Co-existence of electricity, TEP and TGC markets in the Baltic Sea Region

The paper "Co-existence of electricity, TEP and TGC markets in the Baltic Sea Region" by Magnus Hindsberger, Malene Hein Nybroe, Hans F. Ravn and Rune Schmidt, Energy Policy 31 (2003) 85-95, analyses the application of two policy instruments, tradable emission permits (TEPs) and tradable green certificates (TGCs) to the electricity sector in an international context. The paper contains an explicit modelling at two levels of abstraction, one suitable for defining and analysing basic functionalities and one, the Balmorel model, suitable for numerical analysis in relation to countries in the Baltic Sea Region. Emphasis is on estimating implications in quantitative terms for countries in the Baltic Sea Region in 2010 when the TEP market in the analysis extends to four Nordic countries (Denmark, Finland, Norway, Sweden), and the TGC market extends to North European EU countries (Denmark, Finland, Sweden, Germany).

The following Appendix, describing the first of the above mentioned models, was part of the paper. However, in the printing a number of errors were introduced in the mathematics. The correct version follows below.

Appendix

The purpose of this appendix is to define a mathematical model of the problem of introduction of tradable emission permits (TEP) and tradable green certificates (TGC) markets in addition to the electricity market in an international context. Further a compact derivation is given of the prices in the markets, their relationship with the quotas and the international trade. Also expressions for producers' and consumers' surplus are derived along with relaxation and monotonicity properties.

Consider the following model:

$$\max[\sum_{c\in C} D^c(d^c) - \sum_{i\in I} f_i(g_i)] \tag{1}$$

$$\sum_{i\in I} g_i^c + \sum_{a\in C}(x^{(a,c)} - x^{(c,a)}) = d^c + o_1^c,\ c \in C \tag{2}$$

$$\sum_{c\in C_R}\sum_{i\in I_R} g_i^c \geq \sum_{c\in C_R} \alpha^c d^c + o_2 \tag{3}$$

$$\sum_{c\in C_M}\sum_{i\in I_M}\phi_i(g_i^c) \leq \sum_{c\in C_M}\overline{m}^c \tag{4}$$

$$0 \leq x^{(a,b)} \leq \overline{x}^{(a,b)},\ a\in C, b\in C \tag{5}$$

$$\Phi_i(g_i) \leq 0,\ i\in I \tag{6}$$

Here the individual production units are identified by the index i, and the index set I holds all units. Each unit in I is classified as either renewable or emitting, indicated by belonging to one of the index sets I_R and I_M, respectively, where I_R and I_M are mutually exclusive subsets of I, and together constitute I. The set C is the set of countries c. Two subset are defined on C viz., C_R holding the countries in the renewable bubble, C_M holding the countries in the emission bubble. C_R and C_M need not be mutually exclusive, nor together constitute C. The electricity production of unit i is denoted g_i; the notation g_i^c indicates that unit i is located in country c. A notation like $\sum_{i\in I} g_i^c$ is used to indicate the summation over those i that are located in c.

The function D^c describes for country c the consumers' benefit as a function of electricity consumption d^c. The cost of the production g_i on unit i is given by $f_i(g_i)$ and the associated emission by $\phi_i(g_i)$; $\phi_i(g_i) \geq 0$ for all units, and by definition $\phi_i(g_i) = 0$ for $i \in I_R$. Electricity export from country a to country b is indicated by $x^{(a,b)}$. Electricity consumption in country c is d^c.

The variables in the model (1) - (6) are production g_i^c, transmission $x^{(a,b)}$ and consumption d^c. The objective function in (1) describes the sum of producers' and consumers' surplus which is to be maximised. Eq. (2) describes the balance between supply and demand of electricity in country c. The parameters o_1^c and o_2 will be discussed below; they take the value zero. As seen, international transmission is permitted within the limits given in Eq. (5); transmission from a country to itself is not possible, i.e., $\overline{x}^{(c,c)} = 0$. Eq. (3) describes the requirement that a certain part of total consumption in the countries in C_R (derived from the quantities $\alpha^c d^c$ in the individual countries) must be covered by renewable electricity. Eq. (4) describes the limitation of total emission in the countries in C_M where $\overline{m}^c$ is the quantity in country c. Eq. (6) represents all other constraints on the individual production units.

Associate the Lagrange multipliers λ^c, ρ and μ to (2), (3) and (4), respectively, and define the Lagrangian as

$$\begin{aligned} L = \quad & \sum_{c\in C} D^c(d^c) - \sum_{i\in I} f_i(g_i) \\ & +(\sum_{c\in C}\lambda^c(\sum_{i\in I} g_i^c + \sum_{a\in C}(x^{(a,c)} - x^{(c,a)}) - d^c - o_1^c)) \end{aligned} \tag{7}$$

$$+(\rho(\sum_{c\in C}(\sum_{i\in I_R} g_i^c - \alpha^c d^c)) - o_2)$$
$$-(\mu \sum_{c\in C_M}(\sum_{i\in I_M} \phi_i(g_i^c) - \overline{m}^c))$$

For simplicity, Eqs. (5) and (6) have not been included in the definition of the Lagrangian; Eq. (5) will be discussed later.

Now assume that all the functions are once continuously differentiable, that a regularity condition holds and that the solution and the Lagrange multipliers are unique. Then the following interpretations may be given in relation to the optimal solution and Lagrange multipliers.

The value $\partial L/\partial o_1^c = \lambda^c$ is the marginal cost of electricity production in country c, i.e. the additional cost of producing one more unit of electricity. This value may further be taken as the spot price of electricity in that country. Observe that this marginal cost disregards the additional cost associated with the requirement given in (3) and that it can therefore not be interpreted as the marginal cost of satisfying increased consumption, see below.

