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Returns to scale in the electricity supply sector, imperfect competition, and efficiency of climate change policies.

By
Truong P. Truong

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TITLE: **Returns to scale in the electricity supply sector, imperfect competition, and efficiency of climate change policies.**

ABSTRACT: Climate change policies often contain the dual objectives of trying to reduce the level of CO_2 emissions from the use of fossil-fuels while at the same time encouraging the use of renewable energy. In the area of electricity generation, these two objectives can be considered either as complementary or competing with each other. In this paper we show that this depends on the structure of the electricity market and the characteristics of the generation technologies. If the market is perfectly competitive with all technologies subject to constant returns to scale then climate change policies may require only one instrument to achieve the single objective of CO_2 emissions reductions. If on the other hand some fossil-fuel based electricity generation technologies are subject to increasing returns to scale which gives rise to some degree of natural monopolistic power in the electricity generation market then to correct for both the environmental externality which is caused by un-priced CO_2 emissions and the market imperfection caused by the existence of increasing returns to scale, policy makers may need two rather than just one policy objectives (and instruments). The first objective is to correct for the environmental externality and reduce CO_2 emissions while the second objective is to correct for the imperfection in the electricity market. Whether the secondary objective can help or hinder the first objective will depend on how it is designed. In this paper, we illustrate this analysis with an examination of the European Union 20-20-20 climate change policies

KEY WORDS: ***Climate change policy; emissions reduction; carbon tax; renewable electricity; increasing returns to scale; imperfect competition.***

AUTHORS: **Truong**

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CONTACT: INSTITUTE of TRANSPORT and LOGISTICS STUDIES (C13)
The Australian Key Centre in Transport and Logistics Management

The University of Sydney NSW 2006 Australia

Telephone: +612 9114 1824
Facsimile: +612 9114 1722
E-mail: business.itlsinfo@sydney.edu.au
Internet: http://sydney.edu.au/business/itls

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1. Introduction

Climate change policies often contain the dual objectives of trying to reduce the level of CO_2 emissions from the use of fossil-fuels while at the same time also trying to encourage the use of renewable energy sources especially in the area of electricity generation.[1] These two objectives can be considered either as complementary or competing with each other depending on circumstances. If the electricity generation market is perfectly competitive with all technologies being subject to constant returns to scale (CRTS) and the supply of non-fossil fuel based (especially renewable) electricity is highly price elastic then putting an emission price on fossil-fuel based electricity will be sufficient to encourage a substitution towards renewable electricity and therefore there will be a reduction in CO_2 emissions while the impacts on overall electricity price and demand will be minimal. If, however, the electricity generation market is characterized by the existence of increasing returns to scale (IRTS) especially in some fossil fuel based electricity generation technologies which give rise to some degree of natural monopolistic power resulting in imperfectly competitive behavior in the electricity generation market, then in this case, putting a price on CO_2 emissions may simply push up electricity supply price and reduce demand but will do little to encourage a substitution towards renewable electricity. The result is ineffectiveness or inefficiency for climate change policy because the achievement of the primary climate change policy (emissions reductions target) will be achieved but only with greater losses to electricity consumers and the economy. To improve on this efficiency, climate change policy may need to be supplemented with a secondary *energy* policy, such as the targeting of renewable energy (or electricity) share. This secondary policy will seek to correct for the imperfection in the electricity generation market, reducing overall electricity generation costs but also taking into account the objectives of the primary climate change policy. In this paper we illustrate this analysis with an examination of the European Union 20-20-20 climate change policies.

The plan of the paper is as follows. Section 2 presents a theoretical analysis of the supply characteristics in the electricity generation sector. Section 3 considers the theoretical impacts of the imposition of a carbon tax or emissions trading scheme on this sector. Section 4 considers the issues of effectiveness and efficiency of climate change policies under different market conditions. Section 5 applies the theoretical analysis to an examination of the European Union climate change policies. Section 6 concludes the paper.

2. Theoretical analysis of the electricity supply sector

2.1 Constant returns to scale (CRTS) technology

Consider an electricity generation technology which can be described as in Figure 1. Here the technology is assumed to exhibit constant returns to scale (CRTS) which means both the short-run and long run marginal costs are unchanged with production level. Short run marginal cost (SRMC) often consists of fuel, material, labour and other running costs. Long run marginal cost will consist of SRMC plus a component which stands for incremental capital (or capacity) cost. If both of these components are constant with respect to the level of production (and capacity), then the technology can be said to exhibit CRTS. In this case, given any short run capacity level (such as Q_E in Figure 1) the short-run average total cost (ATC) will be a decreasing function of production level up to capacity. However, since capacity can be optimized with respect to long run demand level (assume to be D_{LR} in Figure 1), the level of ATC will be such that when production is close to capacity ATC will reach a minimum level and this is also equal to the LRMC. Of course in the short run, demand may fluctuate around the long-run level. When it is higher than D_{LR} (such as D_2 in Figure 1) then to

[1] A third objective is also often pursued and that is the improvement in energy efficiency. This third objective however is more in line with the general economic objective of improving on economic productivity and hence can be examined separately from the other components of the climate change policy.

balance supply (capacity) with short-run demand, price may have to rise above the LRMC. Conversely, if short run demand is lower than long run demand (D_1 in Figure 1), then to ensure capacity is fully utilized, price may have to drop below LRMC (even if this means the supplier is making some a loss in the short run, but this is to ensure social welfare is maximised). So long as demand returns to D_{LR} in the long run, however, long run supply price will always be equal to the level of LRMC. Electricity supply curve in the *long-run* therefore can be regarded as given by a horizontal line at the level of the LRMC. With different technologies which may have different LRMCs, the long run supply curve may consist of s series of step functions rather than a horizontal line. Furthermore, with increasing competition for scarce resources when production level is increased, rising resource prices[2] may push up the levels of LRMCs and hence in practice, the long run supply curve for electricity generation with CRTS technologies will be a series of slightly upward sloping step functions which can be approximated by a smooth upward sloping curve (as shown in Figure 2).

2.2 Increasing returns to scale (IRTS) technology

Now consider the case when returns to scale cannot be assumed to be constant. This may be the case when capital (capacity) is not continuously variable but can only be changed by large ('lumpy') amounts. In this case capacity will not always be matched with long run demand and the ATC will not always be able to reach its optimum (LRMC) level. The 'long run' ATC therefore cannot be described as the horizontal line at the LRMC level but in fact will be identical to the short run ATC where capacity is fixed at a particular 'long run' level. With the ATC decreasing with production level, this implies there is increasing returns to *scale of production*[3] and this has important implications for the producer's pricing behaviour as will be explained in the following sections.

2.3 Strategic interactions between CRTS and IRTS technologies

A producer with IRTS can be said to possess some degree of 'natural monopolistic power' (Baumol, 1977) because IRTS implies a cost advantage for an incumbent producer which it can use to deter entry by any potential entrant who may use the same technology. However, in a market with both IRTS and CRTS technologies, monopolistic power by the IRTS producer(s) is not absolute, but only relative and depending on the extent of imperfect competition between IRTS and CRTS producers.

In Figure 3, we compare the supply behaviour of IRTS and CRTS producers within the same electricity market. Given an aggregate demand curve for electricity (described by the line *D* in Figure 3(c)), if we take away the aggregate supply of all CRTS technologies (described by an upward sloping curve as shown in Figure 3(b)) then we are left with a 'residual' demand for all IRTS technologies.[4] Based on this residual demand curve, individual IRTS suppliers can then compete for market share and assuming that each supplier acts as a Cournot competitor within this residual market (i.e. by deciding on production level rather than on price level which it cannot affect completely and directly) the equilibrium outcome of this Cournot competition will determine the supply price for the IRTS producers and therefore also for the CRTS producers. For Cournot competition, it is well known that the equilibrium outcome will be somewhere between the absolute monopolistic position (point *M* in Figure 3(a)) and the 'perfectly competitive' position where each producer can earn only zero pure profit (point *A* in Figure 3(a)). Assume that this equilibrium outcome is given by point *I* in Figure 3(a) ('*I*' can stand for *I*mperfectly competitive outcome). Given this equilibrium position for the 'residual' IRTS market, the outcome for the rest of the CRTS market will be determined based on the price elasticity of demand (in the aggregate electricity market) and the price elasticities of supply (of the CRTS technologies). This can be explained as follows.

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[2] Or the use of inferior resources, for example, with wind technologies, poorer quality locations may need to be used with increased production level.

[3] Even though not to *scale of capacity* because the capacity is here fixed.

[4] There may be more than one IRTS technologies, for example, coal-based as well as hydro and nuclear power electricity technologies.

Let q_i be the output of an individual supplier i in the IRTS market, q_c be the output of an individual supplier c in the CRTS market, and Q is the total level of electricity demand in the total market. We have:

$$Q = \sum_i q_i + \sum_c q_c = Q_I + Q_C \tag{1}$$

Let $S_i = (q_i/Q_I)$ be the relative market share of supplier i in the IRTS market and assuming that this market share is initially independent[5] of the strategic decisions of the IRTS suppliers. This means the aggregate price-elasticity of *demand* for total IRTS electricity output (e_I^D) must be related to the individual price elasticity of demand for each IRTS electricity output (e_i^D):

$$\begin{aligned} e_I^D &= -(P_I / Q_I)(\partial Q_I / \partial P_I) \\ &= -(P_I / Q_I) \sum_{i \in IRTS} (\partial q_i / \partial P_I) \\ &= -\sum_{i \in IRTS} S_i (P_I / q_i)(\partial q_i / \partial P_I) \\ &= \sum_{i \in IRTS} S_i e_i^D \end{aligned} \tag{2}$$

Similarly, let $S_c = (q_c/Q_C)$ be the relative market share of supplier c in the CRTS market and assuming that this market share is initially independent of the strategic decisions of the IRTS suppliers, then the aggregate price-elasticity of *supply* for total CRTS electricity output (e_C^S) must be related simply to the individual price elasticity of supply of each CRTS output (e_c^S):

$$\begin{aligned} e_C^S &= (P_C / Q_C)(\partial Q_C / \partial P_C) \\ &= (P_C / Q_C) \sum_{c \in CRTS} (\partial q_c / \partial P_C) \\ &= \sum_{c \in CRTS} S_c (P_C / q_c)(\partial q_c / \partial P_C) \\ &= \sum_{c \in CRTS} S_c e_c^S \end{aligned} \tag{3}$$

Since electricity can be assumed to be a homogeneous commodity in demand (even though heterogeneous in supply due to differences in supply technologies) the price-elasticity of *demand* for all IRTS electricity outputs can be assumed to be the same and therefore it is also equal to the aggregate price elasticity of demand for all IRTS electricity output (i.e. $e_i^D = e_I^D$ for all i's). [6] From equation (1), we can also derive a relationship between the aggregate price elasticity of demand for all IRTS electricity and aggregate price elasticity of supply for all CRTS electricity (if we assume that the percentage changes in price in all markets are the same,[7] i.e. $\partial P / P = \partial P_I / P_I = \partial P_C / P_C$):

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[5] Initially, market shares are unaffected (or negligibly affected) by the oligopolist's decision even though the absolute quantities and prices can be. This assumption, however, applies only to 'short run' analysis when price and quantity changes can be regarded as relatively 'small'. In the long run, short run changes can be used to 'update' the market shares, hence the shares in the long run do not have to be assumed as constant or unaffected by the oligopolist decisions.

[6] Individual price elasticity of *supply* for CRTS electricity, however, is different for different CRTS technologies, therefore in general we will have ($e_c^S \neq e_C^S$).

