A numerical model for cost effective CO_2 mitigation in the EU with stochastic carbon sinks

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Abstract: This paper presents a model for the analysis of the potential of carbon sinks in the EU Emissions Trading Scheme (ETS) under conditions of stochastic carbon sequestration by forest land. A partial equilibrium model is developed which takes into account both the ETS and national commitments. Chance constraint programming is used to analyze the role of stochastic carbon sinks for national and EU-wide costs as well as carbon allowance price. The results show that the inclusion of the carbon sink option can reduce costs by as much as 2/3, but the cost saving is dampened when higher reliability of targets achievement is required. When carbon sinks are included, some countries with large carbon sequestration in relation to carbon emissions can achieve their national commitments without any costly reductions in energy use. However, cost estimates are sensitive to changes in assumed parameter values, in particular to changes in given business-as-usual levels of the use of fossil fuel.

Key words: carbon sequestration, EU emission trading scheme, uncertainty, control costs.

1. Introduction

The potentially detrimental future effects of climatic change have been known for decades and there is by now a relatively large literature on the economics of climate change (see e.g. Stern 2008 for a review). Similarly, the theoretical suggestions and empirical demonstrations of efficient design of policy instrument for mitigation and/or adaptation to climate change abound, where the potential of carbon markets at different spatial and dynamic scales have been in focus. However, in spite of this scientific knowledge, the design of the EU carbon market has met several challenges and one of them is the treatment of carbon sequestration. Carbon sink has been allowed to be treated as carbon emission reduction during the first Kyoto Protocol period, 2008-2012 corresponding to five per cent of total emission reductions from a country. Voices have been raised in favour of including carbon sinks into the EU scheme, since this would decrease total control cost for meeting the overall abatement target (e.g. Stavins, 1999). However, hesitations against a larger role of carbon sequestration include uncertainty about the magnitude of potential sinks and the difficulty of assuring compliance. The purpose of this study is to calculate and analyse the potential of carbon sinks for the EU ETS market with explicit consideration to the stochastic nature of carbon sequestration by forests, which is carried out by use of stochastic programming.

Despite the political concern and the natural science knowledge of carbon sequestration there are to the best of our knowledge no empirical studies on the role of land as stochastic sink for control costs and permit market design. On the contrary, there is a relatively large theoretical and empirical literature on permit markets with heterogeneous stochastic emission sources applied to water quality management (e.g. McSweeney and Shortle, 1990; Shortle, 1990; Byström, et al. 2000; Gren et al., 2002; Elofsson, 2003; Gren, 2008). A common approach of most of these studies is to treat the non-point source pollution as stochastic, where the relation between abatement at the source and impact on the water recipient cannot be established with certainty, and the point sources as deterministic. Another common feature of the literature is the use of static perspective and chance constraint programming where probabilistic constraints are imposed. Following this literature, we will in this paper treat carbon sinks by forest land as a non-point source abatement technology and reductions in carbon dioxide at the emission sources as a point source control technology. Chance constraint programming is used to analyze the role of the different abatement options.

Similar to several empirical studies on the evaluations of costs of carbon trading, a partial equilibrium model is applied based on marginal control costs for different countries (e.g. Böhringer and Löchel, 2009). Limitations are made by including only fossil fuel related carbon dioxide emissions, which account for approximately 80 per cent of total carbon emissions in the EU. Emission control costs for each country are then calculated as decreases in consumer surplus from decreases in use of different types of fossil fuel products; oil products, coal and natural gas. Another limitation is imposed by considering only carbon sequestration from forests, which constitute 90 per cent of carbon sinks as reported in the national inventory plans (UNFCCC, 2009). An advantage with these national plans is the reporting of not only actual carbon sink but also quantified measurements of uncertainty. The main contribution of the paper is then the consideration of forest sinks as stochastic and the evaluation of the associated impact on control costs for different countries and on equilibrium permit price in the trading market. Calculations and comparisons are carried out for different market designs; *i)* the least cost option where all carbon dioxide emission sectors and sinks are included, and *ii)* the more costly options with different restrictions on the inclusion of forest sinks and on trading sectors.

The paper is organised as follows. First, we give a brief presentation of the EU2020 targets. Then, we describe the simple model with stochastic carbon sinks and probabilistic constraints, which builds on the EU2020 targets. Data sources are described in chapter 4. Chapter 5 presents the results, in particular the minimum cost solutions under different scenarios with respect to inclusion of carbon sink, but also for alternative trading markets design. The paper ends with some tentative conclusions.

2. Brief presentation of the EU CO_2 emission reductions

The EU countries face different EU regulations with regards to carbon dioxide emissions. In this paper we focus on two directives; the EU emission trading system (ETS) (Official Journal, Directive 2009/29/EC) and national commitments (Official Journal, Decision 406/2009/EC). The EU ETS is the cornerstone of the EU's strategy for fighting climate change. It is the first and largest international trading system for CO_2 emissions in the world and has been in operation since 2005. As of 1 January 2008 it applies not only to the 27 EU Member States, but also to the other members of the European Economic Area, Norway, Iceland and Liechtenstein.

It currently covers over 10,000 installations in the energy and industrial sectors which are collectively responsible for almost half of the EU's emissions of CO_2 and 40% of its total greenhouse gas emissions. In July 2008, an amendment to the EU ETS Directive was agreed which will bring the aviation sector into the system from 2012 (Official Journal, Directive 2008/101/EC).

The trading system can be divided into three main phases; 2005-2007, 2008-2012, and 2013-2020. The first trading period ran for three years to the end of 2007 and was a 'learning by doing' phase to prepare for the important second trading period. The second trading period began on 1 January 2008 and will run for five years until the end of 2012. The importance of the second trading period stems from the fact that it coincides with the first commitment period of the Kyoto Protocol when the EU and other industrialised countries must meet their targets to limit or reduce greenhouse gas emissions. For the second trading period EU ETS emissions have been capped at around 6.5% below 2005 levels to help ensure that the EU as a whole, and Member States individually, deliver on their commitments.

In the first and second trading periods under the scheme, Member States had to draw up national allocation plans (NAPs) which determine their total level of emissions from the ETS sectors and how many emission allowances each installation in their country receives. In the third phase there will be no NAPs, instead the Commission will allocate allowances to each country based on common harmonised rules, given that total emissions from the trading sectors are reduced by 21 percent by 2020.

The agreed changes to the scheme will apply as of the third trading period, i.e. January 2013. The EU ETS should in the third period be a more efficient, more harmonised and fair system with longer trading periods, 8 years instead of 5 years. The main changes to the existing ETS Directive are the following (European Commission 23/01/2008, MEMO/08/35):

- There will be one EU-wide cap on the number of allowances instead of 27 national caps. The annual cap will decrease along a linear trend, which will continue beyond the end of the third trading period (2013-2020).
- A larger share of allowances will be auctioned instead of allocated free of charge.

- Harmonised rules regarding free allocation will be introduced.
- Part of the rights to auction allowances will be redistributed from the Member States with high per capita income to those with low per capita income. This is in order to strengthen the financial capacity of the latter to invest in climate friendly technologies.
- A number of new industries (e.g. aluminium and ammonia producers) and gases (nitrous oxide and perfluorocarbons) will be included in the ETS; Member States will be allowed to exclude small installations from the scope of the Directive, provided they are subject to equivalent emission reduction measures.