The value $\partial L/\partial o_2 = \rho$ may be interpreted as the marginal cost of increasing the production of renewable electricity. This value may further be taken as the price of the TGC. Observe that this value is not the total marginal cost of the renewable energy production, but only that part which is in addition to the marginal cost given by λ^c for the country c considered.

The marginal cost associated with increasing production of renewable electricity by a small amount and at the same time increasing consumption in country c by the same amount is given as $\partial L/\partial o_1^c + \partial L/\partial o_2 = \lambda^c + \rho$.

The marginal cost of satisfying increased consumption in country c is given as $\partial L/\partial d^c = \lambda^c + \alpha^c \rho$. This may be taken as the consumers' combined electricity and TGC price, i.e. the consumers' marginal cost of acquiring electricity.

The marginal cost of increasing α^c is given as $\partial L/\partial \alpha^c = \rho d^c$.

The marginal cost of increasing emission is given as $\partial L/\partial \overline{m}^c = -\mu$. The marginal cost of reducing emission is then μ. This value may further be taken as the price of the TEP. Observe that this values is the same for all countries in C_M, in contrast to the results relative to renewable energy.

Now consider countries a and b that have a transmission line between them. Let λ^a and λ^b be the associated multipliers relative to (2). If transmission between the two countries is not actively constrained by (5), the optimality condition specifies that the values $\partial L/\partial x^{(a,b)} = \lambda^a - \lambda^b$ and

$\partial L/\partial x^{(b,a)} = \lambda^b - \lambda^a$ are zero, i.e. the spot prices are identical in the two countries. If on the other hand $\lambda^a < \lambda^b$, then country a has maximum export $\overline{x}^{(a,b)}$ to country b and if $\lambda^a > \lambda^b$ the transmission is $\overline{x}^{(b,a)}$, i.e. maximum in the other direction.

The international trade of electricity is given by the optimal values of $x^{(a,b)}$. Assuming that all emission requires a corresponding TEP, the need for TEP in country c is given as $\sum_{i\in I_M} \phi_i(g_i^c)$. It is assumed that the quantity of TEP issued in country c corresponds to $\overline{m}^c$. The net import of TEP to country c is therefore $(\sum_{i\in I_M} \phi_i(g_i^c) - \overline{m}^c)$. The need for TGC in country c is given as $\alpha^c d^c$; the net import of TGC to country c is therefore $(\sum_{i\in I_R} g_i^c - \alpha^c d^c)$.

For countries $c \in C_R$ the consumers' total cost of acquiring electricity is $(d^c(\lambda^c + \alpha^c\rho))$, and their surplus is $(D^c(d^c) - d^c(\lambda^c + \alpha^c\rho))$. For countries not in C_R the same expressions apply with $\alpha^c = 0$. Total consumers' surplus is found by summation over all indexes c.

Producer's surplus with production quantity g_i^c on unit i is $(\lambda^c g_i^c - f_i(g_i^c) + \rho g_i^c - \mu\phi_i(g_i^c))$. The penultimate term represents the income from sale of TGC (zero if $i \in I_M$). The last term represents the cost of acquiring TEP corresponding to the emission (zero if $i \in I_R$). If grand fathering is assumed such that the owner of unit $i \in I_M$ has a permit of $\overline{m}_i^c$ then this producer's surplus is $(\lambda^c g_i^c - f_i(g_i^c) + (\overline{m}_i^c - \phi_i(g_i^c))\mu)$. Total producers' surplus is found by summation over all indexes (c, i).

The following are basic properties of the model (1) - (6).

Eq. (4) may be seen as a combination (relaxation) of a number of equations $\sum_{i\in I_M} \phi_i(g_i^c) \leq \overline{m}^c$, one for each country in C_M. Hence, the model (1) - (6) may be seen as one of cooperation between the countries in C_M in contrast to the model where each country has individual limits $\overline{m}^c$. From properties of relaxation it follows that the total production cost (i.e., the optimal value of Eq. (1)) is not larger with cooperation as in (1) - (6) than with individual limits. Similar considerations apply to Eq. (3).

Now assume in addition to the above that all functions involved are convex, except D^c which is assumed concave. Then the following holds true: the value of λ^c increases weakly with increasing d^c; the value of ρ increases weakly with increasing α^c; the value of μ increases weakly with decreasing $\overline{m}^c$.

In relation to investments in new electricity production technology, the following clarification may be made. Let the capacity already existing at the beginning of the period be given by $\overline{g}_i$ for unit i, then this is included in (6) as $g_i \leq \overline{g}_i$. New capacity may be constructed at specified costs. Therefore one possible specification of the combined costs of production and investment is the following. Assume that production on a new unit i takes place at a constant marginal cost of β_i, and that new capacity may be constructed at a cost of γ_i. Then the cost function f_i for this unit is given as $(\beta_i g_i + \gamma_i g_i)$. With such or any other convex continuously differentiable form of f_i the above conclusions hold true.

Based on these observations the extension to a multi-year dynamic model, where new capacity may be invested at the beginning of each year, is straightforward.

Finally also observe that the extension to a situation where each year is subdivided into time segments to reflect diurnal and seasonal variations is straightforward, although tedious.

Also with such extensions the above conclusions hold true.

A description of the more detailed representation of the dynamic production, transmission and demand systems used in the numerical model calculations may be found in 'The Balmorel Model: Theoretical Background', see www.Balmorel.com.