[7] In all the graphs, we show the equilibrium prices in all market to be at the same level. This is because electricity is a homogeneous commodity; hence its resultant supply price must be the same. However, in practice, differences in qualities of supply and transmission costs) may result in differences in the *levels*, but to maintain the assumption of homogeneity in the nature of the product supplied, we assume that *percentage* changes in its price (due to equilibrium adjustment in the market following changes to production cost) must be similar for all technologies.

$$\begin{aligned} e^D &= -(P/Q)(\partial Q/\partial P) \\ &= -[(Q_I/Q)(P/Q_I)(\partial Q_I/\partial P)] - [(Q_C/Q)(P/Q_C)(\partial Q_C/\partial P)] \\ &= S_I e_I^D - S_C e_C^S \end{aligned} \tag{4}$$

Here e^D is the aggregate price-elasticity of demand for electricity in the total electricity market and $S_I = (Q_I/Q)$, $S_C = (Q_C/Q)$ are the aggregate shares of IRTS and CRTS electricity supply in the total market respectively.

Given the relative market shares and price-elasticities of demand and supply for all technologies, we can now derive the equilibrium position for the IRTS electricity supplier. First, define the (short run) [8] profit function for this supplier as:

$$\pi_i = [Pq_i - m_i q_i - F_i] \tag{5}$$

where q_i is the output level of supplier i, m_i is the SRMC of supplier i (assumed to be constant with respect to output but can be influenced by factors such as taxes and per unit transmission costs specific to each supplier), F_i is the level of fixed cost. Maximising this profit function with respect to q_i will give the following first order condition for each supplier i:

$$P_I = m_i / [1 - (S_i / e_i^D)]; \quad \text{for all } i\text{'s} \tag{6}$$

Substituting the values of (equilibrium) elasticities as determined from equations (2)-(4) into (6) and assuming that $e_i^D = e_I^D$ for all IRTS suppliers, we have:

$$P_I = m_i / [1 - (S_i / \{(1/S_I)e^D + (S_C/S_I)e_C^S\})] \tag{7}$$

Equation (7) can be used to forecast the changes to the equilibrium price level P_I in the IRTS electricity market following a ‘shock’ to the value of SRMC (m_i) which may be caused, for example, by the imposition of a carbon tax. This change to the equilibrium price can be affected by several factors: firstly the changes to the level of short run marginal cost in the IRTS market (m_i) due to the imposition of the carbon tax itself; secondly the relative shares of different technologies (S_i, S_I, S_C); thirdly, the aggregate price-elasticity of demand for the electricity market as a whole (e^D); and finally, the aggregate price-elasticity of supply of CRTS electricity (e_C^S). Given any changes in the quantity and price level in the IRTS market, the changes in price and quantity level in the CRTS market as well as in the aggregate supply market can then be inferred, using the overall quantity restriction (1) and relationship between aggregate price elasticities as described by equation (4).

[8] In the short run, capital (capacity) is assumed to be fixed, hence we distinguish between short run marginal (running) cost (SRMC) and average fixed (i.e. capital or capacity) cost (AFC). The sum of these two terms make up the average total cost (ATC).

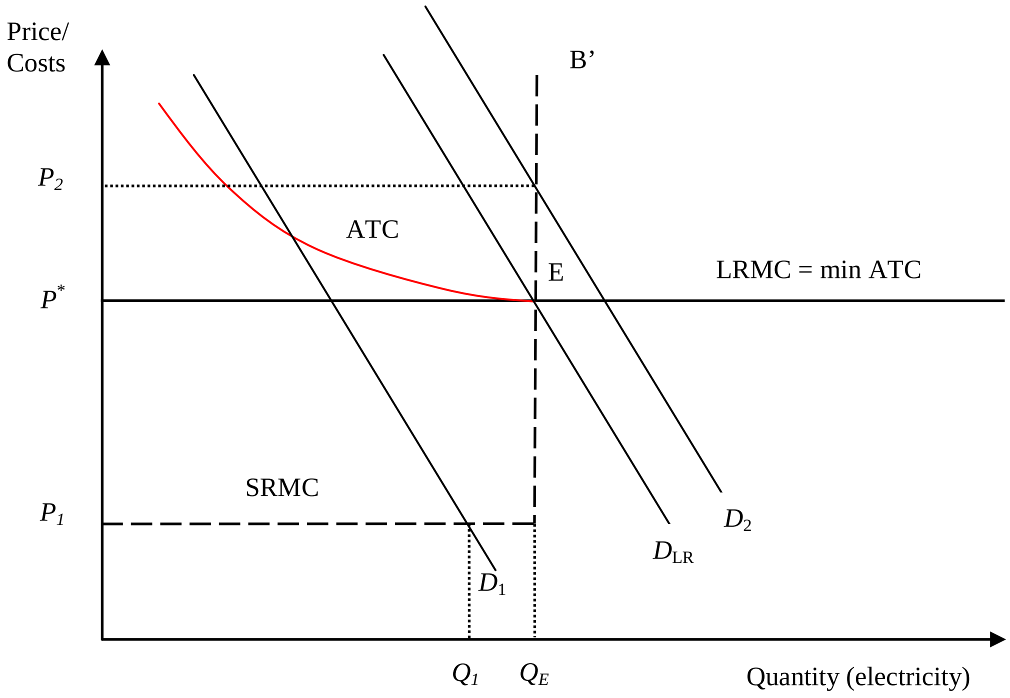

Figure 1: Cost curves for a technology with constant returns to scale in the long-run when capital is infinitely divisible (i.e. continuously variable).

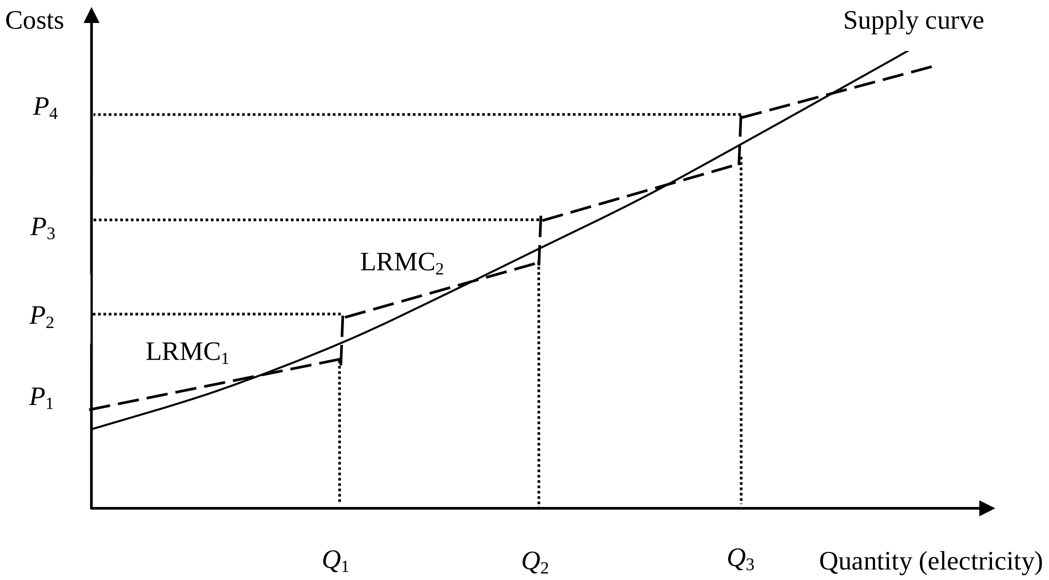

Figure 2: Agregate long run supply curve for all technologies with constant returns to scale and with continuously variable capital level.

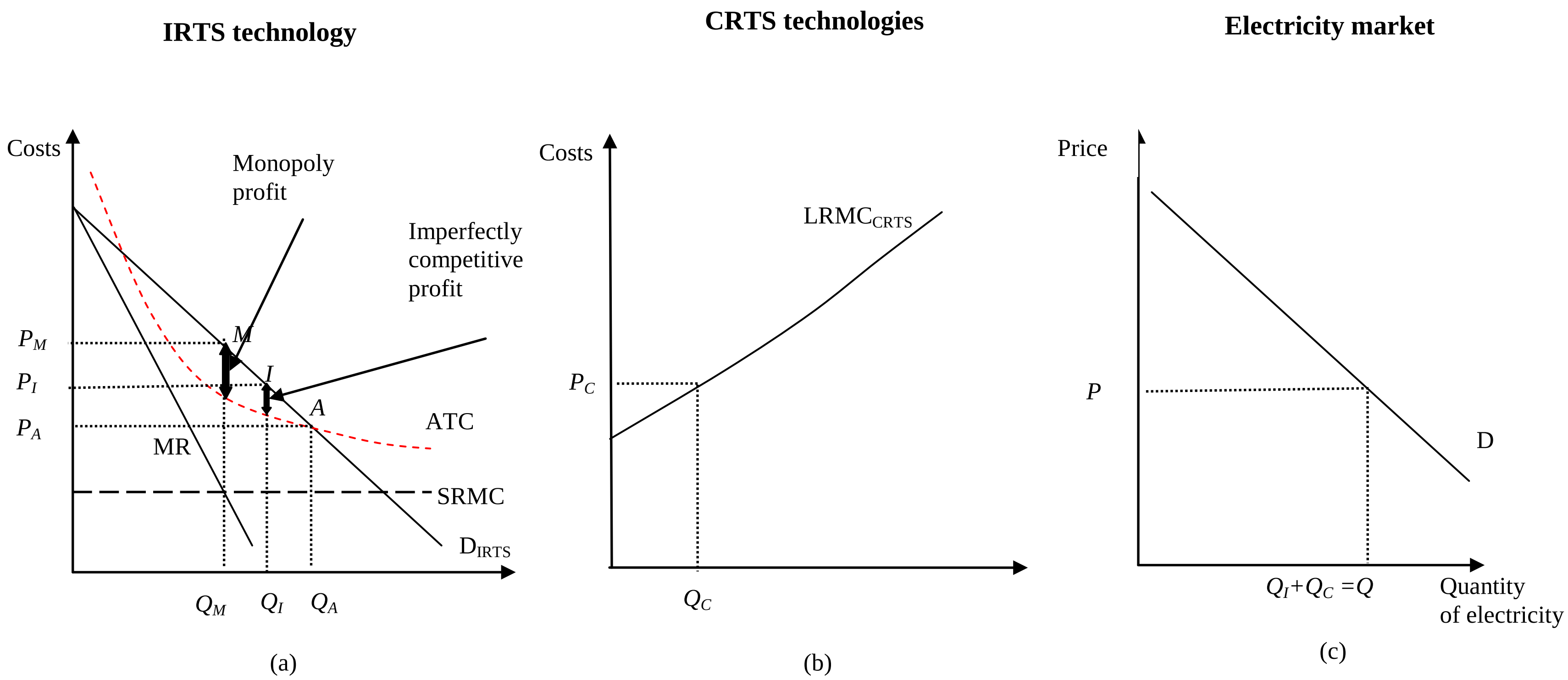

Figure 3: Strategic behaviour in the supply of electricity between (a) firms with IRTS technologies, (b) firms with CRTS technologies, in (c) the aggregate electricity supply market (graphs are not to scale).

3. Impacts of climate change policies in the electricity generation market

Consider now the impacts of the imposition of a carbon tax or an emissions trading scheme[9] in the electricity generation market. Assuming that at least one of the IRTS technologies (such as coal-based electricity) is affected by the carbon tax.[10] Following the imposition of a carbon tax in electricity market, the SRMC and hence also the ATC of the coal-based technology will shift upwards as shown in Figure 4(a) while assuming that the LRMCs of the CRTS technologies will remain unchanged.[11] Depending on the shape and position of the ATC curve of the IRTS technology relative to its strategic demand curve, this shift in the ATC curve can produce two possible outcomes. If the initial position of the ATC curve is relatively high and close to the strategic demand curve (for example, when aggregate demand in the IRTS electricity is low and/or the share of coal-based IRTS electricity in this market is small) and also if the slope of the strategic demand curve is relatively 'flat' (due to the high price elasticity of *supply* of renewable electricity – see equation (5)), then a small upward shift in the ATC curve may bring it close to touching the strategic demand curve, or even lying above it. This means the three points *M, I, A* will merge to a single point (*I'* in Figure 4(a)) or even disappear altogether.[12] The reduction in coal-based electricity production in this case is quite significant and so is the increase in renewable electricity production (Figure 4(b)). The total impact on aggregate electricity price and quantity is small (Figure 4(c)).[13] Climate change policy in this case therefore can be said to be most effective with large reduction in CO_2 emission being associated with small changes in overall electricity supply price. This can be referred to as the 'best case scenario' for climate change policy.