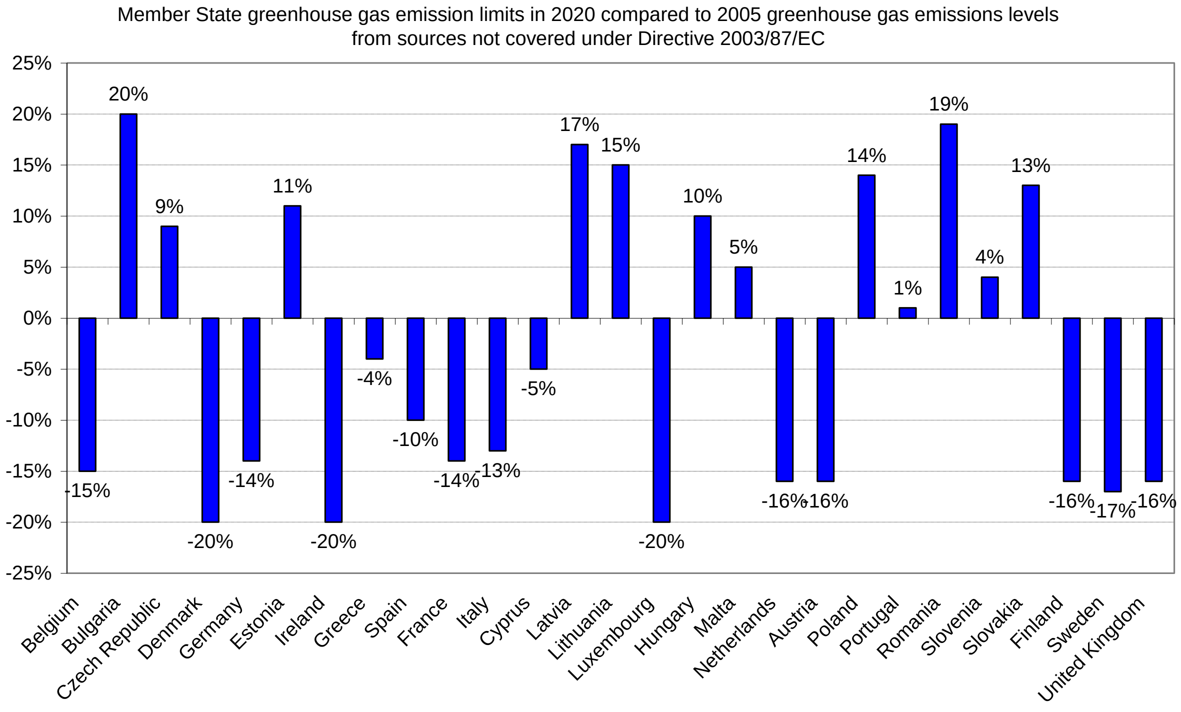
Credits from carbon sinks will not be eligible for use in the EU ETS. The Commission has analysed the possibility of allowing credits from certain types of land use, land-use change and forestry (LULUCF) projects and concluded that doing so could undermine the environmental integrity of the EU ETS for the following reasons:

- LULUCF projects do not deliver permanent emissions reductions. Insufficient solutions have been developed to deal with the uncertainties, non-permanence of carbon storage and potential emissions 'leakage' problems arising from sink projects. The Commissions believes that the temporary and reversible nature of such activities would pose considerable risks in a company-based trading system and impose liability risks on Member States.
- The inclusion of LULUCF projects in the ETS would require a similar quality of monitoring and reporting as the monitoring and reporting of emissions from installations currently covered by the system. This is not available at present and could possibly incur costs which would reduce the attractiveness of including sink projects.
- The simplicity, transparency and predictability of the ETS could potentially be considerably reduced. Moreover, the sheer quantity of potential credits entering the system could undermine the functioning of the carbon market unless their role were limited, in which case their potential benefits would become marginal.

The Commission, the Council and the European Parliament believe that other instruments can better address global deforestation. Suggestions have been put forward for using part of the proceeds from auctioning allowances in the EU ETS to generate additional means to invest in LULUCF activities both inside and outside the EU. That may provide a model for future expansion. In this respect the Commission has proposed to set up the Global Forest Carbon

Mechanism that would be a performance-based system for financing reductions in deforestation levels in developing countries[1].

In addition to the EU ETS, the Member States all have individual targets expressed as a percentage from the 2005 emission level, which are shown in figure 1. The Commission has used GDP/capita as the main criterion when setting the national targets. These targets should be met by sectors outside the EU ETS. This approach should ensure that the actual efforts and the associated costs are distributed in a fair and equitable manner, and should allow for further, accelerated growth in less wealthy countries where economic development still needs to catch up with other Member States.



Figur 1: EU Member States non-ETS emission limits

Source: European Parliament, "Shared effort to reduce greenhouse gas emissions" 17.12.2008

Countries with a low GDP per capita will be allowed to emit more than they did in 2005 in non–ETS sectors. Their economic growth has increased relatively more than EU average and given this trend, growth in these countries will probably be accompanied by more rapidly increased emissions in e.g. the transport sector. The reduction required in Member States

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[1] Communication from the Commission "Addressing the challenges of deforestation and forest degradation to tackle climate change and

where GDP/capita is below the EU average is therefore correspondingly lower (i.e. less than average level of 10 per cent reduction from the 2005 levels). Less wealthy Member States will be allowed to increase their emissions in non-ETS sectors by up to 20 % above 2005 levels. However, these targets still represent a cap on their emissions and will still require a reduction effort. By contrast, in the wealthier Member States an emission reduction above the EU average is required, up to a maximum of 20 % reduction compared to 2005 in the countries with the highest GDP/capita. The 20 % limit on national emission reductions and increases compared with 2005 should ensure that the targets for each country remain feasible and that there is no unreasonable increase in overall costs.

In sectors that do not come under the EU ETS, such as buildings and road transport, many of the important decisions will be made at Member State level. Individual EU governments can for example introduce policies and measures to lower emissions such as traffic management, shifts away from carbon-based transport, taxation regimes, the promotion of public transport, biofuels, improved energy performance standards for buildings, more efficient heating systems, and renewable energy for heating. Measures to reduce and recycle waste streams, and to reduce landfilling can also have a significant impact on GHG emissions. In this respect, there have been revisions in the guidelines for State aid in the area of environment during 2008 to increase the ability of Member States to implement such measures, while avoiding distortions of competition in the internal market.

A number of other EU-wide measures will also help Member States to reduce emissions and thus meet their national targets. For example, new efficiency standards for boilers and water heaters together with adequate labelling systems to inform consumers, could help deliver major emissions reductions in buildings. The full implementation of the Landfill Directive in 2016 will deliver further important emission reductions, as reducing the landfilling of biodegradable waste will bring a major reduction in emissions of methane, a powerful greenhouse gas. In addition, Member States can also use credits from Clean Development Mechanism (CDM) and Joint Implementation (JI) projects.

