$

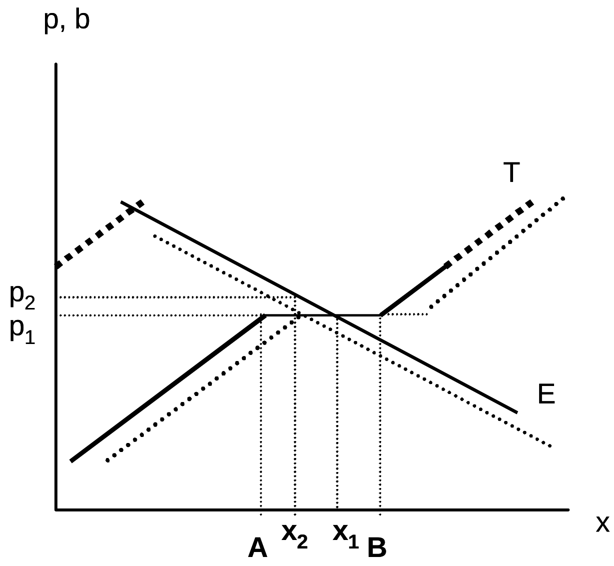
Purchaser prices increase and domestic demand decreases.

3.1 Imports

In an import situation, supply (foreign supply) is infinitely elastic around the equilibrium point as long as the transmission capacity is not exceeded, see $A - B$ in figure (3). The supply curve, T, left of point A is domestic supply. Domestic supply also forms the increasing part of the supply curve to the right of point B.

The domestic demand is downward sloping (E), and the equilibrium with imports and idle transmission capacity is in (p_1, x_1). The import is $(x_1 - A)$. A

Figure 3: Import of energy and the effect of green certificates

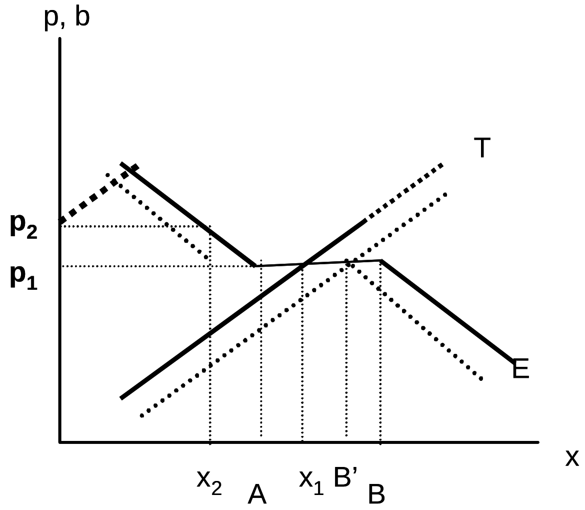


domestic purchaser green certificate requirement ("tax") shifts domestic demand downwards (to the left). A certificate to the domestic producer ("subsidy") shifts domestic supply outwards (to the right) (cf. the dotted demand and supply curves in figure (3)). We notice that a shift in the supply curve and a shift in the domestic demand do not change the energy price, p_1, as long as transmission capacity limits are not exceeded (the flat part - or the infinite elastic part - of the supply curve). The domestic purchaser price (20) increases, p_2, and domestic demand decreases, x_2. Increased domestic supply and reduced domestic demand both contribute to reduced imports (in figure (3) to zero). Under import conditions a domestic green certificate market causes a downward shift in transmission losses as imports are reduced. The profitability of the transmission network is reduced as capacity utilization decreases.

3.2 Exports

Let us reverse trade, i.e. the relevant country is net exporting at fixed prices, see figure (4). Domestic demand is the left of A downward sloping solid curve and exports are the infinitely elastic part of demand (between A and B) as long as transmission capacity is sufficient. The right of B downward sloping part of

Figure 4: Export of energy and the effect of green certificates



demand is the residual domestic demand when transmission capacity is exceeded. Supply is a normal upward continuous sloping curve, since exporting implies just domestic supply in this market. Demand is infinitely elastic around equilibrium (p_1, x_1). Domestic demand is A, export is $(x_1 - A)$, while transmission capacity is $B - A$. A purchaser green certificate requirement ("tax") shift domestic demand downwards (to the left). A domestic certificate on green production ("subsidy") shift domestic supply outwards (to the right). cf. the dotted demand and supply curves. We notice that this shift in both the domestic supply and demand curve do not change the energy price, p_1, as long as transmission capacity limits are not exceeded $(B' - x_2) \leq (B - A)$. The domestic purchaser price (20) increases to p_2, and domestic demand decreases to x_2. Increased domestic supply and reduced domestic demand both contribute to increased exports by $(A - x_1) + (B' - x_1)$. In an export situation then, a domestic green certificate market cause an upward shift in both power losses and the profitability of the transmission network as capacity utilization increases.