In contrast, if we now consider an opposite situation where the supply of renewable electricity is price inelastic which makes the residual demand for coal-based electricity also price inelastic. Any upward shift of the ATC curve in this case will result in a large increase in the supply price of electricity but only with a small reduction in the level of coal-based electricity production. The increase in renewable electricity supply is also small and the overall impact on aggregate electricity price is large and this can result in large welfare losses to the consumers. The effectiveness of climate change policy in this case is therefore much reduced and this situation can be referred to as 'the worst case scenario' for climate change policy (Figure 5).

We can now compare the above two scenarios with the case of 'conventional' analysis where *all* electricity generation technologies are assumed to be subject to CRTS and the supply market for

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[9] From an efficiency point of view, a carbon tax (CT) is not different from an emission trading scheme (ETS). However, from a practical and distributional viewpoint, they can be different depending on how the revenue from the CT or revenue from the auctioning of the emissions permits in an ETS is recycled. Here we are not considering these issues hence we will treat the CT or an ETS as though equivalent.

[10] Other IRTS technologies can be non-fossil fuel based, such as nuclear or hydro electricity and these are not directly affected by the carbon tax.

[11] For simplicity of exposition, we assume that all renewable electricity technologies are of the CRTS type. In practice, some fossil-fuel based technologies can also be subject to CRTS. In this latter case, the aggregate supply curve of CRTS technologies will also shift upwards following the imposition of a carbon tax. This minor detail will not affect the basic arguments of our analysis which focus mainly on IRTS technologies.

[12] This means the plant will become uneconomic and has to shut down. This, however, applies only to the marginal plants while the intra-marginal plants can still continue to operate due to the existence of some degree of cost buffer (i.e. their ATC curves may still remain below the strategic demand curve).

[13] Note that for convenience of illustration, in Figure 5 (and subsequent Figures) we show the level of supply prices P_I, P_C, and P as though they are on the same absolute level. However, in practice, because of differences in qualities of supply and transmission costs, these price levels can differ in absolute terms, even though in percentage change terms, they can be assumed (as in equation (5)) to be similar, i.e. $\partial P / P = \partial P_I / P_I = \partial P_C / P_C$.

electricity is assumed to be perfectly competitive (see Figure 6). In this case, following the imposition of a carbon tax which shifts both the SRMC and LRMC curves for coal-based electricity upward as seen in Figure 6(a), the effect of this shift will be a cut back in the production of coal-based electricity. This is then compensated for by an increase in the supply of renewable electricity (if the price elasticity of supply of renewable electricity is large) hence the net result will be just a small reduction in total electricity supply and a small increase in overall electricity price.[14] This 'conventional' scenario produces an outcome which is closer to the IRTS 'best case' scenario.

4. Effectiveness of climate change policies

From a theoretical viewpoint, emissions trading scheme or carbon tax is the most efficient (or cost effective) instrument to be used for achieving any given level of CO_2 emissions reduction. From the analysis given in the previous section, it can be seen that this conclusion depends on the particular characteristics of the production technologies and also the structure of the electricity market. If the market is perfectly competitive with all suppliers behaving as price takers with constant returns to scale (CRTS) technologies and highly price elastic supply curves, then this conclusion certainly holds true. If, however, a dominant coal-based electricity supplier is using an IRTS technology which allows it to possess some degree of 'natural monopolistic' power in the market, then imperfect competition in this market may produce results which are quite different from those predicted by perfectly competitive analysis. To correct for the distortions created by imperfect competition, climate change policy may need two rather than one policy components: one (emissions reduction target) to correct for the environmental externality, but the second (renewable energy or electricity share target) is to correct for market imperfection in the electricity market. This imperfection prevents optimal technology substitution in the electricity sector which implies the overall costs of electricity production (including emission abatement costs) may not be minimised and therefore the efficiency of the first component of the climate change policy may not be maximised.

To explain this, we re-examine the IRTS 'worst case scenario' as described in the previous section (see Figure 5) but now with the use of a secondary energy policy to improve on the effectiveness of the primary climate policy. In Figure 7(a) we assume that with the full[15] application of the primary policy instrument (carbon tax), the primary target of CO_2 emissions reduction is still not achieved (due to the existence of imperfect competition), i.e. production of coal-based electricity is reduced from Q_I to Q'_I rather than Q^t_I as required. To try to reduce production further to Q^t_I will require a even larger carbon tax which will produce a risk of increasing the electricity price still further from P'_I to P''_I which is quite high resulting in substantial welfare losses to the consumers equal to the area of the triangle $E'E''E^*$ as shown in Figure 7(c).

To avoid this situation from happening, the government can use a secondary policy aiming at increasing the supply of renewable electricity, from Q'_C to Q^t_C, but without the risk of electricity price rising above the level P'. The policy can consist of simply stipulating a mandatory renewable electricity share equal to $[Q^t_C/(Q^t_I + Q^t_C)]$. To achieve this share, renewable electricity production must increase but without a price increase, this can only mean a *shift* of the supply curve rightwards from position N' to N^*, and this can only occur if there is a subsidy to the production of renewable electricity. The rightward shift in the supply curve of renewable electricity will imply a leftward shift in the 'residual' demand curve for IRTS electricity from I' to I^*. In subsidising the production of renewable electricity, a deadweight loss equal to the area $N'N^*N^{**}$ will be incurred but this can be compensated for by the savings in emissions abatement cost (or carbon tax payment by IRTS suppliers) equal to the area *GHKL*. So long as the area *GHKL* is at least as great as the area $N'N^*N^{**}$ then the renewable electricity share targeting policy can be regarded as efficient. For this efficiency to be achieved, the following condition must be satisfied (see Appendix for more details):

[14] This depends on price elasticities of supply of all technologies but also on the aggregate price elasticity of demand for electricity.

[15] By this we mean the maximum value of the carbon tax needed to achieve the emissions reduction target if in fact the electricity supply market is characterised by CRTS and perfect competition.

$$[P_C(Q^t{}_C) - P_C(Q^{'}{}_C)] = T(Q_I^{'}) \quad (8)$$

P_C(.) represents the supply curve for renewable electricity, therefore the terms in the bracket on the left hand side of equation (8) represents the amount of 'subsidy' to be provided to renewable electricity production. The function *T*(.) on the right hand side of equation (8) stands for the marginal abatement cost (or carbon tax payment) function for the IRTS coal-based electricity producer, therefore equation (8) says that efficiency is maximised if the 'subsidy' to renewable electricity production is equal to the (savings in) abatement cost (or carbon tax payment) at the margin. Under the 'perfectly competitive' market assumption and with an efficient emission trading scheme condition (8) can be achieved automatically without government intervention because producers being price takers will try to minimise production cost to maximise profit. Cost minimisation in this situation requires that a producer of electricity will take into account the emission cost if a unit of coal-based electricity is produced, but also the savings or reduction in production cost if a unit of renewable electricity is produced instead. Therefore, condition (8) will automatically be applied. to the electricity sector if total electricity production cost is minimised. Condition (8) may be achieved in practice either by cross-subsidising between coal-based an renewable electricity production if a producer uses both of these technologies, or it can come about from emissions trading between coal-based and renewable electricity producers. There is thus no need for government intervention provided the market works perfectly with producers being price takers as described. The only obstacle to this perfect market condition is the fact that producers of coal-based electricity may not behave as perfectly competitive price takers because of the existence of IRTS in their production, hence it may be in their interests of some (IRTS) producers to let the price rise above the 'efficient' level to maximise their own profit rather than be concerned with minimum production costs for the industry.as a whole. Condition (8) therefore may not be achieved. To restore this efficiency condition, government may want to provide an actual subsidy to renewable electricity to help its production level towards the most efficient level. However, government may also want to impose a *mandatory* renewable electricity share target without providing any subsidy. This will force the producers to achieve the optimum condition (8) and bear the *nomimal* costs of this policy. The *real* costs (and distribution of the benefits) however depends on the ultimate rise in electricity price, which in turn depends on the relativity of the price elasticities of supply and demand for electricity faced by different producers. In other words, the *efficiency* of the mandatory renewable electricity targeting policy is not dependent on the distribution of the benefits and costs of such a policy (which depends on whether an actual government subsidy is provided or not or whether the revenue of the carbon tax or an emission trading scheme[16] is recycled back into the industry), but only on the magnitude of the targets and for these targets to be 'optimal' (i.e. most efficient), they must follow from condition (8).

[16] In the case when emissions permits in such a scheme are auctioned rather than by 'grand-fathering' i.e. distributed freely.

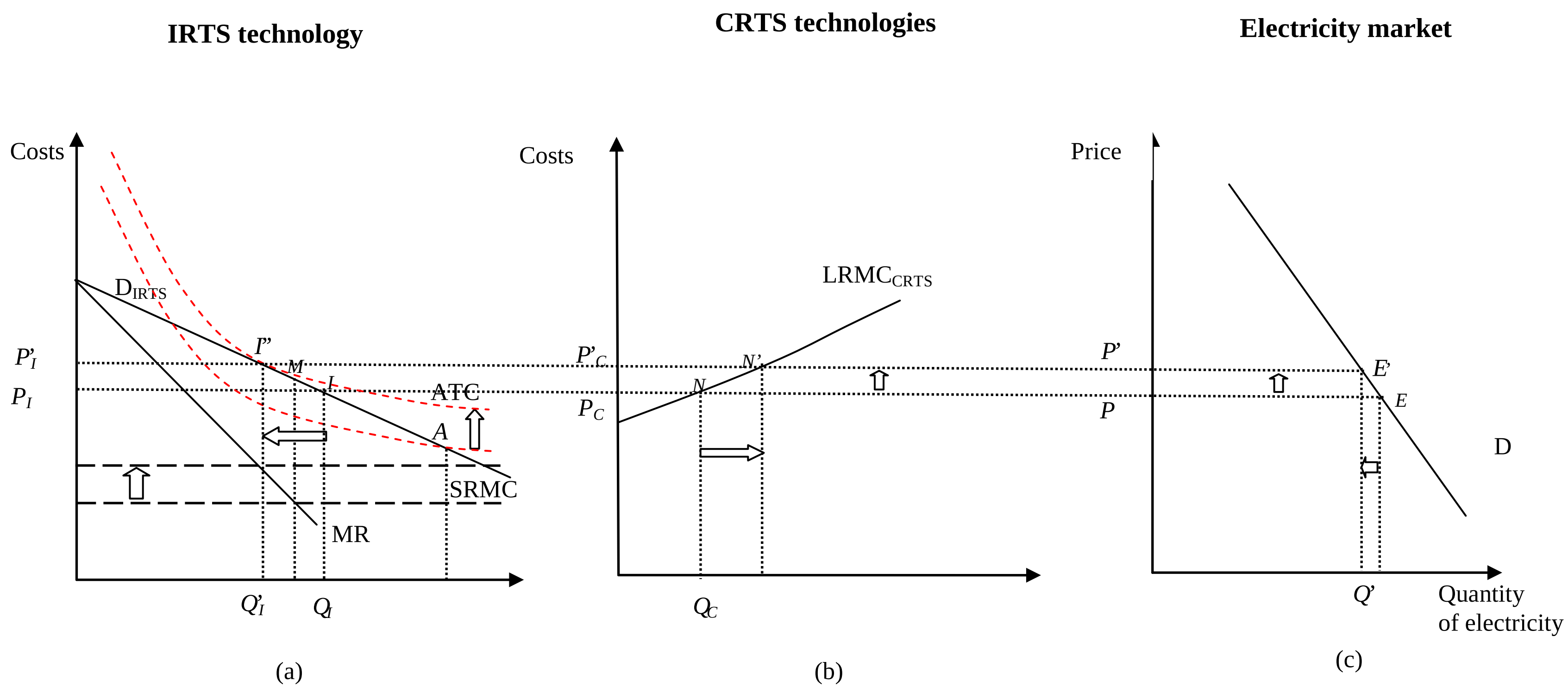

Figure 4: Best case scenario: impacts of the imposition of a carbon tax in the electricity market when the share of IRTS technologies is small and the supply of CRTS electricity is price elastic (graphs are not to scale).