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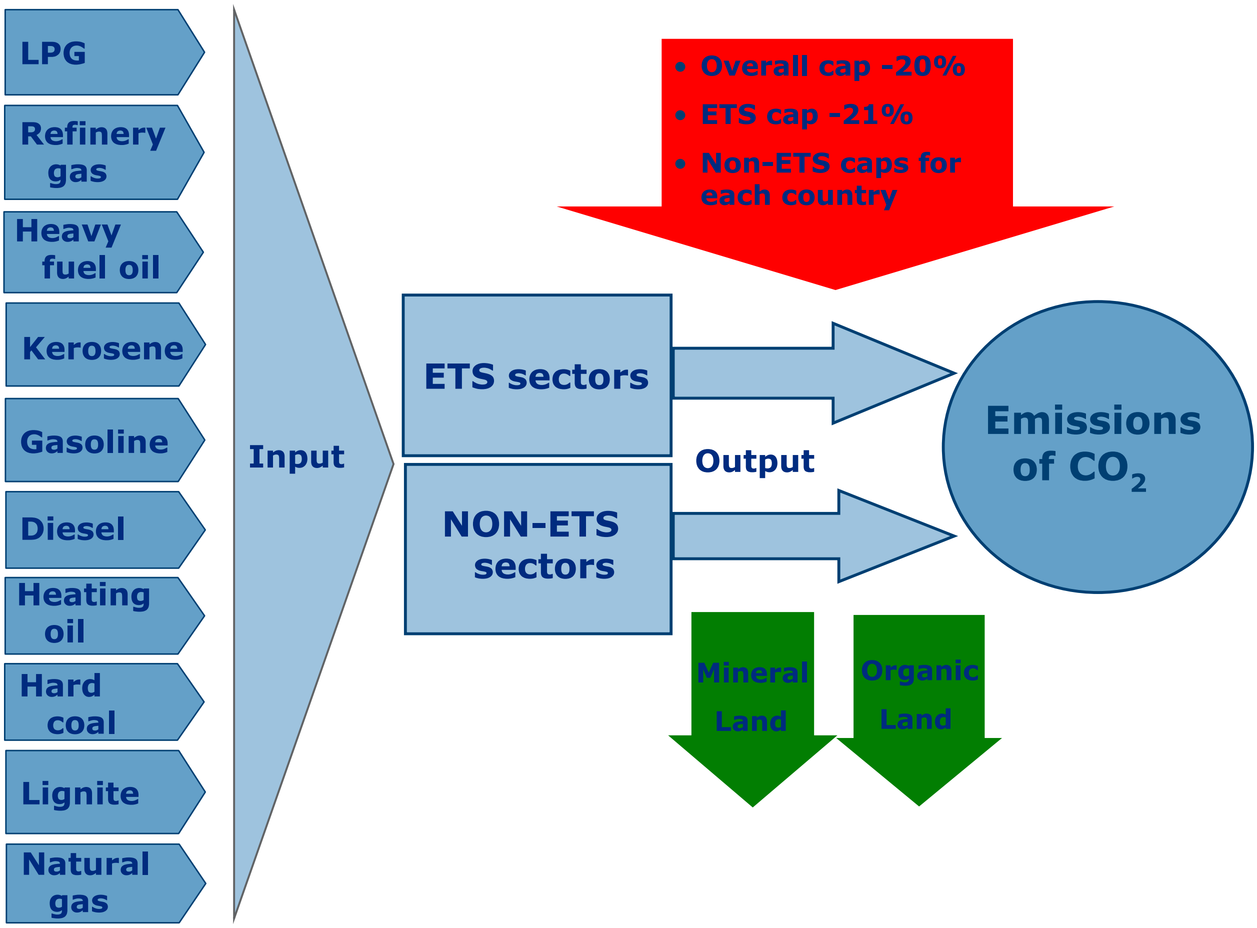
biodiversity loss", COM(2008) 645 final

3. The model

The numerical model builds on the EU2020 targets as briefly described in chapter two. It is based on ten different energy demand functions, as is visualized in figure 2. These energy sources are used as inputs in the ETS and NON-ETS sectors. From the burning of these fossil fuel energy sources there is an externality in the form of emissions of greenhouse gases and in particular CO_2. In our model, we have also introduced reductions of emissions in the form of uncertain carbon sinks. In other words, some emissions are taken up by the forest and will thereby leave the atmosphere. The main structure of the model including emission sources, sinks, and targets is illustrated in figure 2.



Figur 2. Visualisation of the numerical model

As illustrated in figure 2, there are two main strategies available for each country to reduce emissions of CO_2; mitigation of carbon dioxide emissions at source, such as reductions in oil or coal consumption, and the use of carbon sequestration. The emission of carbon dioxide from fossil fuel combustion is determined by use of energy, X_{ij} where $i=1,..,27$ EU countries and $j=1,..,8$ energy types, and their conversions into carbon dioxide, α_j. Two types of soil for forest sink are included; organic and mineral soils. The use of energy is divided among the trading and non-trading sectors, X_{ij}^{ETS} and X_{ij}^{NETS} respectively. Total carbon dioxide emission from fossil fuels is then written as

$$E' = \sum_{i=1}^{27} \sum_{j=1}^{8} \alpha_j (X_{ij}^{ETS} + X_{ij}^{NETS}) \tag{1}$$

Carbon sequestration from a certain forest land use, S_{ik}, with $k=1,2$ different sequestration options from land with organic and mineral soils is defined as

$$S_{ik} = S_{ik}(A_{ik}, \nu_i)\,, \tag{2}$$

where A_{ik} is the land cover of the forest type and ν_{ik} is the stochastic term which is assumed to be normally distributed with $N(\mu_{ik}, \sigma_{jk})$. It is assumed that S_{ik} is increasing in A_{ik}. When allowing sink to meet the prespecified targets for the ETS and national allocation plans, we need to allocate the carbon sink in (2), between the trading and non-trading sectors. It is simply assumed that these are divided according to the share of emission from these sectors in relation to total emission in each country, s_i^{ETS} and s_i^{NETS} respectively. Total emissions from the sectors in the ETS is then

$$E^{ETS} = \sum_{i=1}^{27} \left(\sum_{j=1}^{8} \alpha_j X_{ij}^{ETS} - s_i^{ETS} \sum_{k=1}^{2} S_{ik} \right) \tag{3}$$

and the emission from the non-trading sectors in each county is written as

$$E_i^{NETS} = \sum_{j=1}^{8} \alpha_j X_{ij}^{NETS} - s_i^{NETS} \sum_{k=1}^{2} S_{ik} \tag{4}$$

Control costs for emission reductions from the business as usual (BAU) emission levels are calculated as associated decrease in consumer surplus. This is the only possibility of mitigating carbon emission for fossil fuel combustion as long as the different carbon capture technologies (CCS) are in their early development stages and not available for firms as a control option. An advantage with calculations of costs based on revealed demand for inputs at given input prices is that this approach accounts for adjustments by firms to exogenous changes in energy prices. It is then assumed that each EU country is a price taker at the global fossil fuel market.

Control costs of decreases in emissions from reductions in energy uses are estimated by means of the inverted demand function for each energy input and country. This is illustrated in figure 3 for an energy input *X*, with given price and optimal input use in BAU as *P'* and *X'* respectively.

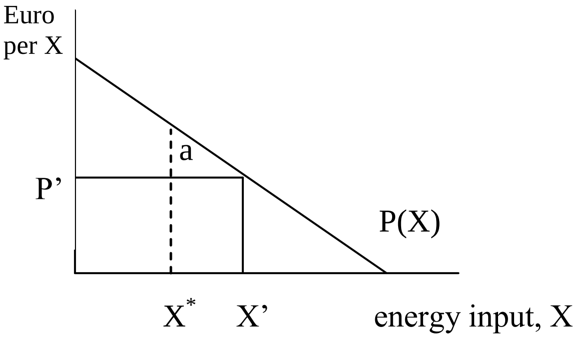


Figure 3: Illustration of control costs of reduction in the use of an energy input X

In figure 3, the inverted demand function for *X* is shown by the curve *P(X)* along which the optimal use of inputs is determined where the value of marginal product, i.e. *P(X)*, equals the given input price, which occurs at *X'* for the price *P'* in BAU before introductions of regulations. The cost for reductions in *X* are estimated as decreases in consumer surplus which corresponds to the area a for the energy use *X**. Such cost functions are derived for each sector, trading and non-trading, country, and for each type of energy use shown in figure 2.