3.3 Transmission capacity limits

For both an import and export situation, when capacity limits on the transmission network is reached, i.e. (import $\geq B - A \leq$ export), the model reduces to produce autarky results. Even though Europe is a common competitive market, with each country behaving as price takers, transmission capacity restrictions between countries reduces the market. The above theory with ambiguous results for prices and volumes may then be relevant, if not for every period of time, at least in the periods where transmission capacity is restricted.

3.4 One international energy and certificate market

Several countries in the EU are discussing common rules for domestic green certificates and the European Commission advocates this. When adding all European production capacities it is reasonable to assume increasing marginal cost for producing energy in the total market, i.e. an upward sloping supply curve both for traditional energy and renewable energy. On the demand side we face the common downward sloping curve. This makes the model produce autarky results for the whole European market and the contra intuitive results of decreasing purchaser prices, when the imposition of green certificate share increases, prevails.

4 Some empirical evidence

The North European power market is presently characterized by excess producer capacity and low market prices. It is expected that the market will tighten in a few years and capacity expansion will occur. The Norwegian power market is almost totally based on hydropower. On the margin, new hydropower capacity expansion is still in question in a limited amount. But as the market tightens and prices increase, natural gas power technology is the most probable backstop technology, disregarding environmental problems. As a potential number of natural gas power plants are actualized, and Norwegian greenhouse gas objectives endure, emission permit prices will increase and so will cost of gas power production. Therefore, even in a hydro-based power market, as for instance the Norwegian market, politicians discuss a green certificate market to stimulate green technologies to keep emissions from thermal power plants out of the market. Introduction of green certificates to obtain this is hardly efficient compared to application of other instruments, but this is not the subject of this article.

The Norwegian production capacity of hydropower, when precipitation and inflow is normal, is approximately 118 TWh a year (2001). Actual production in 2001 was 122 TWh due to heavy rainfall and abnormal precipitation. Based on detailed information about possible hydropower plant projects (see NWE 2000) and cost estimates for natural gas power plants we establish a long term marginal cost curve and estimate the supply elasticity in this market, see T_1 in figure (5). In our model this is calculated to 0.3 in a Cobb Douglas specification of the supply function, see Appendix 1. We calibrate the supply model to a normal precipitation year.

Demand of electricity in 2001 was somewhat higher than supply due to a cold year. Johnsen (2000) estimated the overall elasticity of demand for electricity in the Norwegian market to 0.1, see D in figure (5). Based on a macro economic model for the Norwegian economy, Bye et al. (1998) estimated an annual growth of demand by slightly more than 1 TWh a year taking into account that prices would increase from 15 to 20 øre/kWh[7] in a five years future. In the domestic market the equilibrium price at a future volume of 132 TWh then is estimated to approximately 20 øre/kWh, which equalizes approximately the total unit cost of a natural gas power plant when a greenhouse gas permit price is exempted.

The Norwegian Water and Energy Authority (NWE 2000) states that the cheapest green renewable technology for producing electricity in the Norwegian market is approximately 25 øre/kWh, remembering that large hydro power plants are not allowed under the green technology definition in most countries' green certificate plan, see Voogt et al. (2000). At this price per kWh the green technologies are too expensive to penetrate the market without any support. Although NWE (2000) operates with discrete projects we smooth the supply curve to fit with an elasticity of substitution of 0.3 and an intercept of 25 øre/kWh, see the left supply curve T_2 in figure (5).

Equilibrium in this market before the introduction of green certificates is then characterized by a purchaser price of 20 øre/kWh and a volume of 132 TWh, in our illustration year 2010 - i.e. the mid period of the targeted years in the Kyoto protocol, see point A in figure(5).

We introduce a consumer commitment of purchasing green certificates issued to green producers in this market and convey a model simulation of the new equilibrium when the green share (α) is set to 10 per cent. The new equilibrium seller's

[7] 20 øre/kWh equals approximately 3 US cent/kWh.