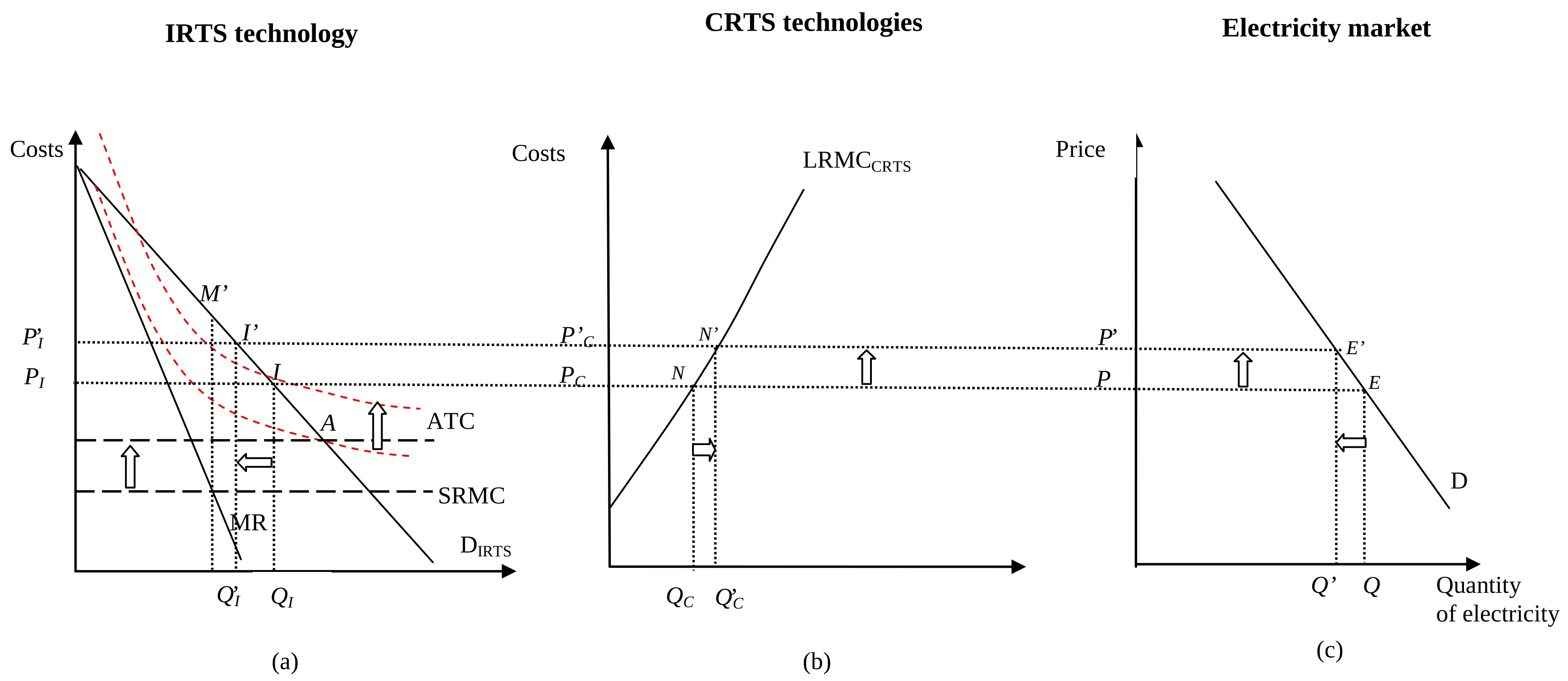

Figure 5: Worst case scenario: impacts of the imposition of a carbon tax in the electricity market when the share of IRTS technologies is large and the supply of CRTS electricity is price inelastic (graphs are not to scale).

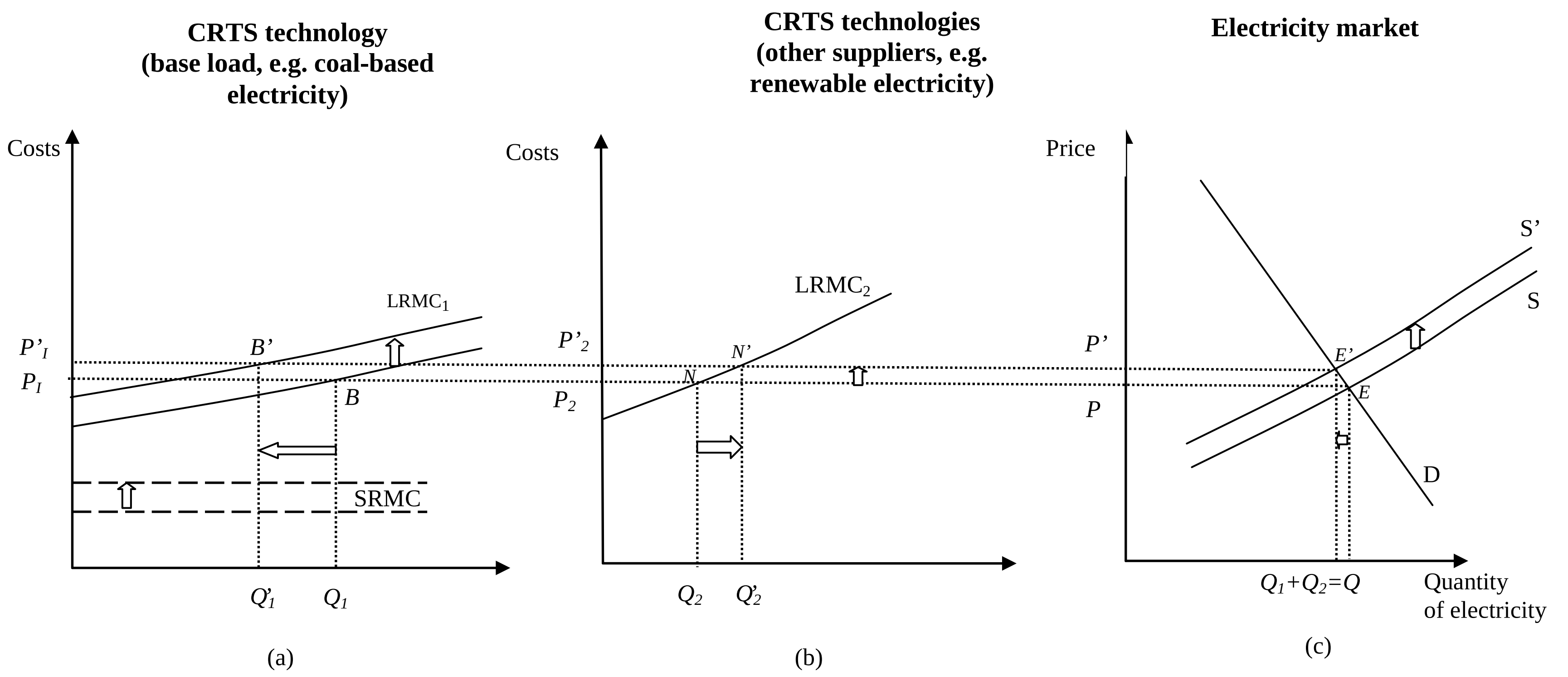

Figure 6: Conventional analysis of the impacts of the imposition of a carbon tax in the electricity market when all technologies are assumed to exhibit CRTS with price elastic supply and all suppliers are price takers in a perfectly competitive market (graphs are not to scale).

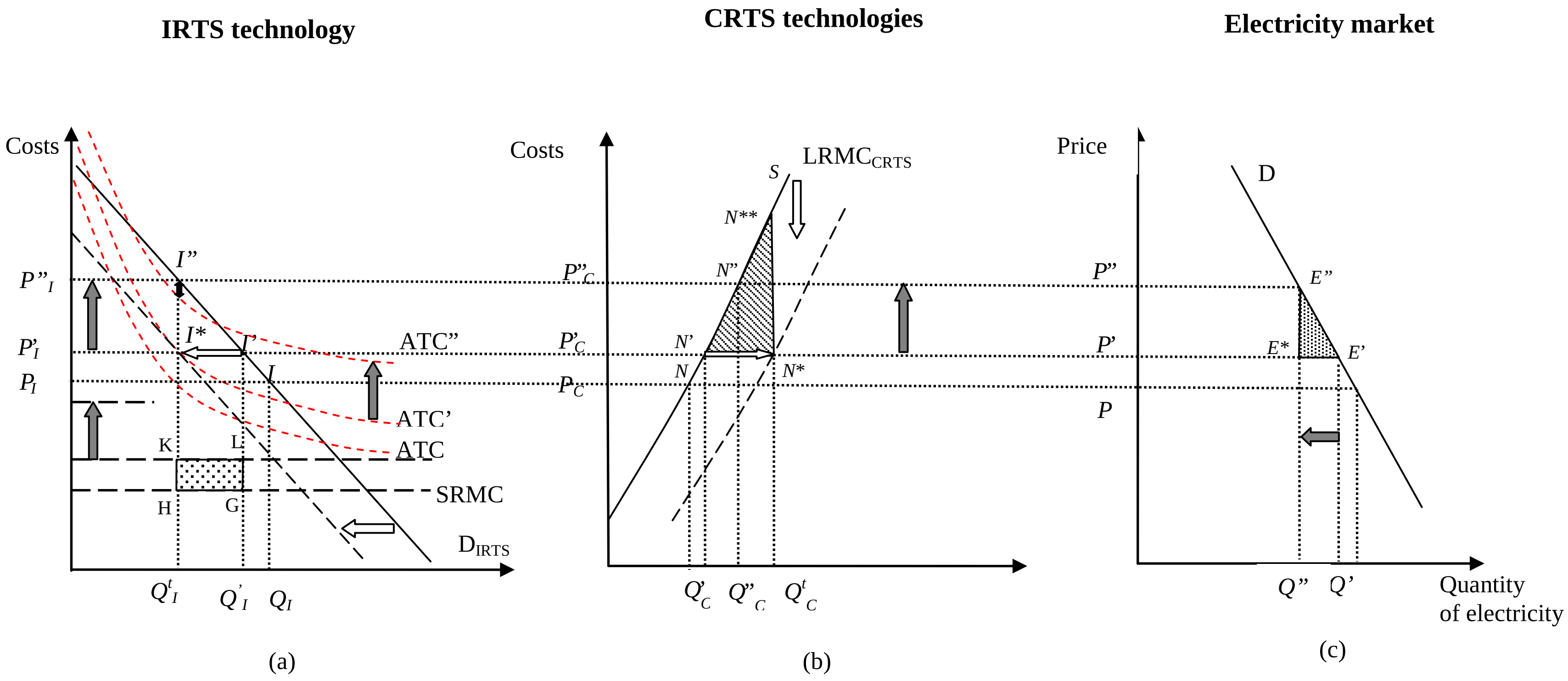

Figure 7: The use of a secondary instrument to correct for a market imperfection to improve on the effectiveness of primary climate change policy and maintain its efficiency (graphs are not to scale).