Since quantified inverted linear demand functions are not available for all energy types and countries in the EU, inverted demand functions are calculated by means of available estimates of price elasticities, ε_{ijh}, and the BAU levels of prices and input use, P_{ijh}' and X_{ijh}' respectively where h=*ETS*, *NETS*, which is described in Appendix A. Control cost of reductions in energy type j in sector h, country i can then be written as a function of these parameters and the energy use, $X_{ijh} < X_{ijh}'$, as

$$TC_{ijh} = \int_{X_{ijh}}^{X_{ijh}'} \frac{P_{ijh}'}{\varepsilon_{ijh}} \left((1 + \varepsilon_{ijh} - \frac{X_{ijh}}{X_{ijh}'} \right) dX_{ijh} - P_{ijh}'(X_{ijh}' - X_{ijh}) \tag{5}$$

Costs for carbon sinks are determined by the management and opportunity cost of the area of forest land, $C_{ik}(A_{ik})$, which are assumed to be increasing and convex in A_{ik}.

The decision problem under the EU2020 scenario is now formulated as the minimization of total costs under a probabilistic restriction on total emissions, where ρ is the chosen probability of achieving a certain maximum level of total emission in the ETS, $\overline{E}^{ETS}$, and total emissions from the non-trading sectors in each country, $\overline{E}_i^{NETS}$. It is further assumed that the energy sources cannot be reduced completely, i.e. the demand must be larger than a predefined level. Furthermore, there is a restriction on the availability of land suitable for carbon sequestration, $\overline{A}_{ik}$.

Stochastic programming is applied, where it is assumed that the objective of the policy maker is to minimize total abatement costs for achieving a probabilistic target constraint for maximum allowable emissions (see e.g. Charnes and Cooper, 1964; Birge and Louveaux, 1997). It is then required that a predetermined pollution target, $\overline{E}$, is to be obtained with a minimum level of a chosen probability $\rho \in (0,1)$. It is assumed that the chosen reliability levels are the same for all targets and all countries. The decision problem is then formulated as

$$\underset{X_{ijh}, A_{ik}}{Min} \qquad TC = \sum_{i=1}^{27} \left(\sum_{j=1}^{8} C_{ijh} + \sum_{k=1}^{2} C_{ik}(A_{ik}) \right) \tag{6}$$

Subject to

$$X_{ij} \geq \overline{X}_{ij} \tag{7}$$

$$A_{ik} \leq \overline{A}_{ik} \qquad (8)$$

$$\Pr\left[E^{ETS} \leq \overline{E}^{ETS}\right] \geq \rho \qquad (9)$$

$$\Pr\left[E_i^{NETS} \leq \overline{E}_i^{NETS}\right] \geq \rho \qquad (10)$$

where $\overline{E}^{ETS}$ is the total cap on emissions for the trading sectors in the 27 EU member states, and $\overline{E}_i^{NETS}$ are the emission targets set by the national commitments.

There exist a number of studies where this method has been used to include probabilistic constraints in models, for example Paris and Easter (1985), Milon (1987), McSweeny and Shortle (1990), Shortle (1990), Byström et al. (2000), Gren et al. (2002), Elofsson, (2003). The technique is to standardize the variables of the probabilistic constraints in (9) and (10) and utilize the properties of the standard distribution to obtain a deterministic equivalent which can replace the probabilistic formulation in (9) and (10). The deterministic equivalent to the pollution constraint in (9) can be written as:

$$Exp[E^{ETS}] + \phi^{\alpha} Var(E^{ETS})^{1/2} \leq \overline{E}^{ETS}, \qquad (11)$$

where

$$Var(E^{ETS}) = \sum_i Var(s_i^{ETS} S_i) + \sum_i \sum_{k \neq i} Cov(s_i^{ETS} S_i, s_k^{ETS} S_k) \;\; , \qquad (12)$$

The deterministic equivalents to the national targets are written in the same way except for the summation over all countries and the change in indexes describing *NETS* instead of *ETS*. *Exp* is the expectation operator, and ϕ^{α} is a standard number such that $\int_{-\infty}^{\phi_{\alpha}} f(\varphi) d\varphi = \rho$, φ is the standardized distribution of *E* and $f(\varphi)$ is the probability density function for φ. In order to avoid positive probabilities for negative loads to the atmosphere we assume a lognormal distribution in the total load, *E*, but no assumptions are imposed on the probability distributions for E_i . For given expected loads, probability, and coefficient of variation for *E*, the number for this standard distribution can be obtained from statistical tables (see e.g. Gren et al., 2002). It can be seen from the probabilistic restriction (8) that minimum costs for a probabilistic constraint are always higher than for the deterministic case when the variance in

E is disregarded, which has been shown theoretically in several studies and demonstrated empirically in some (e.g. McSweeney and Shortle, 1990; Shortle, 1990; Elofsson, 2003; Gren et al. 2002). In the following, we simplify by assuming that the covariances are zero. The first order condition with respect to X_{ijh} delivers

$$\left(\frac{P_{ijh}'}{2\varepsilon_{ijh}}\left(\frac{2X_{ijh}}{X_{ijh}'}-2\right)+\beta_{ijh}\right)=-(\lambda+\gamma_i)\alpha_j \tag{13}$$

where β_{ij}, λ, and γ_i are the Lagrange multipliers for the lower bounds on energy use, the overall emission target for the trading sectors, and for the national allocation plans. However, both emission targets can not act for each sector, when $h=ETS$ we have that $\gamma_i=0$ and when $h=NETS$, then $\lambda=0$.

According to (13) the minimum cost solution for the trading sectors is obtained where the marginal costs of emission reductions, the left hand side of (13), are equal for all energy types and countries and corresponds to λ. We can also see from (13) that the marginal cost, and hence total cost, increases (decreases) when the BAU price, i.e. P_{ij}', increases (decreases), the BAU energy use, i.e. X_{ij}', decreases (increases) and when ε_{ij} decreases (increases).

In a similar vein the first order conditions for optimal choice of forest land for carbon sequestration, A_{ik}, are

$$\frac{\partial C_{ik}}{\partial A_{ik}}-\theta_{ik}=\lambda\left(\frac{\partial ExpE^{ETS}}{\partial A_{ik}}-\psi\frac{\partial Var(E^{ETS})}{\partial A_{ik}}\right)+\gamma_i\left(\frac{\partial ExpE_i^{NETS}}{\partial A_{ik}}-\eta_i\frac{\partial Var(E_i^{NETS})}{\partial A_{ik}}\right) \tag{14}$$

where θ_{ik} is the Lagrange multiplier for the restriction on area of forest land,

$\psi=\frac{\phi^{\alpha}Var(E^{ETS})^{-1/2}}{2}$, $\eta_i=\frac{\phi^{\alpha}Var(E^{NETS})^{-1/2}}{2}$, and

$$\frac{\partial Var(E)}{\partial A_{ik}}=\frac{\partial Var(S)}{\partial A_{ik}} \tag{15}$$

The left hand side of (14) shows the marginal costs of carbon sequestration, and the right-hand side presents the marginal impacts on the targets $\overline{E}^{ETS}$ and $\overline{E}_i^{NETS}$. The latter consists of two main parts; the marginal impact on expected emission and on variance in sequestration.