Figure 5: Equilibrium with and without a green share

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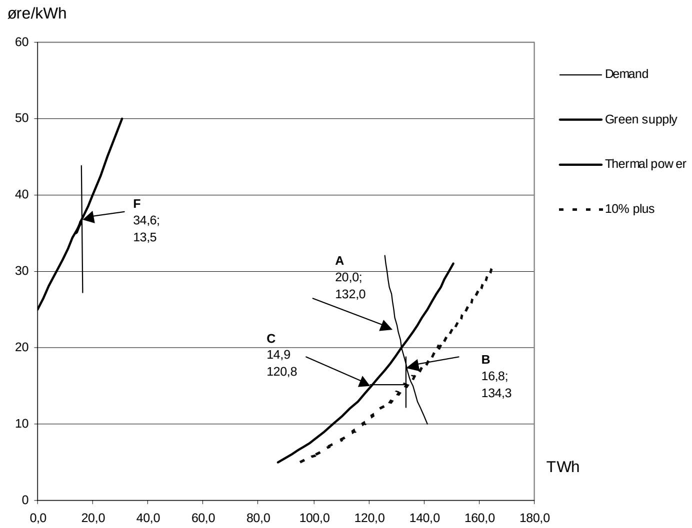
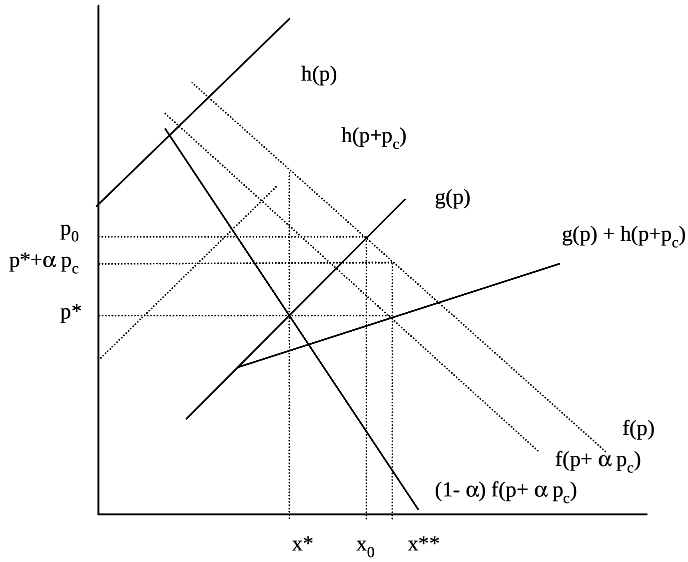


price for energy is reduced by 25 per cent to 14,9 øre/kWh and the volume of traditional energy is reduced by 8,5 per cent to 120,8 TWh, see point C in Figure.(5) The marginal cost of the green technology in the equilibrium point is 34,6 øre/kWh (see point F in Figure (5)), i.e. the certificate price is 10 per cent of the difference (34,5-14,9)*0.1=1.9. The total purchaser price, including the green certificate price, is 16,8 øre/kWh a reduction by 16 per cent and the total energy production is of 134,3 TWh, an increase by close to 2 per cent, see point B in Figure (5).

The purchaser price in the new equilibrium then is substantially lower than the equilibrium price in the calculation without the certificate commitment. The volume is consequently higher. Introducing a green certificate in this market, i.e. a "tax" on dirty producers and a "subsidy" to green producers, imply a transfer of producer surplus in the ordinary energy market to both a producer surplus for the green production and a consumer surplus. In this simulation the traditional producers bear the whole burden of the regulation while consumers harvest a net gain.

Before we introduce the green certificates producer surplus is measured as the triangle between the price line p_0, the equilibrium point $(x_0, p_0)$and the supply

Figure 6: Consumer and producer surplus



function $g(p)$ in figure (6). Consumer surplus is measured by the area between the price line p_0, the equilibrium point and the demand function $f(p)$. When introducing green certificate requirements the producer surplus in the ordinary energy market PS_T drops by

$$\Delta PS_T = p_0 x_0 - p^* x^* - \int_{p^*}^{p_0} g(p) \partial p \tag{21}$$

as the volume of traditional energy and the price of energy decreases. Consumer surplus CS increases by

$$\Delta CS = \int_{p_0}^{p^* + \alpha p_c} f(p) \partial p - p_0(x^{**} - x_0) + [p_0 - (p^* + \alpha p_c)]\, x_0. \tag{22}$$