5. Applications to the case of the European Union climate change policies

We apply the approach described in the previous sections to analyse the impacts of the European Union (EU) climate change policies using a model called WIATEC.[17] The EU climate change policies are aimed at contributing to the world climate change strategy which aims to limit the rise in global average temperature to 2°C above pre-industrial levels (CEC, 2008). The range of policies undertaken by the EU consists of three main components: (1) a commitment to reduce the level of greenhouse gas (GHG) emissions in the EU by 20% compared to 1990 level by the year 2020 (30% reduction if there is an international agreement), (2) an increase in the share of renewable energy in final energy consumption to 20% by 2020, (3) an increase in energy efficiency by 20% by 2020. To reduce GHG emissions by 20% below 1990 level by 2020, the EU relies on the EU Emissions Trading Scheme (EU-ETS). This scheme was launched on January 1, 2005 and aims to control the level of CO_2 emissions by large and medium sized installations in the energy and industry production sectors[18] which cover about 45% of the total CO_2 emissions in the European Union. Emissions by other installations and sectors not covered by the EU-ETS are controlled through other regulations. To reduce the total level of CO_2 emissions in the EU by 20% below 1990 level (or about 14.6% below 2005 level) the level of emissions by the EU-ETS sectors need to be cut by about 20% below the 2005 level and that of the non-ETS sectors by about 9.1%. To increase the share of renewable energy usage in energy consumption activities, the EU introduced policies such as feed-in tariff in the electricity sector and the use of bio-fuels in the transport sector. To improve on energy efficiency in consumption activities, there are policies which help to provide finance for national and local schemes that aim to improve on energy-efficiency in the residential housing sector. This sector accounts for about 25% of the total energy consumption in the EU. In this paper, we consider only the first two components of the EU climate policies, namely emissions reduction target and renewable energy share target, and consider some experiments which will try to simulate these two policies.[19]

5.1 Scenarios

First, we define a Reference or 'Business-as-Usual' (BaU) Scenario which can be used as a reference point for comparison with other scenarios. The Reference Scenario is based on two major sets of assumptions, one regarding real GDP[20] growth and the other, population growth (see Table 1). The projected BaU growth rates for GDP and population are based on UROSTAT and UNDP statistics.[21] In addition to GDP and population growth rates, we also make some

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[17] See Truong and Kemfert (2010).

[18] The energy sector consists of combustion installations with a rated thermal input exceeding 20 MW, and also installations handling mineral oil refineries, coke ovens. The production sector consists of installations producing and processing ferrous metals, minerals (cement clinker, glass and ceramic bricks), pulp, paper, and also other activities.

[19] See also Kemfert *et al* (2006) for more details on similar experiments.

[20] GDP is only a 'proxy' for general resource utilization level. What 'drives' emissions are growth rates of individual resource factors such as employment, capital, land-use and natural resources (energy). To some extent, capital growth is determined endogenously within the model but labour (employment) and natural resource growth are still to be determined exogenously. Hence, when GDP growth is set as an exogenous assumption, the growth of employment and natural resources will to some extent be determined by this assumption.

[21]: http://epp.eurostat.ec.europa.eu/portal/page/portal/statistics/search_database
http://unstats.un.org/unsd/snaama/dnlList.asp.

assumptions on the future changes in emission intensity[22] by running the WIATEC model over the historical period 2005-2007 and then use the results in this historical simulation to provide some forecast for future levels. These are shown in Table 2. The resulting emission levels for the Reference scenario is shown in Table 3. It can be seen that under the Reference scenario, the level of CO_2 emissions in the EU27 would have increased by 8.7% (from 2005 to 2020) while that of the world as would have increased by 64.4%.

Next, we define a scenario which can simulate the implementation of the first component of the EU climate policies (i.e. the reduction of CO_2 emissions in the EU by 20% compared to 1990 level by 2020). This reduction is achieved via the implementation of the EU emissions trading scheme (ETS) therefore we refer to this as the EU-ETS scenario. Table 4 shows the level of CO_2 emissions under the EU-ETS scenario and this can be compared with emissions level for the Reference scenario as shown in Table 3. It can be seen that under the EU-ETS scenario, emissions in the EU27 as a whole would decrease by 15.2% (implying a net decrease of some 24% compared to the Reference scenario) while that of the world as would have increased by 56.6% (assuming that the rest of the world except the EU27 would not implement any climate change policies) a net decrease of some 8% compared to the Reference scenario. The split between EU-ETS trading sectors and non trading sectors is as follows: trading sectors would decrease emissions by 20% as a result of the ETS (instead of increasing by 13.2% as in the Reference scenario), while non-trading sectors would decrease emissions by 10% (instead of increasing by 3.8% as in the Reference scenario).

We note that the EU-ETS is implemented over three phases: 2005-2007, 2007-2012, and 2012-2020. In the first and second phases, it is assumed that there are national allocation plans (NAPs) which distribute emissions caps for the ETS sectors in each member countries of the EU. Although there are separate plans, because emission permits are traded freely between EU regions, this will result in a single uniform permit price for all EU countries. The ETS-sectors permit price however will differ from the shadow prices or marginal emission abatement costs in the non-ETS sectors. In theory there can be as many shadow prices as there are regulation regimes in the non-ETS sectors. However, to simplify the analysis and for comparison with the ETS sectors, we assume that there is only a single uniform shadow price for emissions in the non-ETS sectors. [23]

We can estimate the permit price or carbon tax for the EU-ETS scenario under three conditions. Firstly, under 'conventional analysis' where all electricity supply technologies are assumed to be subject to constant returns to scale and t he supply market is perfectly competitive with all suppliers acting as price takers who try to minimise the total cost of production by ensuring that at the margin, all marginal costs of production by all technologies must be the same.[24] We will refer to this situation as the (EU-ETS) PC ('perfect competition') scenario. Next, under the hypothesis that coal based electricity supply (as well as hydro and nuclear powered electricity)[25] may be subject to increasing returns to scale and producers using these technologies may not

[22] Alternatively, we can also use the rate of change in energy intensity (or its inverse, the rate of improvement in energy efficiency) as a measure of technological change in the energy sector. We use (the rate of change in) emission intensity for convenience because emissions is the policy variable of interest in this paper.

[23] Although the reduction in CO_2 emissions in the EU is via an emission trading scheme rather than via a carbon tax, hence we refer to an emissions trading price or marginal abatement cost. This is however, also equal to the 'carbon tax' if such a tax is imposed to achieve the same emissions reduction target, hence we often use the terms permit price, marginal abatement cost, and carbon tax interchangeably.

[24] This implies a condition such as equation (8) must be satisfied and this is achieved under perfect competition because all producers are price takers, hence profit is maximised only if costs of production (including emissions costs) must be minimised.

[25] Hydro and nuclear powered electricity, however, are not subject to carbon tax, hence their behaviour will not impact directly on the electricity market as compared to those of coal-based electricity producers.

behave as price takers in a perfectly competitive market, but as Cournot strategic suppliers[26]. using their degrees of monopolistic power to set their own production level and maximise their (regulated or unregulated) profits. We refer to this situation as the (EU-ETS) IC (imperfect competition) scenario. With this scenario, we distinguish between two different situations: one where there is *no* government intervention to correct for the imperfection in the market and we refer to this as the ICN ('N' for *no* government intervention) scenario, and one *with* government intervention in the form of a mandatory renewable electricity share target (as discussed in section 4. We refer to this latter situation as the ICW ('W' for *with* government intervention) scenario. [27]

Table 1: Reference scenario - macroeconomic drivers

Macroeconomic drivers for emissions (average growth rate per annum)									
GDP	2005-2007	2007-2012	2012-2020	2005-2020	Population	2005-2007	2007-2012	2012-2020	2005-2020
FRA	2.43	0.27	1.53	1.23	FRA	1.42	0.24	0.57	0.57
DEU	3.24	0.75	1.63	1.55	DEU	-0.29	-0.05	-0.12	-0.12
ITA	2.04	-1.06	1.32	0.61	ITA	2.07	0.29	0.83	0.80
ESP	3.49	-0.78	0.76	0.60	ESP	4.61	0.73	1.82	1.80
UK	2.65	-0.31	1.97	1.30	UK	1.65	0.19	0.66	0.63
POL	6.08	2.99	3.15	3.48	POL	-0.06	-0.01	-0.03	-0.03
RWEU	2.97	0.06	2.03	1.50	RWEU	1.61	0.25	0.64	0.64
REU27	3.11	-0.10	2.06	1.47	REU27	-0.07	0.00	-0.03	-0.02
USA	2.30	0.81	1.96	1.62	USA	2.44	0.39	0.97	0.97
JPN	2.52	0.57	1.52	1.34	JPN	-0.12	0.00	-0.08	-0.06
KOR	5.81	3.18	2.94	3.40	KOR	1.36	0.24	0.23	0.37
BRA	5.36	4.18	4.34	4.43	BRA	2.45	0.43	0.97	1.01
RUS	7.87	1.88	4.81	4.22	RUS	-0.96	-0.20	-0.39	-0.40
CHN	12.16	8.02	6.86	7.94	CHN	1.58	0.25	0.63	0.63
IND	8.88	7.16	7.52	7.58	IND	3.63	0.53	1.44	1.42
AUS	3.26	2.72	4.12	3.53	AUS	3.97	0.76	1.27	1.42
RoW	3.94	1.97	2.80	2.67	RoW	3.00	0.56	1.19	1.25
EU27	2.88	0.02	1.70	1.29	EU27	1.18	0.17	0.49	0.47

[26] As a condition for being a Cournot strategic competitor, we require that the price elasticity of strategic demand (for the IRTS supplier) must be greater than 1. This price elasticity is estimated endogenously during simulation runs using equations (2)-(4). If the condition is not satisfied, the IRTS supplier is assumed to behave as a price taker just like other CRTS producers.

[27] In this situation, it is immaterial whether government mandatory renewable share target is imposed with or without government subsidy. This latter consideration only affects the nominal distribution of the burden of adjustment (to achieve the mandatory targets) but not the efficiency of the adjustment which is determined only by the magnitudes of the mandatory targets. For these magnitudes to be described as 'optimal', we use condition (8) as discussed in previous section 4.

Table 2: Reference scenario - emission intensities (kg CO_2e/$)

	Historical			Projected			
Region	2005	2006	2007	2008	2012	2016	2020
FRA	0.18	0.17	0.17	0.17	0.16	0.16	0.15
DEU	0.28	0.27	0.26	0.26	0.25	0.24	0.24
ITA	0.26	0.25	0.24	0.25	0.25	0.24	0.23
ESP	0.31	0.29	0.29	0.29	0.29	0.29	0.28
UK	0.27	0.26	0.25	0.25	0.26	0.25	0.24
POL	1.17	1.14	1.06	1.05	1.03	1.02	0.99
RWEU	0.26	0.26	0.24	0.24	0.24	0.24	0.23
REU27	0.67	0.64	0.63	0.63	0.63	0.61	0.59
USA	0.51	0.49	0.48	0.48	0.48	0.46	0.45
JPN	0.23	0.22	0.22	0.23	0.22	0.22	0.21
KOR	0.55	0.53	0.53	0.53	0.51	0.50	0.48
BRA	0.48	0.47	0.46	0.45	0.43	0.40	0.38
RUS	2.57	2.47	2.27	2.27	2.29	2.21	2.13
CHN	2.43	2.39	2.25	2.23	2.12	1.99	1.86
IND	1.57	1.55	1.50	1.52	1.48	1.47	1.46
AUS	0.57	0.56	0.55	0.54	0.53	0.51	0.49
RoW	0.99	0.97	0.98	0.99	0.98	0.96	0.94