Let us for a moment neglect the stochastic nature of carbon sink and capacity constraints and focus on the emission trading market. The equilibrium permit price is then determined by the Lagrange multiplier, λ, where marginal costs are equal for emission reduction measures and the carbon sink option. From (14) we then have that the introduction of carbon sink will affect the permit price only when $\dfrac{\left(\dfrac{\partial C_{ik}}{\partial A_{ik}} - \gamma_i \dfrac{\partial E_i^{NETS}}{\partial A_{il}}\right)}{\dfrac{\partial E_{ik}^{ETS}}{\partial A_{ik}}} < \dfrac{\dfrac{-\partial C_{ijh}}{\partial X_{ijh}}}{\alpha_j}$. When this condition holds, total control costs for achieving the target $\overline{E}^{ETS}$ are reduced by the introduction of carbon sinks and the permit price is reduced.

Consideration of the probabilistic constraint with a positive impact of marginal changes in carbon sinks on the variance implies that the uniform character of the two options vanish, one unit reduction of emissions does not correspond to one unit increase in carbon sinks any longer. The optimal trading ratio on the EU ETS between carbon dioxide emission reduction by any energy input and sequestration, T^r, is determined by the marginal impacts of the two classes of measures which gives

$$T^r \equiv \left(\frac{\partial Exp(E^{ETS})}{\partial A_{ik}} - \psi \frac{\partial Var(E^{ETS})}{\partial A_{ik}}\right) \Big/ 1 \qquad (16)$$

Similar to other studies, carbon sink entails a relative cost advantage/disadvantage when the variance is decreasing/increasing in sequestration (e.g. Shortle and Horan, 2008). When $\dfrac{\partial Var(E^{ETS})}{\partial A_{ik}} < 0$, the marginal impacts on the constraint are increased, $T^r > 1$, and total minimum costs are decreased as compared to when the marginal impacts on variances are non-negative. However, whether or not the marginal impacts on the variances are negative depend on the probability distributions and the functional relation between emission and sequestration. In the empirical application in section 4, linear functions are assumed for the impact of the measures on the atmospheric load. The marginal impacts on the variances from the measures are then negative on total variance.

By altering the level of reliability, i.e. ρ, we can derive a standard reliability expansion path which shows the optimal portfolio allocation of reliability and total control cost, see example in figure 4.

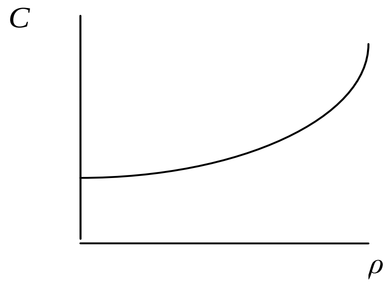


Figure 4: Illustration of reliability and cost expansion path in carbon dioxide control for achieving a given target

The curve in figure 4 shows the optimal trade off between risk and total control cost. As the predetermined probability of achieving is increased, the reliability of achieving the target is increased. From (11) and (12) it is seen that the constraint is made more stringent with higher reliability, which, in turn, implies higher control cost, C in figure 4.

4. Data retrieval

Three types of data sets are required for the calculations in the next chapter; abatement costs, emissions from energy uses, forest sinks, and forest sink variances. Data are obtained for all the 27 EU member countries, which are reported in the following section.

4.1 Carbon dioxide emissions, input prices and price elasticities

Due to lack of data for costs of conversions of land for increasing carbon sequestration, this paper evaluates the potential of actual carbon sequestration from forest land, which is obtained from conventional forestry. The inclusion of forest sinks then implies that emission reductions are achieved at no cost. As will be evident from section 4.2, the share of sequestration by forest land is considerable, and some countries are able to achieve their national commitments without costly reductions in energy use.

As shown in section 3, the calculations of control costs due to reductions in energy input use require data on input prices and use, and price elasticities of demand for different energy users.

We distinguish between the trading and non-trading industry sectors, the power sector, and the households (see Figure B1, Table B1 and B2 in Appendix B). As shown in figure 1, the following fossil fuels are included: hard coal, lignite, natural gas (derived gases included), heavy fuel oil, light fuel oil/heating oil, gasoline, diesel and jet kerosene (An overview of the classification of petroleum fuels is provided in Table B3.). Consumed quantities of these fuels in the 27 EU Member States in 2006 are obtained from Eurostat (see Table B4 and B5). Carbon dioxide emissions are then calculated by means of emission conversion for each type of fossil fuel (see Table B6).

Except for gasoline and diesel, consumptions of all fossil fuel categories are divided among sectors and households, which allow for the classification of their uses into the ETS and NETS. The use of NETS gasoline and diesel is reported in the transport sector, but there is no division among household and the non-trading production sectors. Such data were found for Sweden, according to which the division of gasoline use among households and production sectors are 67 per cent and 33 per cent respectively (SCB, 2009). The corresponding allocation of diesel is 7 and 93 per cent, respectively.

Given all assumptions, the calculated CO_2 emissions for different countries and sectors are as presented in table 1.

Table 1: Calculated carbon dioxide emissions from combustion on fossil fuels, million tons of CO_2 in 2006

	ETS			*NETS*		
	Trading industry	*Air transport*	*Power sector*	*Non-trading industry*	*Households*	*Total*
AT, Austria	14	2.1	13.5	26.9	13.3	69.8
BE, Belgium	22.5	3.4	18.6	61.3	22.7	128.5
BG, Bulgaria	7.3	0.6	26.5	9.7	2.9	47
CY, Cyprus	0.6	0.9	3.2	2.5	1.3	8.5
CZ, Check republic	18.1	1.1	62	21.8	13.7	116.7
DE, Germany	100.3	26.2	329.9	184.5	175.5	816.4
DK, Denmark	3.2	2.8	28.1	19.3	7.5	60.9
EE, Estonia	0.4	0.1	10.3	3.1	0.9	14.8
ES, Spain	53.2	16.7	108.9	137.2	39.4	355.4
FI, Finland	12.4	1.8	31.7	15.1	6.3	67.3
FR, France	61.2	21.2	41.9	168.3	91.1	383.7
GR, Greece	9.3	3.9	43.2	29.6	17.9	103.9
HU, Hungary	6	0.8	17.4	16.3	13.0	53.5
IE, Ireland	3.5	2.6	15.1	14.6	11.6	47.4
IT, Itlay	67.2	11.8	136.3	143.8	87.5	446.6
LT, Lithuania	2.5	0.2	3.7	5.2	1.6	13.2
LU, Luxembourg	1	1.2	1.3	6.3	2.6	12.4
LV, Latvia	0.7	0.2	2.1	4.4	1.4	8.8
MT, Malta	0.1	0.2	1.7	0.5	0.3	2.8
NL, Netherlands	32	11.1	49.4	104.9	27.7	225.1
PO, Poland	32.4	0.8	169.7	63.5	44	310.4
PT, Portugal	5.9	2.8	21.6	21.7	6.9	58.9
RO, Romania	19.5	0.4	41.3	21.1	10.9	93.2
SE, Sweden	11.5	2.6	5.1	24.1	9.3	52.6
SI, Slovenia	1.4	0.1	6.3	5	2.8	15.6
SK, Slovakia	11.5	0.1	9.6	9.5	4.7	35.4
UK, United Kingdom	50.2	38.9	199.1	160.2	119.4	567.8
Total	*548*	*155*	*1398*	*1280*	*736*	4117

Source: Calculations based on tables B1-B6 in appendix B

The trading sector includes the trading industry, air transports, and the power sectors, which together account for 51 per cent of all emission from the combustion of fossil fuels. Total emissions in turn accounts from approximately 80 per cent of all greenhouse gas emissions from the 27 EU countries.