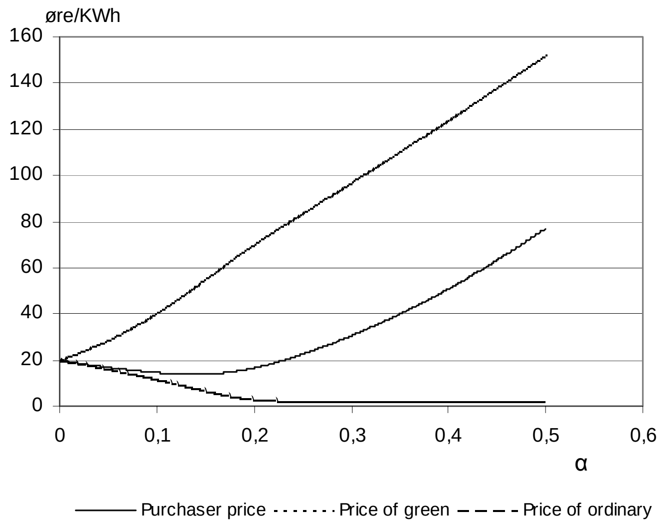
The production of green energy is

$$x_g = x^{**} - x^* \tag{23}$$

and producer surplus in the green production is the difference between total producer surplus and the surplus in traditional production

$$PS_G = p^* x^{**} - \int_0^{p^*} [g(p) + h(p + p_c)]\, \partial p - \int_0^{p^*} g(p) \partial p.$$

Figure 7: Prices as a function of increasing green shares



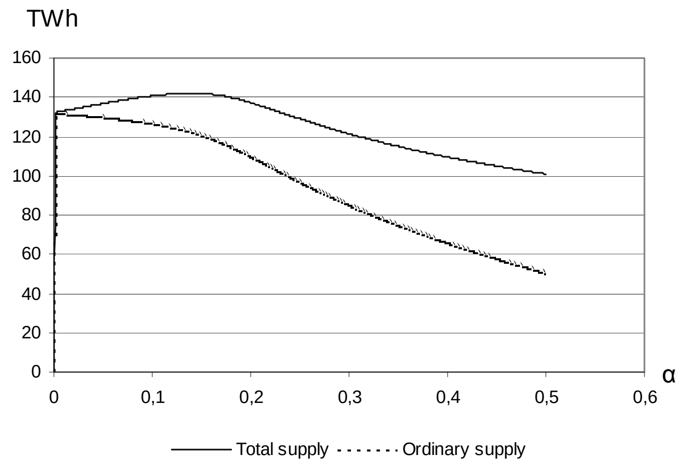
At a green share of 10 per cent the loss for ordinary producers is 5.9 billion Norwegian kroner (0.4 billion US$). The consumer surplus increases by 4.3 billion Norwegian kroner, as total volume increases and purchaser price drops. The green producers receives their profit from their production and the α share of the certificate price for the total energy volume. The producer surplus in the green energy reaches 0.6 billion Norwegian kroner. Thus, total welfare, defined as the producer and consumer surplus in the two markets, decreases by 1 billion Norwegian kroner a year. The environmental benefit should exceed this sum to make the policy decision of introducing green certificates welfare optimal.[8]

So far we have shown that the possible theoretical outcome with decreasing purchaser price and increasing volumes actually happens in this market when the green share obligation is set to 10 per cent. What happens when we vary the green share obligation?

In Figure (7) we have simulated the model for a whole range of green share obligations from zero to 60 per cent. As we increase the required amount of green energy, the price of ordinary energy drops and the price of green energy increases, both as expected. The purchaser price, i.e. the aggregate price of energy and

[8]Presumes that no other more cost efficient instrument is feasible.

Figure 8: Optimal production as a function of the green share



the certificate starts dropping and reaches a minimum at a commitment share of approximately 15 per cent. Then it starts rising and passes the initial equilibrium level at a share of 24 per cent and increases sharply as the relative importance of the costly green technology increases.