Table 3: Reference scenario – CO_2 emissions

CO_2 emissions by regions					CO_2 emissions by type of sectors				
	($GtCO_2$/year)			% change 2005-2020	ETS sectors total	($GtCO_2$/year)			% change 2005-2020
Regions	2005	2012	2020			2005	2012	2020	
FRA	0.38	0.36	0.38	1.0	FRA	0.11	0.10	0.11	0.4
DEU	0.77	0.76	0.81	5.6	DEU	0.42	0.43	0.46	10.2
ITA	0.44	0.41	0.42	-5.4	ITA	0.21	0.20	0.20	-3.5
ESP	0.33	0.34	0.35	4.1	ESP	0.17	0.18	0.18	4.4
UK	0.59	0.58	0.64	8.5	UK	0.29	0.31	0.35	19.3
POL	0.28	0.34	0.42	48.0	POL	0.20	0.25	0.31	51.6
RWEU	0.58	0.58	0.64	10.5	RWEU	0.29	0.29	0.32	9.5
REU27	0.56	0.56	0.62	10.7	REU27	0.35	0.35	0.39	10.8
EU27	3.94	3.92	4.28	8.7	EU27	2.04	2.12	2.31	13.2
	($GtCO_2$/year)			% change 2005-2020	Non-ETS sectors total	($GtCO_2$/year)			% change 2005-2020
Regions	2005	2012	2020			2005	2012	2020	
USA	6.08	6.31	6.93	13.9	FRA	0.27	0.26	0.27	1.2
JPN	1.08	1.12	1.21	12.2	DEU	0.36	0.33	0.36	0.2
KOR	0.38	0.47	0.58	49.8	ITA	0.23	0.21	0.22	-7.2
BRA	0.30	0.36	0.43	40.3	ESP	0.16	0.16	0.17	3.9
RUS	1.56	1.87	2.54	62.7	UK	0.30	0.26	0.29	-2.1
CHN	4.97	8.61	14.61	194.2	POL	0.08	0.09	0.11	39.0
IND	1.10	1.87	3.53	220.7	RWEU	0.29	0.29	0.33	11.5
AUS	0.37	0.42	0.48	28.6	REU27	0.20	0.20	0.23	10.4
RoW	6.95	8.10	9.38	34.9	EU27	1.89	1.80	1.97	3.8
World	26.73	33.06	43.95	64.4					

Table 4: EU-ETS scenario - CO_2 emissions

CO_2 emissions by regions					CO_2 emissions by type of sectors				
Regions	($GtCO_2$/year)			% change 2005-2020	ETS sectors total	($GtCO_2$/year)			% change 2005-2020
	2005	2012	2020			2005	2012	2020	
FRA	0.38	0.33	0.33	-13.7	FRA	0.11	0.09	0.09	-19.3
DEU	0.77	0.70	0.66	-14.5	DEU	0.42	0.39	0.34	-17.5
ITA	0.44	0.37	0.34	-23.3	ITA	0.21	0.17	0.14	-34.0
ESP	0.33	0.31	0.29	-14.0	ESP	0.17	0.16	0.14	-20.8
UK	0.59	0.50	0.49	-16.7	UK	0.29	0.27	0.25	-12.8
POL	0.28	0.27	0.26	-6.4	POL	0.20	0.20	0.18	-10.8
RWEU	0.58	0.53	0.53	-9.0	RWEU	0.29	0.26	0.24	-17.0
REU27	0.56	0.48	0.44	-20.8	REU27	0.35	0.30	0.25	-28.3
EU27	3.94	3.50	3.34	-15.2	EU27	2.04	1.85	1.63	-20.0
Regions	($GtCO_2$/year)			% change 2005-2020	Non-ETS sectors total	($GtCO_2$/year)			% change 2005-2020
	2005	2012	2020			2005	2012	2020	
USA	6.08	6.64	7.31	20.2	FRA	0.27	0.24	0.24	-11.5
JPN	1.08	1.14	1.21	12.5	DEU	0.36	0.31	0.32	-11.0
KOR	0.38	0.47	0.58	50.2	ITA	0.23	0.20	0.20	-13.7
BRA	0.30	0.37	0.43	41.3	ESP	0.16	0.15	0.15	-6.8
RUS	1.56	2.10	2.93	88.1	UK	0.30	0.23	0.24	-20.5
CHN	4.97	9.24	15.70	216.0	POL	0.08	0.07	0.08	4.8
IND	1.10	1.85	3.07	178.6	RWEU	0.29	0.27	0.29	-1.0
AUS	0.37	0.44	0.52	39.9	REU27	0.20	0.18	0.19	-7.8
RoW	6.95	8.19	9.59	38.0	EU27	1.89	1.65	1.71	-10.0
World	30.67	37.42	48.01	56.6					

5.2 Results

Tables 5-6 show the emission permit price (in US2004$/t$CO_2$)[28] for the EU-ETS scenario under various assumptions about the electricity market structure and price elasticity of supply and demand in the market. For a standard analysis, we assume the aggregate price elasticity of demand for the electricity market (e^D) in all regions to be equal to 2 (this is consistent with the empirical findings in Wade (2005), Espey and Espey (2004), for example) and the price elasticity of supply for all non-hydro renewable electricity (e_C^S) as being equal to 3 (also consistent with the empirical findings in studies such as Johnson (2010) for the USA).[29] For sensitivity analysis, we can allow for e^D to take on higher values such as 3 and 4 (but not a lower value such as 1 because such a low value will imply the price elasticity of strategic demand for all IRTS suppliers will be less than 1 and this means all IRTS producers will revert back to being price takers in a perfectly competitive market which is the case considered under the heading of PC (perfectly competitive) scenario).[30] For sensitivity analysis, we also allow the price elasticity of supply of non-hydro renewable electricity (e_C^S) to take on values ranging from 1 to 6. We therefore label the various scenarios for sensitivity analysis as follows: PC-*f*-*r* = perfect competition scenario with price elasticity of supply of fossil-fuel based electricity being equal to *f* and price elasticity of supply of renewable electricity assumed to be equal to *r*. Similarly with scenarios ICN-*f*-*r* and ICW-*f*-*r*; although in the case of IC scenarios, only the price elasticity of supply of CRTS fossil-fuel based electricity (i.e. ElyGas and ElyOil) are relevant because the ‘supply’ of IRTS electricity is determined by strategic Cournot competitive behaviour rather than by a simple supply curve.

From Table 5, it can be seen that under the perfectly competitive (PC) market assumption, the permit price for the EU-ETS trading sector[31] will start from a zero value in 2005 and rise to a level of about $14/t$CO_2$ in 2020 for the PC-3-*r* scenarios (*r* can range from 1 to 6 without affecting the results greatly), but to a higher value of nearly $38/t$CO_2$ in 2020 for the PC-1-*r* scenarios (again irrespective of the value of *m*). This result shows clearly that the emission price for the PC scenarios is crucially dependent only on the price elasticity of supply of *fossil-fuel* based electricity and not that of renewable electricity. This is as expected and can be explained as follows. a lower/higher price elasticity of supply of fossil-fuel based electricity implies a ‘steeper’/’flatter’ supply curve and therefore, all things remaining the same, a larger/smaller shift in the supply curve (caused by the permit price or carbon tax) will be required to reduce supply by any given amount. The price elasticity of supply of renewable electricity therefore is not a crucial parameter in determining the permit price (see also Figure 8 for an overall summary) However, it is an important factor for determining the *market share* of renewable electricity as can be seen in Table 6. This is also as expected because the larger the price elasticity of supply of renewable electricity, the easier it would be for renewable electricity to gain market share following a given increase in electricity price. From Table 6, it can be seen that the market share of renewable electricity will increase from a level of about 4.5% (for the EU27 as a whole) in 2005 to a level in 2020 which depends on the relative magnitudes of the supply elasticity of coal-based electricity and that of renewable electricity. If the latter is much larger than the former (i.e., for scenarios PC-1-3, PC-2-5, PC-3-6 in Table 6) then the increase

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[28] We use the GTAP data base version 7, see Narayanan, B and Walmsley, T. (2008), which has a base year of 2004, hence all values are in US$2004.

[29] In all cases, price elasticity of supply of hydro and nuclear electricity is kept at 1.5.

[30] It turns out that the aggregate price elasticity of demand of electricity does not affect the results greatly (in terms of a comparison between PC and IC scenarios)

[31] We focus mainly on the trading sector, but Table 5 also gives the *shadow* emission permit price for the non-trading sector which is always much higher than that for the trading sector and often not affected greatly by assumptions regarding price elasticities in the electricity sector.

in market share of renewable electricity will be most significant (around 25%-35% in 2020). On the other hand, if it is much lower (i.e. scenarios PC-2-1, PC-3-1 in Table 6) then the increase in market share of renewable electricity will be minimal. If the targeted increase in market share for renewable electricity is about 20% in 2020 then from Table 6, this seems to require that the price elasticity of supply of renewable electricity would have to be about twice the level of the price elasticity of supply of coal-based electricity (i.e. for scenarios PC-1-2, PC-2-4, and PC-3-5) (see also Figure 9 for an overall summary).

Tables 7-8 shows the results for the cases of imperfectly competitive market with *no* government intervention (ICN) and Tables 9-10 shows similar results for the cases of imperfectly competitive market *with* government intervention (ICW). In these case, the permit price for the EU-ETS trading sector in the year 2020 is also seen to be dependent only on the price elasticity of supply of fossil-fuel based electricity and not that of renewable electricity (as in the case of PC scenarios). However, with coal-based electricity now behaves as Cournot competitor rather than perfect competitor, the price elasticity of supply of 'fossil-fuel' based electricity now only refer to gas and oil-based electricity supply, therefore, this takes out some of the sensitivity of permit price with respect to those price elasticities (as can also be seen from Figure 8). In general, the permit prices of the ICN scenarios are higher than those of the PC scenarios as expected (except for scenarios PC-1-*r* where the permit prices are highly sensitive to coal-based elasticity of supply). The permit prices of ICW scenarios, however, are much closer to those of the PC scenarios (again except for scenarios PC-1-*r*).

Turning to market shares, Table 8 shows that market share of renewable electricity is much lower for ICN scenarios as compared to PC (or ICW) scenarios and stay very much unchanged from the base year at the level of around 5-8%. In contrast, these market shares are much higher and closer to the results of the PC scenarios if the ICW scenarios are considered. The market shares are similar to those of the PC scenarios if price elasticity of supply of gas and oil-based electricity is assumed to be around 2, but will be slightly lower (slightly higher) than the results of PC scenarios if this price elasticity of supply falls to 1 (rise to 3) due primarily to the sensitivity of the PC results. Overall, a market share of 20% for renewable electricity in the EU27 for the year 2020 can be achieved if the ratio of price elasticity of supply of renewable electricity to that of gas and oil-based electricity is around the ratio of 4/3 to 3/1, i.e. for scenarios ICW-1-3, ICW-2-4, and ICW-3-4 (see Figure 9).

Table 11 shows the details of market shares of non-hydro renewable electricity for individual EU27 countries in the years 2005 and 2020 for the ICW-3-4 scenario. It can be seen here that the most significant contribution to renewable electricity shares in 2020 is mostly from wind technology (ElyWind) and this primarily comes from Germany (DEU), Spain (ESP), Italy (ITA), the UK (UK) and the 'rest of western EU region' (RWEU), while France (FRA) still relies heavily on nuclear electricity (ElyNu) and Poland (POL) on coal-based electricity (ElyCoa).

Table 5: Emission permit price ($/tCO2) for the EU-ETS-PC scenarios under various assumptions regarding price elasticities of supply and demand in the electricity market

Scenarios	Year							
	2006	2008	2010	2012	2014	2016	2018	2020
	EU-ETS *non*-trading sectors							
All scenarios (*)	7.64	34.71	44.92	68.34	73.54	79.60	85.91	93.21
	EU-ETS trading sectors							
PC-1-1	1.98	5.69	9.55	14.75	19.84	25.49	31.42	37.51
PC-1-2	1.99	5.72	9.60	14.84	19.96	25.64	31.59	37.66
PC-1-3	2.00	5.74	9.64	14.91	20.05	25.74	31.69	37.78
PC-2-1	1.24	3.41	5.38	8.23	10.97	13.96	17.05	20.19
PC-2-2	1.24	3.42	5.40	8.27	11.03	14.06	17.19	20.37
PC-2-3	1.25	3.43	5.42	8.30	11.09	14.14	17.27	20.44
PC-2-4	1.25	3.45	5.44	8.34	11.13	14.18	17.32	20.47
PC-2-5	1.26	3.46	5.46	8.36	11.16	14.22	17.35	20.53
PC-3-1	0.93	2.48	3.71	5.67	7.55	9.59	11.69	13.81
PC-3-2	0.93	2.48	3.73	5.69	7.59	9.65	11.78	13.92
PC-3-3	0.94	2.49	3.74	5.72	7.63	9.71	11.84	13.99
PC-3-4	0.94	2.50	3.75	5.74	7.65	9.74	11.88	14.03
PC-3-5	0.94	2.51	3.76	5.75	7.68	9.77	11.90	14.05
PC-3-6	0.94	2.51	3.77	5.77	7.69	9.79	11.93	14.07
Average	1.27	3.52	5.60	8.60	11.50	14.69	17.99	21.34

Notes: PC-*f*-*r* implies perfect competition assumption with price elasticity of supply of fossil-fuel based electricity being equal to *f*, and that of renewable electricity equal to *r*; in all cases, price elasticity of supply of hydro and nuclear electricity is kept at 1.5 and aggregate price electricity of demand for the electricity market as a whole is kept at 2.