Our reference scenario, projecting emissions of CO_2 from fossil fuel combustion in 2020, is based on the Baseline scenario in Capros et al (2008b), which in turn emanates from the PRIMES energy model (see Appendix C for a brief presentation of the assumptions and data underlying the forecast under BAU in 2020). In total, the energy related carbon emissions are expected to increase by 11 per cent as compared to the calculated emissions in 2006 shown in Table 1.

Prices of petroleum products (except jet fuel) and natural gas have been obtained from Eurostats data base. Prices are recorded twice a year – the first of January and the first of July – for three different levels of taxation – no taxes; all taxes except VAT; and all taxes included. The EU countries differ with respect to tax exempts for some industries, and it is difficult to trace the level of tax deduction for the trading and non-trading sectors. We therefore simply assign the prices without VAT to the trading and non-trading sectors, and prices including all taxes for the households in the numerical model. The price of natural gas is reported for five different household consumer groups and seven industrial consumer groups, based on annual consumption levels and – for industrial consumers – load factors (number of delivery days per year). In this model, average levels of prices are used for households and industries respectively.

Data on the price of jet fuel is gathered from the AEA (Association of European Airlines 2007), and represent the average for all scheduled flights in 2006. Price data on hard coal products – coke and steam coal – have been obtained from The German Coal Importer Federation (Passon, Personal communication). Coke is primarily used within the industrial sector, while thermal power and district heating plants primarily use steam coal. Lignite is generally not shipped into Europe, and is rarely traded under open market conditions. We have assumed that the price per ton of oil equivalent for all coal products is the average of the price for steam coal and hard coal coke.

Factors for converting the price data from the units used in the data sources to Euros per ton of oil equivalent (toe) are presented in the last column of Table B7, and average prices in Table B8 in Appendix B.

The main difficulty with respect to data retrieval is to obtain price elasticities of all included fossil fuels for all countries. In fact, there is no type of price elasticity which is available for all countries. The main data sources with large coverage of countries are Holtsmark and Maestad (2002) on elasticities for oil, coal and natural gas, and Graham and Glaester (2002) with estimated gasoline price elasticities, see Table B5 in Appendix B. It is assumed that the price elasticities of demand for diesel use are the same as for gasoline.

A review of the literature on air transportation indicates that jet fuel demand is very price inelastic. Wohlgemuth (1997), Mazraati & Faquih (2008) and Olsthoorn (2001) all estimate the price elasticity of jet fuel to be less than -0.1. Wohlgemut is the only one of these who presents a specific estimate for Europe, at -0.09. This estimate is used for all the member countries.

4.2 Carbon sinks

Carbon sequestration is associated with biomass growth, which, in turn, depends on a number of different factors such as forest management, climate conditions and soil quality (see e.g. van Kooten et al. 2004). We apply a simple method in this paper where two different land categories – forests on organic and mineral soils respectively – are assigned constant amount of sequestration per unit land area and category, see table B10 in appendix B. Both sequestration coefficients and land areas are obtained from country reports (UNFCCC, 2009). The numerical model in this paper includes only sinks on forest land, which is motivated by the fact that forest sinks is by far the most important sink category, and also the one where data availability is most uniformal across the Member States. Hence, sinks and sources from other types of land categories (cropland, grassland, wetland, settlements, and other land) are omitted.

The current considerable sink of European forest is largely documented, by both forestry institutions and the scientific community (EEA 2008). For many centuries, most European forests have been intensively exploited and depleted of carbon. However, since the middle of the 20th century, growth rates started to increase. Overall, in the last 50 years, forests of Europe have increased by 75% their biomass stocks per hectare. Among the likely causes of this increased forest growth - not easily separable among them - the scientific community has suggested: 1) harvesting less than the increment, especially in central and southern Europe, 2) young age structure, i.e. most forests are still recovering from past overexploitation and are still an exponential growth phase, 3) increased fertility of forest soils due to improved silvicultural practices, and 4) fertilizing effects of increased nitrogen deposition and atmospheric CO2 concentration.

Despite a general tendency of increased forest growth, as explained above, the net carbon stock change per hectar varies considerably among member states and between the two types of soils, see table B10. For forests on mineral soils the net emission factors ranges from -0.18 ton C per hectar and year in Greece to -2.30 in Italy.[2] Forests on organic soils are less common – primarily reported from Finland and Sweden – and can act as either sinks or sources of carbon. Net emission factor ranges from -1.91 in the United Kingdom to +0.28 in Estonia. This wide range in net emission factors may be explained by a series of factors, including the intensity of management, natural events (fires, storms), and ecological potential under different climatic zones and historical management patterns. Largely because of this diversity, the definition of "forest" differs among Member States. Because of the different ecological and socio-economic conditions in the various countries, and also for historical reasons, it is not possible to develop a harmonized definition from these different definitions. As with the forest definitions, the methods for the collection of data in forest inventories differ among Member States in terms of design, spatial intensity, frequency of field survey, and latest information available.

However, the EU reports constitute the most comprehensive source of emission coefficients, and are therefore used for calculating forest carbon sinks in the EU member states, see table 2.

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[2] The net emission factors is based on reported changes in carbon stock in living biomass, dead organic matter (DOM) and soils. Negative sign implies removal of carbon from the atmosphere, i.e. a carbon sink.

Table 2: Carbon dioxide emissions in 2005, forest carbon sinks, and shares of carbon sink of total emission

	2005 energy related CO_2 emissions, thousand tonnes[1]	*Calculated carbon sink, thousand tonnes*[2]	*Carbon sink/2005 energy related CO_2 emissions*
AT, Austria	73700	19794	0.27
BE, Belgium	107800	2780	0.03
BG, Bulgaria[3]	45100	7031	0.16
CY, Cyprus[4]	7400	0	0.00
CZ, Check republic	114800	4534	0.04
DE, Germany	804800	79264	0.10
DK, Denmark	48900	2655	0.05
EE, Estonia[3]	15200	3607	0.24
ES, Spain	339400	33331	0.10
FI, Finland	54100	40931	0.76
FR, France	378400	84783	0.22
GR, Greece	96200	4333	0.05
HU, Hungary[3]	55000	4639	0.08
IE, Ireland	45700	986	0.02
IT, Italy	451000	95057	0.21
LT, Lithuania[3]	12600	8493	0.67
LU, Luxembourg	12400	0	0.00
LV, Latvia[3]	7300	17951	2.46
MT, Malta[5]	3000	0	0.00
NL, Netherlands	171600	2512	0.01
PO, Poland	290700	54387	0.19
PT, Portugal	61600	6122	0.10
RO, Romania[3]	89700	37432	0.42
SE, Sweden	48500	28105	0.58
SI, Slovenia[3]	15200	4738	0.31
SK, Slovakia[3]	37100	3119	0.08
UK, United Kingdom	559700	15276	0.03
Total	*3946900*	*561860*	0.14

1) Capros et al. 2008a; 2) Calculations based on tables B10 and B11 in appendix B

The carbon sink corresponds to 14 per cent of the calculated energy related CO_2 emission. The non-zero share of carbon sink varies between 0.01 (the Netherlands) and 2.07 (Latvia). Thus, the carbon sink can play a varying role for countries in fulfilling their national commitments.

4.3 Uncertainties in measurement of carbon sink

As indicated in Chapter 4.2, there are several classes of uncertainties associated with the measurements of carbon sinks. The majority of the member states performed some uncertainty assessment for the LULUCF sector. However, given the complexity and difficulty in performing a full uncertainty assessment – highlighted by several Member States – in most cases the reported uncertainty did not cover the whole sector. While some Member States provide detailed calculations of uncertainty, others only give a total uncertainty value for the entire LULUCF sector.