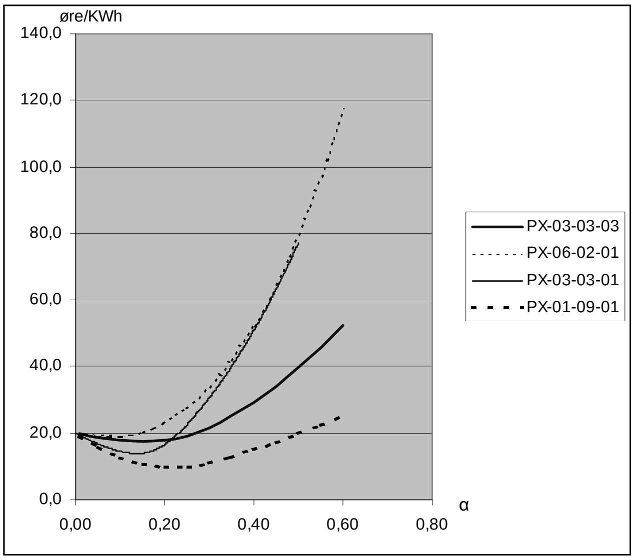
Figure (8) shows the consistent volume part that mirrors the price movements. Even though the ordinary supply drops all the way, total supply increases up to the minimum price level, then starts dropping fast, turn the earlier equilibrium level and continue to drop, although slower.

This certainly shows that when policy makers wish to speed up the introduction of green technologies by introducing green certificates the outcome may well be in conflict with other goals on limiting total energy use. The only way to obtain both goals may be to increase the required green energy share substantially.

The discussion of the total price effect in (7) showed that the relative elasticities (or the derivatives) of supply, h'/g',could be important for the findings. In table 1 we illustrate some alternative combinations of the relative supply elasticities and the demand elasticity.

Figure (9) shows that our results holds is general; In all alternatives the purchaser price decreases when the imposed green share increases up to a certain level. However, when the relative supply elasticity h'/g' (the green supply elasticity over the traditional supply elasticity) decreases purchaser prices hardly decrease when

Figure 9: Purchaser price effect under different elasticities



the certificate share rise ($PX - 06 - 02 - 01$). On the opposite, when the relative supply elasticity, h'/g' increases the purchaser prices decrease substantially when the green share rises ($PX - 01 - 09 - 01$). A high elasticity of demand diminish the tendency to lower purchaser prices as the green share rises.

Table 1: Alternative combinations of elasticities

Alternatives	Supply elasticity		Demand elasticity
	Traditional	Green	
$PX - 03 - 03 - 01$	0.3	0.3	-0.1
$PX - 06 - 02 - 01$	0.6	0.2	-0.1
$PX - 01 - 09 - 01$	0.1	0.9	-0.1
$PX - 03 - 03 - 03$	0.3	0.3	-0.3

Even if the elasticities of supply and demand are important for the simulations they do not seem to interfere with the general conclusion that in a perfect competitive market existing producers of energy have to endure a producer surplus loss if government wants to introduce a green certificate instrument into the market to foster renewable technologies. The consumers could enjoy this enforcement since their surplus increases with lowered prices and increased volumes.

5 Conclusions

Several governments in Europe point to green certificates as important instruments to solve greenhouse gas issues, help green immature technologies to enter the market, and reduce energy use etc. In this article we establish a market model for energy both produced by ordinary and green technologies, in which the profitability of the green technology is raised through a green certificate and a purchaser commitment instrument. Both the theoretical and applied calibrated model produce ambiguous results for the equilibrium purchaser prices and volumes of energy. The mechanism could be compared to the effects of a tax on ordinary energy demand combined with a subsidy on green energy supply. However, by the green certificate set up these two instruments are reduced to one, acting together with the governments decision concerning the share of green energy wanted in the market. The numerical model simulations indicates that the ambiguous results apply for small to even large shares of green energy commitments. When the green share increases above 25 per cent normal results, i.e. increasing prices and reduced volume, are obtained. These results may prevail both under autarky and free trade. Under free trade, the transmission capacity are exceeded now and then, and autarky results persist. Even under no restriction on transmission capacity ambiguity may arise. Since several European countries want to introduce green certificates, the total European supply is an increasing function of prices, which is a necessary condition for ambiguity in the model.

Even if the elasticities of supply and demand are important when discussing the theoretical results they do not seem to interfere with the general conclusion that in a perfect competitive market existing producers of energy have to endure a producer surplus loss if the government introduces a green certificate instrument to foster renewable technologies. The consumers benefit from this enforcement since their surplus increases with lowered prices and increased volumes.

The literature provides arguments in favour of support of immature renewable technologies because of a possible learning by doing effect that may raise the profitability of such technologies. However, it is not obvious how the certificate market will work as an appropriate supporting instrument in this respect, see Bye, Rosendahl and Greaker (2002).