(*) The results for the EU-ETS *non*-trading sectors remain essentially unchanged for all scenarios, hence only the average value for all scenarios is displayed.

Table 6: Market shares (%) for different electricity generation technologies in the EU27 in 2020 for the EU-ETS-PC scenarios under various assumptions regarding price elasticities of supply and demand in the electricity market

Scenarios	Year							
	2006	2008	2010	2012	2014	2016	2018	2020
PC-1-1	4.52	4.92	5.41	6.30	7.07	7.98	8.95	9.99
PC-1-2	4.53	5.27	6.25	8.07	9.77	12.05	15.03	18.97
PC-1-3	4.53	5.62	7.12	10.10	13.38	18.52	26.08	36.40
PC-2-1	4.52	4.81	5.13	5.72	6.18	6.73	7.28	7.83
PC-2-2	4.53	5.01	5.59	6.63	7.52	8.58	9.74	11.02
PC-2-3	4.53	5.21	6.04	7.60	9.00	10.82	13.04	15.80
PC-2-4	4.53	5.41	6.51	8.64	10.76	13.76	17.76	23.04
PC-2-5	4.54	5.60	6.99	9.83	12.94	17.67	24.29	33.04
PC-3-1	4.52	4.77	5.03	5.50	5.86	6.29	6.71	7.12
PC-3-2	4.53	4.91	5.33	6.11	6.74	7.48	8.25	9.04
PC-3-3	4.53	5.05	5.64	6.74	7.67	8.81	10.07	11.49
PC-3-4	4.53	5.19	5.95	7.39	8.70	10.37	12.38	14.83
PC-3-5	4.54	5.33	6.26	8.10	9.87	12.28	15.38	19.32
PC-3-6	4.54	5.46	6.58	8.86	11.23	14.63	19.19	25.15

See Table 5 for notes.

Table 7: Emission permit price ($/tCO2) for the EU-ETS-ICN scenario under various assumptions regarding price elasticities of supply and demand in the electricity market

Scenarios	Year							
	2006	2008	2010	2012	2014	2016	2018	2020
	EU-ETS *non*-trading sectors							
All scenarios (*)	7.63	34.73	45.09	68.66	74.02	80.29	86.89	94.63
	EU-ETS trading sectors							
ICN-1-1	1.45	4.19	7.01	10.80	14.49	18.58	22.94	27.58
ICN-1-2	1.45	4.19	7.01	10.81	14.49	18.58	22.94	27.57
ICN-1-3	1.45	4.19	7.01	10.81	14.49	18.58	22.94	27.57
ICN-2-1	1.34	3.80	6.19	9.51	12.67	16.15	19.84	23.77
ICN-2-2	1.34	3.80	6.19	9.51	12.67	16.15	19.84	23.77
ICN-2-3	1.34	3.80	6.20	9.51	12.67	16.15	19.84	23.76
ICN-2-4	1.34	3.80	6.20	9.51	12.67	16.15	19.84	23.76
ICN-2-5	1.34	3.81	6.20	9.51	12.67	16.15	19.76	23.53
ICN-3-1	1.23	3.46	5.51	8.45	11.23	14.30	17.55	21.02
ICN-3-2	1.23	3.46	5.51	8.45	11.23	14.30	17.55	21.02
ICN-3-3	1.23	3.46	5.51	8.45	11.24	14.30	17.55	21.01
ICN-3-4	1.23	3.46	5.51	8.45	11.24	14.30	17.54	21.01
ICN-3-5	1.23	3.46	5.52	8.20	10.77	13.64	16.71	20.00
ICN-3-6	1.23	3.29	5.11	7.82	10.43	13.33	16.42	19.74

Notes: ICN-*f*-*r* implies *im*perfect competition with *no* government intervention; price elasticity of supply of fossil-fuel based electricity being equal to *f*, and that of renewable electricity equal to *r*; in all cases, price elasticity of supply of hydro and nuclear electricity is kept at 1.5 and aggregate price electricity of demand for the electricity market as a whole is kept at 2.

(*) The results for the EU-ETS *non*-trading sectors remain essentially unchanged for all scenarios, hence only the average value for all scenarios is displayed.

Table 8: Market shares (%) for different electricity generation technologies in the EU27 in 2020 for the EU-ETS-ICN scenarios under various assumptions regarding price elasticities of supply and demand in the electricity market

Scenarios	Year							
	2006	2008	2010	2012	2014	2016	2018	2020
ICN-1-1	4.52	4.65	4.85	5.11	5.32	5.53	5.74	5.94
ICN-1-2	4.52	4.66	4.98	5.35	5.65	5.96	6.27	6.56
ICN-1-3	4.51	4.68	5.12	5.59	5.99	6.40	6.81	7.22
ICN-2-1	4.52	4.65	4.85	5.12	5.32	5.54	5.76	5.96
ICN-2-2	4.51	4.66	4.97	5.33	5.62	5.92	6.22	6.51
ICN-2-3	4.51	4.67	5.09	5.54	5.93	6.32	6.71	7.10
ICN-2-4	4.51	4.69	5.22	5.76	6.25	6.73	7.22	7.72
ICN-2-5	4.50	4.70	5.34	5.98	6.58	7.16	7.77	8.34
ICN-3-1	4.52	4.65	4.84	5.12	5.32	5.54	5.75	5.96
ICN-3-2	4.51	4.66	4.96	5.31	5.59	5.89	6.18	6.46
ICN-3-3	4.51	4.67	5.07	5.50	5.88	6.25	6.62	6.99
ICN-3-4	4.51	4.68	5.18	5.70	6.17	6.62	7.08	7.56
ICN-3-5	4.50	4.69	5.30	5.87	6.34	6.81	7.28	7.77
ICN-3-6	4.50	4.68	5.30	5.86	6.39	6.90	7.43	7.99

See Table 7 for notes.

Table 9: Emission permit price (\$/tCO2) for the EU-ETS-ICW scenario under various assumptions regarding price elasticities of supply and demand in the electricity market

Scenarios	Year							
	2006	2008	2010	2012	2014	2016	2018	2020
	EU-ETS *non*-trading sectors							
All scenarios (*)	7.64	34.73	45.07	68.61	73.92	80.10	86.55	94.05
	EU-ETS trading sectors							
ICW-1-1	1.45	4.19	7.01	10.80	14.49	18.58	22.94	27.58
ICW-1-2	1.37	3.94	6.53	9.93	13.14	16.58	20.09	23.64
ICW-1-3	1.34	3.81	6.26	9.41	12.28	15.23	18.65	22.08
ICW-2-1	1.31	3.70	6.01	9.20	12.22	15.53	19.01	22.68
ICW-2-2	1.27	3.60	5.82	8.85	11.67	14.71	17.83	21.04
ICW-2-3	1.24	3.49	5.61	8.45	11.03	13.83	16.81	19.85
ICW-2-4	1.21	3.39	5.39	8.08	10.61	13.32	16.13	19.01
ICW-2-5	1.18	3.28	5.26	7.90	10.38	13.04	15.81	18.72
ICW-3-1	1.21	3.38	5.38	8.23	10.92	13.86	16.97	20.28
ICW-3-2	1.18	3.31	5.24	7.98	10.53	13.29	16.15	19.13
ICW-3-3	1.16	3.23	5.09	7.69	10.07	12.64	15.32	18.11
ICW-3-4	1.14	3.15	4.93	7.36	9.62	12.07	14.59	17.16
ICW-3-5	1.11	3.03	4.66	6.99	9.17	11.52	13.92	16.39
ICW-3-6	1.09	2.95	4.47	6.73	8.84	11.16	13.53	15.91

Notes: ICW-*f*-*r* implies *im*perfect competition with *no* government intervention; price elasticity of supply of fossil-fuel based electricity being equal to *f*, and that of renewable electricity equal to *r*; in all cases, price elasticity of supply of hydro and nuclear electricity is kept at 1.5 and aggregate price electricity of demand for the electricity market as a whole is kept at 2.

(*) The results for the EU-ETS *non*-trading sectors remain essentially unchanged for all scenarios, hence only the average value for all scenarios is displayed.

Table 10: Market shares (%) for different electricity generation technologies in the EU27 in 2020 for the EU-ETS-ICW scenarios under various assumptions regarding price elasticities of supply and demand in the electricity market

Scenarios	Year							
	2006	2008	2010	2012	2014	2016	2018	2020
ICW-1-1	4.52	4.65	4.85	5.11	5.32	5.53	5.74	5.94
ICW-1-2	4.52	5.08	5.90	7.29	8.55	10.10	11.93	14.14
ICW-1-3	4.51	5.28	6.47	8.48	10.43	12.96	16.29	20.74
ICW-2-1	4.52	4.85	5.26	5.97	6.56	7.26	8.01	8.81
ICW-2-2	4.51	5.05	5.78	7.04	8.15	9.50	11.05	12.87
ICW-2-3	4.51	5.23	6.28	8.09	9.79	11.95	14.69	18.16
ICW-2-4	4.51	5.40	6.76	9.14	11.52	14.77	19.08	24.67
ICW-2-5	4.50	5.55	7.23	10.23	13.47	18.13	24.31	32.79
ICW-3-1	4.52	4.83	5.21	5.87	6.41	7.05	7.73	8.45
ICW-3-2	4.51	5.02	5.68	6.83	7.83	9.03	10.39	11.97
ICW-3-3	4.51	5.19	6.13	7.78	9.30	11.14	13.38	16.19
ICW-3-4	4.51	5.34	6.57	8.70	10.68	13.36	16.70	20.98
ICW-3-5	4.50	5.49	6.84	9.29	11.73	15.16	19.68	25.57
ICW-3-6	4.50	5.60	7.09	10.03	13.13	17.70	23.98	32.19

See Table 9 for notes.