For the activity data, the analysis for the several land-use categories, and the related changes, invariably means that datasets differing in terms of format, spatial resolution, reference years and other attributes need to be combined. It follows that a high degree of uncertainty is associated with the land area activity data in general. Furthermore, given the usually relatively small area of land converted to other lands, some Member States underlined the significantly higher uncertainty associated with the emissions/removals of these subcategories (e.g. area of land converted to forest land is not easily estimated with sample-based forest inventories).

Similar or even greater difficulties are reported for the emission factors, mainly due to the fact that a lot of input data are not based on statistical or representative surveys, especially for non-CO2 gases and soil carbon, and initiating a statistically-sound new data acquisition is very difficult. In some cases, such as the effect of land use change or specific management activities on soil C, there is little consensus from the available literature. Typically, “forest land remaining forest land” is the subcategory where the uncertainty parameters are better reported compared to other subcategories.

The heterogeneity of the reporting methods and the incompleteness of the estimates make it rather difficult to assess uncertainty at the EU level. However, given the relative availability of uncertainty estimates for C stock changes in the living biomass of “forest land remaining forest land”, for this pool and subcategory it is possible to compile a synthesis table with the information reported by Member States. This has been carried out for EU15. Under assumptions of transferability to other countries, uncertainty is measured as coefficient of variation for all EU member states, see table 3.

Table 3: Uncertainties and coefficients of variation in forest carbon sinks

	Detailed uncertainty measurement:		*Combined uncertainty*
	Activity data	*Emission factors*	
AT, Austria[1]		0.3	0.3
BE, Belgium[1]			0.1
BG, Bulgaria[2]			0.80
CY, Cyprus[2]			0.80
CZ, Check republic[3]			0.3
DE, Germany[3]			0.3
DK, Denmark[1]	0.2	0.2	0.28
EE, Estonia[4]			0.37
ES, Spain[5]			0.40
FI, Finland[1]	0	0.37	0.37
FR, France[1]	0.3	0.5	0.58
GR, Greece[1]	0.10	0.79	0.80
HU, Hungary[3]			0.3
IE, Ireland[1]	0.3	1	1.04
IT, Italy[1]	0.3	0.54	0.62
LT, Lithuania[3]			0.3
LU, Luxembourg[6]			0.67
LV, Latvia[3]			0.3
MT, Malta[5]			0.62
NL, Netherlands[1]	0.25	0.62	0.67
PO, Poland[3]			0.3
PT, Portugal[1]	0.007	0.40	0.40
RO, Romania[2]			0.80
SE, Sweden			0.20
SI, Slovenia[2]			0.8
SK, Slovakia[2]			0.8
UK, United Kingdom[1]	0.01	0.23	0.23

1. UNFCCC, 2009
2. Assumed to be the same as for Greece
3. Assumed to be the same as for Austria
4. Assumed to be the same as for Finland
5. Assumed to be the same as for Portugal
6. Assumed to be the same as for the Netherlands

Recently, a study under EEC 2152/2003 “Forest Focus regulation on developing harmonized methods for assessing carbon sequestration in European forests” (MASCAREF) has been launched with the purpose to facilitate the development of a monitoring scheme for carbon sequestration in EU forests, in order to i) strengthening and harmonizing the existing national systems to better meet the requirements of international monitoring and reporting of GHG emissions and sinks, and ii) improving the comparability, transparency and accuracy of the GHG inventory reports of the LULUCF sector of Member States, as implemented in the EC Monitoring Mechanism.

5. Minimum cost solutions with and without carbon sinks

Given the model framework and all assumptions, costs are calculated under different scenarios with respect to inclusion of carbon sinks and size of the trading market. We also carry out sensitivity analysis for changes in parameters in the energy reduction cost functions and the measurement of forest sink uncertainty.

5.1 Costs for achieving the NAP and trading target under the EU2020

Minimum costs are presented in figure 5 for achieving the target for the trading sector by 21 percent and the NAP under conditions of no option for carbon sink and with carbon sink under different reliability levels

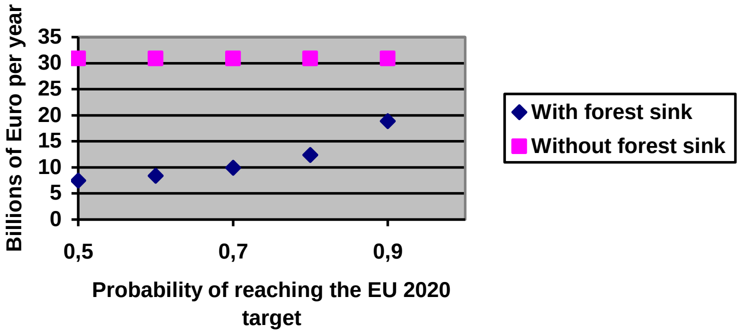

Figure 5: Reliability and cost expansion paths for reaching the target of 21 % emission reduction by the trading sector and the national allocation plans.

The total cost without the forest sink option is approximately four times as expensive as when all forest sink capacities are included and the chosen probability of achieving the targets in 0.5. The costs are more than doubled for reliability levels of 0.9 compared to the case when sinks are included but stochasticity is ignored. Higher levels can not be achieved due to the large share of forest sinks in Romania and the relatively high uncertainty as measures in coefficient of variation, see table 3 in chapter 4. Romania, together with Ireland, are also the only country that would lose from moving from the no sink option to the case when forest sinks are included and the reliability level is 0.9, see table 4.

Table 4: Allocation of costs, million Euro/year, and shadow costs, Euro/ton CO_2 of national targets under different forest sink scenarios

	No sink		*Sink without risk*		*Sink with ρ=0.9*	
	Total cost,	*Shadow cost,*	*Total cost,*	*Shadow cost,*	*Total cost,*	*Shadow cost,*
AT, Austria	840	144	5	0	139	55
BE, Belgium	1137	133	929	123	960	83
BG, Bulgaria	160	77	12	0	183	89
CY, Cyprus	12	54	10	54	11	38
CZ, Check republic	232	54	24	7	89	15
DE, Germany	4598	133	352	41	1794	69
DK, Denmark	588	250	318	189	419	124
EE, Estonia	79	107	5	0	19	10
ES, Spain	3055	173	730	80	1815	100
FI, Finland	228	96	8	0	27	5
FR, France	2519	119	11	0	1525	72
GR, Greece	237	59	73	36	227	48
HU, Hungary	588	195	185	71	315	111
IE, Ireland	487	144	399	124	519	124
IT, Italy	5262	155	160	25	4022	112
LT, Lithuania	5	4	1	0	2	5
LU, Luxembourg	224	149	222	149	223	123
LV, Latvia	400	431	1	0	2	8
MT, Malta	1	3	0.1	3	0.2	7
NL, Netherlands	1261	84	1105	80	1204	55
PO, Poland	929	80	79	0	315	11
PT, Portugal	251	74	30	25	136	53
RO, Romania	851	123	24	0	1445	503
SE, Sweden	2243	381	2	0	35	36
SI, Slovenia	189	148	4	0	37	48
SK, Slovakia	477	158	177	121	302	126
UK, United Kingdom	4110	174	2627	143	3133	111
Total	*30975*		*7489*		*18903*	
Market price of permits		*18*		*4*		*8*

The results presented in table 4 also reveal considerable changes in the shadow costs of the national target from introduction of carbon sinks. For some countries – Austria, Bulgaria, Finland, France, Latvia, Poland, Romania, Sweden, and Slovenia – the national targets are achieved by the carbon sink. Control costs emerge only from participation in the EU ETS. However, under reliability concern, all countries face costs for meeting their national target.