6 Appendix A: A formal derivation of price effects

The first order derivative of equation (9)

$$-f + (1-\alpha)f' \cdot \left(\frac{\partial p}{\partial \alpha} + \alpha \frac{\partial p_c}{\partial \alpha} + p_c\right) = g' \cdot \left(\frac{\partial p}{\partial \alpha}\right) \quad , \tag{24}$$

having introduced

$$g' = \frac{\partial g}{\partial (p)} > 0 \quad . \tag{25}$$

A reformulation of (24) implies

$$\left[(1-\alpha)f' - g'\right] \frac{\partial p}{\partial \alpha} + (1-\alpha)\alpha f' \frac{\partial p_c}{\partial \alpha} = f - (1-\alpha)f' p_c. \tag{26}$$

The first order derivative of (10) is

$$f + f' \cdot \alpha \left(\frac{\partial p}{\partial \alpha} + \alpha \frac{\partial p_c}{\partial \alpha} + p_c\right) = h' \cdot \left(\frac{\partial p}{\partial \alpha} + \frac{\partial p_c}{\partial \alpha}\right) \quad , \tag{27}$$

having introduced

$$\begin{aligned} f &= f(p + \alpha p_c), & (28)\\ f' &= \frac{\partial f}{\partial (p + \alpha p_c)} < 0 \ , & (29)\\ h' &= \frac{\partial h}{\partial (p + p_c)} > 0 \ . & (30) \end{aligned}$$

A reformulation of (27) implies

$$(\alpha f' - h') \frac{\partial p}{\partial \alpha} + (\alpha^2 f' - h') \frac{\partial p_c}{\partial \alpha} = -f - \alpha f' p_c. \tag{31}$$

We apply Cramer's rule to solve for $\frac{\partial P}{\partial \alpha}$, $\frac{\partial P_c}{\partial \alpha}$, and $\frac{\partial P_x}{\partial \alpha}$. Equation (31) and (26)

reduces to

$$\begin{aligned} a_{11} \frac{\partial p}{\partial \alpha} + a_{12} \frac{\partial p_c}{\partial \alpha} &= b_1 \ , & (32)\\ a_{21} \frac{\partial p}{\partial \alpha} + a_{22} \frac{\partial p_c}{\partial \alpha} &= b2 \ . \end{aligned}$$

when we introduce the following relationships

$$\begin{aligned}
a_{11} &= \alpha f' - h' \ , \\
a_{12} &= \alpha^2 f' - h' \ , \\
a_{21} &= (1-\alpha) f' - g' \ , \\
a_{22} &= \alpha(1-\alpha) f' \ , \\
b_1 &= -f - \alpha f' p_c \ , \\
b_2 &= f - (1-\alpha) f' p_c \ .
\end{aligned} \tag{33}$$

Then the determinant

$$\begin{aligned}
|A| &= a_{11}a_{22} - a_{12}a_{21} \\
&= (\alpha f' - h')\alpha(1-\alpha) f' - (\alpha^2 f' - h')((1-\alpha) f' - g') \\
&= \alpha^2(1-\alpha) f'^2 - \alpha(1-\alpha) f' h' - \alpha^2(1-\alpha) f'^2 \\
&\quad + \alpha^2 f' g' + h'(1-\alpha) f' - h' g' \\
&= (1-\alpha)^2 f' h' + \alpha^2 f' g' - h' g' \\
|A| &< 0
\end{aligned} \tag{34}$$

is negative as all the terms are negative (remember that h' and g' are both positive (30 and 25) and f' is negative (29). The first cofactor

$$\begin{aligned}
|A_1| &= \begin{vmatrix} b_1 & a_{12} \\ b_2 & a_{22} \end{vmatrix} \\
&= (-f - \alpha f' p_c)\alpha(1-\alpha) f' - (\alpha^2 f' - h')(f - (1-\alpha) f' p_c) \qquad (35) \\
&= -\alpha(1-\alpha) f f' - \alpha^2(1-\alpha) f'^2 P_c - \alpha^2 f f' + \\
&\quad h' f + \alpha^2(1-\alpha) f'^2 p_c - (1-\alpha) f' p_c h' \\
&= -\alpha f f' + h' f - (1-\alpha) f' h' p_c > 0 \qquad (36)
\end{aligned}$$

is positive as all the terms are positive. Then

$$\frac{\partial p}{\partial \alpha} = \frac{A_1}{|A|} = \frac{-f'(\alpha f + (1-\alpha) h' p_c) + h' f}{f'((1-\alpha)^2 h' + \alpha^2 g') - h' g'} < 0 \tag{37}$$