Table 11: Market shares (%) for different electricity generation technologies in individual EU27 countries for the base year 2005 and target year 2020 for the ICW-3-4 scenario

Region	Technology									Total non-Hydro Renewable
	ElyCoa	ElyOil	ElyGas	ElyBio	ElyNu	ElyHyd	ElySol	ElyWind	ElyOth	
	2005									
FRA	4.5	1.2	3.8	0.9	78.8	10.6	0.1	0.1	0.0	1.1
DEU	48.4	1.5	12.2	2.7	27.7	3.2	0.1	4.2	0.0	7.0
ITA	16.1	14.6	50.4	2.3	0.0	14.1	0.0	0.6	1.9	4.8
ESP	21.9	7.6	21.1	1.5	27.5	13.4	0.0	6.8	0.0	8.3
UK	38.4	1.3	35.7	2.4	20.7	1.1	0.0	0.5	0.0	2.9
POL	94.6	1.5	2.0	0.8	0.0	1.0	0.0	0.1	0.0	0.9
RWEU	18.4	2.1	23.5	5.7	27.3	21.0	0.0	2.0	0.0	7.7
REU27	41.0	6.2	14.8	0.9	24.3	12.2	0.0	0.5	0.0	1.5
Total EU27	30.3	3.8	19.5	2.4	31.7	10.2	0.0	1.9	0.2	4.5
	2020									
FRA	2.2	0.4	1.4	1.5	80.9	10.9	1.2	1.4	0.0	4.2
DEU	35.1	0.7	11.8	5.0	26.9	3.1	0.4	17.1	0.0	22.4
ITA	8.8	7.0	48.1	4.5	0.0	18.2	0.1	3.4	10.0	17.9
ESP	2.8	1.3	7.6	1.3	15.3	7.8	0.2	63.7	0.0	65.2
UK	27.4	0.8	35.7	5.3	24.7	1.3	0.0	5.0	0.0	10.2
POL	92.2	1.1	2.1	1.9	0.0	1.5	0.0	1.2	0.0	3.1
RWEU	8.2	0.9	17.4	10.2	25.8	20.0	0.1	17.3	0.0	27.7
REU27	30.9	3.4	12.5	2.2	30.4	15.4	0.0	5.1	0.2	7.5
Total EU27	18.2	1.6	14.8	4.1	31.5	10.2	0.3	18.5	0.8	23.7

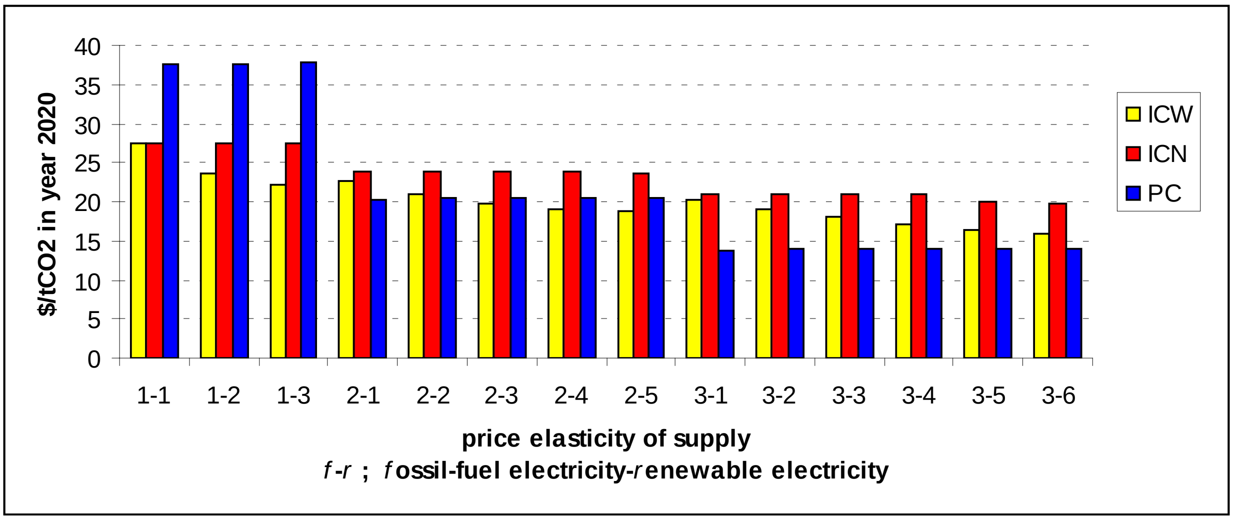

Figure 8: Sensitivity of emissions permit price in the year 2020 with respect to the price elasticities of supply of fossil-fuel based (f) and renewable (r) electricity - indicated by f-r on the horizontal axis

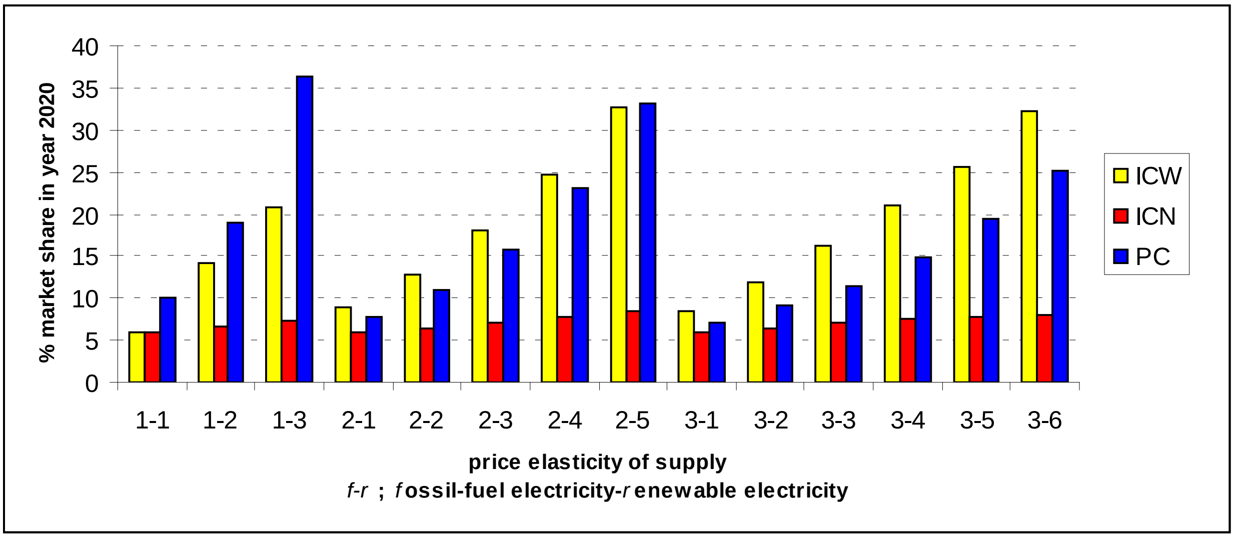

Figure 9: Sensitivity of renewable electricity market share in the year 2020 with respect to the price elasticities of supply of fossil-fuel based (f) and renewable (r) electricity - indicated by f-r on the horizontal axis

6. Conclusion.

Climate change is an important and highly complex issue and therefore to tackle with this issue, often a combination of different policy targets and instruments are used. In Australia, for example, the Australian government climate change policy consists of the introduction of a carbon tax (since July 1, 2012) and also some energy policy components aiming at encouraging business investment in renewable energy technology in the electricity generation sector.[32] In the European Union, this multiple-policy approach is seen more clearly with a policy 'package' which seeks to impose, not just one policy target but three: a 20 % reduction in greenhouse gas emissions relative to 1990 level, a 20 % renewable energy share in consumption activities and a 20% improvement in energy efficiency by the year 2020. Because of this multiple-targeting approach, there have been some debate concerning the efficiency of this approach. On the one hand, there is a view that multiple-targeting policy is inefficient (see for example Böhringer *et al.*, 2009) while on the other hand, there is the contrary view that such a policy is not only helpful but necessary (see for example, Kemfert and Diekman, 2009). In this paper, we examine this issue by looking at the characteristics of the electricity generation sector. We suggest that if the sector can be characterised as perfectly competitive with all suppliers acting price takers and using constant returns to scale technologies then the first view can be considered as valid. On the other hand, if the market in this sector is imperfectly competitive, with some increasing returns to scale coal-based electricity suppliers acting as natural monopolists or as Cournot strategic competitors then climate change policy which has only one policy component (such as carbon tax, or emissions trading scheme) may be inefficient. In this case, the use of a secondary (energy) policy component such as mandatory renewable electricity (or energy) targeting may be helpful or even necessary, depending on crucial assumptions regarding the price elasticity of supply of renewable. In the case of the EU climate change policy package, we found that if the price elasticity of supply of renewable electricity is about twice the level of the price elasticity of supply of fossil-fuel based electricity then a mandatory renewable electricity share target of about 20% in the year 2020 would seem to be reasonable and near the optimal level. If however, the reverse is true, i.e. the price elasticity of supply of renewable electricity is only about half the level of the price elasticity of supply of fossil-fuel based electricity then the target for renewable electricity share in the year 2020 should be only about half of that target, i.e. 10%. This shows that future studies on the issue of renewable electricity targeting should concentrate on the empirical measurement of the price elasticity of supply of renewable electricity, and also on the question of how far, government policies (such as subsidies on R&D investment) can influence the magnitudes of these elasticities in the long run.

[32] See Commonwealth of Australia (2012).

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Appendix A

Derivation of the optimal subsidy

The optimal subsidy can be defined by the following optimization problem:

$$Max \quad W = \left[-\int_{Q_I^{'}}^{Q_I^{''}} T(Q_I^{'})dQ_I + \int_{Q_C^{'}}^{Q_C^{*}} [P_C(Q_C) - P_C^{'}(Q_C^{'})]dQ_C \right] \tag{A1}$$

subject to the quantity constraint

$$dQ_I + dQ_C = dQ = 0 \tag{A2}$$

where $P_C(Q_C)$ is the supply function for CRTS (i.e. renewable) electricity, $T(Q_I)$ is the carbon tax or marginal abatement cost function for IRTS (fossil-fuel based) electricity. The terms in the square brackets on the right hand side of equation (1) represent the areas *GHKL* and *N'N*N*** of Figure 7 respectively. From equation (1), the first order condition for optimal subsidy can be derived:

$$\begin{aligned} dW &= 0 \\ &= -T(Q_I^{'})dQ_I + [P_C(Q_C) - P_C^{'}(Q_C)]dQ_C \end{aligned} \tag{A3}$$

which gives (using (2)):

$$\text{subsidy} = [P_C(Q_C) - P_C^{'}(Q_C)] = T(Q_I^{'}) = \text{carbon tax} \tag{A4}$$

Appendix B

Details on sectoral and regional aggregation in the WIATEC model

The WIATEC model can use different regional and sectoral aggregations for different studies depending on the focus of analysis. For this particular study, we concentrate on some individual EU member countries to highlight their differences in the use of different techniques for generating electricity (see Table B1). For the sectors, we distinguish between basic energy producing sectors (the first five sectors in Table B2), agricultural sectors, energy intensive and manufacturing sectors, transport sectors, and other services sectors

Table B1: Details on regional aggregation

No.	Region	Description
1	FRA	France
2	DEU	Germany
3	ITA	Italy
4	ESP	Spain
5	UK	The United Kingdom
6	POL	Poland
7	RWEU	Rest of Western Europe which belong to EU27 (Austria, Belgium, Denmark, Finland, Ireland, Luxembourg, Netherlands, Sweden)
8	REU27	Rest of Eastern and Southern Europe which belong to EU27 (Cyprus, Greece, Malta, Portugal, Czech Republic, Estonia, Hungary, Latvia, Lithuania, Slovakia, Slovenia, Bulgaria, Romania)
9	USA	United States
10	JPN	Japan
11	KOR	Republic of Korea (South Korea)
12	BRA	Brazil
13	RUS	Russian Federation
14	CHN	China & Hong Kong
15	IND	India
16	AUS	Australia
17	RoW	Rest of the World

Note: Regions 1-8 sum up to EU27. Switzerland and Norway do not belong to EU27; hence they are included in RoW.

Table B2: Details on sectoral aggregation

No.	Sector	Description
1	coa	coal mining
2	oil	crude oil
3	gas	natural gas extraction + gas distribution
4	p_c	refined oil products
5	ely	Electricity disaggregated into different technologies: ElyCoa, ElyGas, ElyOil, ElyBio, ElyNu, ElyHydro, ElySol, ElyWind, ElyOth.
6	CROPS	paddy rice, wheat, cereal grains nec, vegetables, fruit, nuts, oil seeds, sugar cane, sugar beet, plant-based fibers, crops nec.
7	OAGFF	other agriculture (bovine cattle, sheep and goats, horses, animal products nec, raw milk, wool, silk-worm cocoons), forestry, and fishing
8	MIN	minerals nec
9	CRP	chemical, rubber, plastic production
10	EII	energy intensive industries (ferrous and non-ferrous metals, metal products).
11	OMF	other manufacturing (textiles, wearing apparel , leather, wood, and paper products, publishing, motor vehicles and parts, transport equipment nec, electronic equipment, machinery and equipment nec, manufactures nec).
12	TRN	transport (air, water, sea, land)
13	SER	services (water, construction, trade, communication, financial, insurance, business services nec, recreational, public admin., defence, education, health, ownership of dwellings).