The second cofactor is

$$\begin{aligned}
|A_2| &= \begin{vmatrix} a_{11} & b_1 \\ a_{21} & b_2 \end{vmatrix} \\
&= (\alpha f' - h')(f - (1-\alpha)f'p_c) - (-f - \alpha f'p_c)((1-\alpha)f' - g') \qquad (38) \\
&= \alpha f'f - fh' - \alpha(1-\alpha)f'^2 p_c + (1-\alpha)f'h'p_c \\
&\quad +(1-\alpha)ff' - fg' + \alpha(1-\alpha)f'^2 p_c - \alpha f'g'p_c \\
&= ff' - f(h' + g') + f'p_c((1-\alpha)h' - \alpha g')
\end{aligned}$$

Then

$$\frac{\partial P_c}{\partial \alpha} = \frac{A_2}{|A|} = \frac{ff' - f(h'+g') + f'p_c((1-\alpha)h' - \alpha g')}{f'((1-\alpha)^2 h' + \alpha^2 g') - h'g'} > 0 \tag{39}$$

The purchaser price is a weighted average of the change in the producer price, the change in the certificate price and the absolute value of the certificate price.

$$\frac{\partial p_x}{\partial \alpha} = \frac{\partial p}{\partial \alpha} + \alpha \frac{\partial p_c}{\partial \alpha} + p_c \tag{40}$$

Manipulating gives

$$\frac{\partial p_x}{\partial \alpha} = \frac{1}{|A|} \left[\begin{array}{c} (1-\alpha)fh' - \alpha fg' - (1-\alpha)^2 f'h'p_c - \\ \alpha^2 f'g'p_c + (1-\alpha)^2 f'h'p_c + \alpha^2 f'g'p_c - p_c h'g' \end{array}, \right] \tag{41}$$

which reduces to

$$\frac{\partial p_x}{\partial \alpha} = \frac{1}{|A|} \left\{ f((1-\alpha)h' - \alpha g') - h'g'p_c \right\} \tag{42}$$

7 Appendix B: The calibrated model applied in the paper

A Cobb Douglas specification of the demand function f

$$X^D = A^D (p + \alpha p_c)^{\varepsilon} \tag{43}$$

where A^D is the calibration and ε is the elasticity of demand. The supply function h for traditional energy

$$X^v = A^v(p)^{\kappa_v} \quad (44)$$

where A^v is the calibration factor and κ_v is the supply elasticity. The supply g for green energy

$$X^g = A^g(p_g)^{\kappa_g} - \xi_g \quad (45)$$

where A^g is the calibration factor and κ_g is the supply elasticity, ξ_g representing the intercept (for this energy carrier). This could alternatively be formulated as

$$X^g = A^g(p + p_c)^{\kappa_g} - \xi_g \quad (46)$$

Total supply now is

$$X^T = X^v + X^g = A^v(p)^{\kappa_v} + A^g(p + p_c)^{\kappa_g} - \xi_g \quad (47)$$

In equilibrium demand of energy should equal supply of energy

$$A^D \left[(1-\alpha)p + \alpha p_c\right]^{\varepsilon} = A^v(p)^{\kappa_v} + A^g(p + p_c)^{\kappa_g} - \xi_g \quad (48)$$

In equilibrium demand for green energy (plus certificates) should equal green supply, and demand for traditional energy should equal traditional supply

$$\alpha A^D \left[p + \alpha p_c\right]^{\varepsilon} = A^g(p + p_c)^{\kappa_g} - \xi_g \quad (49)$$

$$(1-\alpha) A^D \left[p + \alpha p_c\right]^{\varepsilon} = A^v(p)^{\kappa_v} \quad (50)$$

Table A.1 Four alternative parameters in the demand and supply functions

Alternative	Constant			Elasticities			Intercept
	A^v	A^g	A^D	κ_v	κ_g	ε	ξ_g
$PX-03-03-01$	53.75	50	178.1	0.3	0.3	-0.1	131.3
$PX-06-02-03$	21.9	69	178.1	0.6	0.2	-0.1	131.3
$PX-03-03-03$	97.8	7.2	178.1	0.1	0.9	-0.1	131.3
$PX-03-03-03$	53.75	50	324.3	0.3	0.3	-0.3	131.3

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