5.2 Control costs when trading markets include all sectors

The range in the shadow cost of the national target shows that gains can be made from a market including all sectors. The targets set by the market for the trading sector and the national target imply an overall reduction of 15.5 percent. This reduction is lower than the stipulated target by 20 per cent since the objectives of improved energy efficiency and renewable energy are not included. Since this level of reduction is close to the amount of the total carbon sink, the overall cost for meeting the target without reliability constraints amounts to 909 million Euro, which is insignificant. However, total costs increase at higher reliability levels and are close to the costs without carbon sinks at probability levels of 0.99, see figures 6a and b.

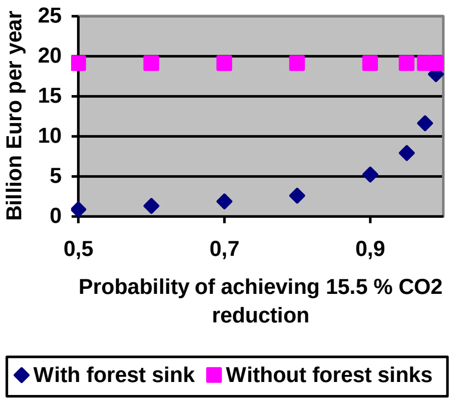

Figure 6a: Total costs of achieving 15.5 per cent CO_2 reduction on an EU wide market including all sectors without and with forest sinks at different reliability levels.

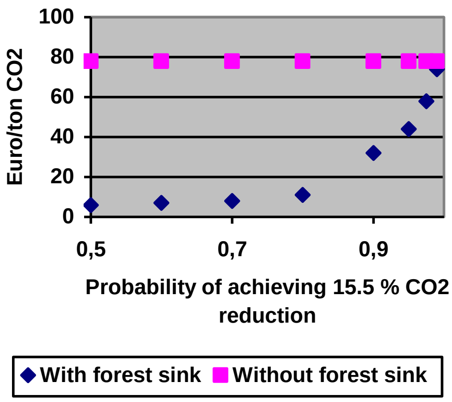

Figure 6b Marginal costs of achieving 15.5 per cent CO_2 reduction on an EU wide market including all sectors without and with forest sinks at different reliability levels

When the required probability of achieving the target increase, the gains, decreases in total and equilibrium permit price, from introduction of carbon sink decreases, and approaches zero for $\rho=0.9$. However, the difference in gains among countries is large, see table 5.

Table 5: Allocation of total control costs, MEUR/year, for an overall reduction of 15.5 per cent under different forest sink scenarios when all sectors trade.

	No sink	*Sink with $\rho=0.9$*	*Sink with $\rho=0.99$*
AT, Austria	421	87	384
BE, Belgium	597	127	554
BG, Bulgaria	250	107	243
CY, Cyprus	57	10	52
CZ, Check republic	391	216	376
DE, Germany	2706	936	2539
DK, Denmark	127	54	119
EE, Estonia	58	35	56
ES, Spain	1799	376	1656
FI, Finland	316	96	294
FR, France	1682	362	1547
GR, Greece	517	139	481
HU, Hungary	441	100	426
IE, Ireland	358	69	330
IT, Italy	2829	599	2582
LT, Lithuania	88	18	86
LU, Luxembourg	77	13	71
LV, Latvia	86	27	81
MT, Malta	18	3	17
NL, Netherlands	1354	269	1251
PO, Poland	1203	581	1154
PT, Portugal	533	93	491
RO, Romania	899	245	865
SE, Sweden	210	52	191
SI, Slovenia	104	26	97
SK, Slovakia	207	67	201
UK, United Kingdom	1772	544	1625
Total	*19112*	*5257*	*17780*
Market price of permits, Euro/ton CO_2	*78*	*32*	*74*

In average, control costs with forest sinks and a probability of 0.9 is 0.28 of total cost without the forest sink option. These cost shares vary among countries, being approximately 0.6 for Check Republic and Estonia and 0.17 for Romania and Malta. The variation in corresponding cost shares when $\rho=0.99$ is lower, between 0.91 (Sweden) and 0.98 (Lithuania). The value of forest sink for reducing overall costs for CO2 emission reduction increases for higher levels of reduction when disregarding the stochastic aspect of the sink, see figure 7.

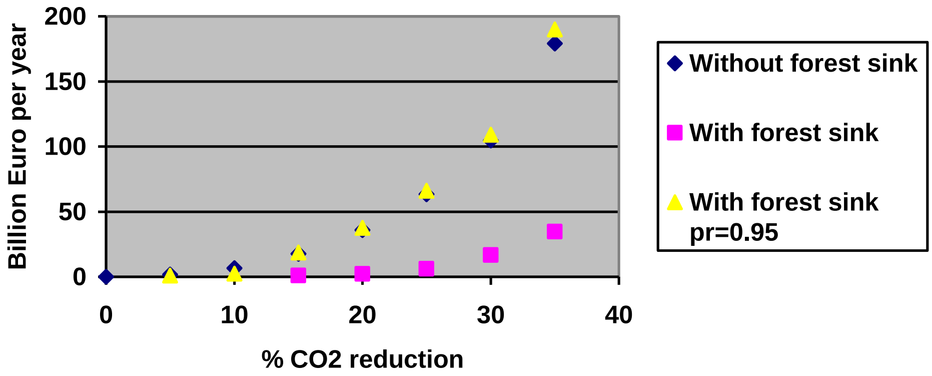

Figure 7: Total control costs with and without forest sinks for different emission reduction levels and reliability levels.

Since forest carbon sinks accounts for 14 per cent of the total emission in 2005, there are no control costs for reductions up to this level when there are no reliability constraints. At probability level of 0.95, the costs are similar to the control costs without forest sinks, slightly lower at reduction levels below 15 percent somewhat higher at larger reduction levels.

5.3 Sensitivity analysis

As reported in the modelling and data retrieval chapters, our cost functions of emission reduction rely on given price elasticities, and input prices and the use of energy in 2006, and the uncertainty quantification of forest carbon sinks is based on data from most, but not all countries. Therefore, we carry out sensitivity analysis with changes in these parameters. These are evaluated at the EU2020 targets on emissions caps for the trading sector and national commitments for each country, see table 6.

Table 6: Total and marginal costs, TC in MEURO, and MC in Euro/ton CO_2, for the EU2020 targets on the trading sector and NAP under different changes in data parameters in relation to the reference scenario.

Scenario	*No sink:*		*Sink without risk:*		*Sink with $\rho=0.9$:*	
	TC	*MC*	*TC*	*MC*	*TC*	*MC*
Price elasticities:						
Increase by 10 %	28504	16	6862	4	17353	8
Decrease by 10 %	33974	20	8250	5	20781	9
Price level:						
Increase by 10 %	34076	20	8237	5	23123	9
Decrease by 10 %	27879	16	6740	4	17012	8
Input uses:						
Increase by 5 %	49339	48	14794	6	22684[1]	9
Decrease by 5 %	18297	9	3311	2	9670	5
Forest sink capacity:						
Increase by 5 %			7114	4	18576	8
Decrease by 5 %			7908	5	19254	9

[1] $\rho=0.8$ since the solution is infeasible when $\rho=0.9$ for Romania

The results in table 6 indicate that the estimated total and marginal costs are most sensitive for changes in level of input uses under BAU. An increase in input use by 5 per cent raises the cost by 2/3 when carbon sinks are not included. The reason is the higher carbon dioxide emission levels which require larger reductions in order to meet the targets. Under the carbon sink option, the national commitment can not be met for all countries when $\rho=0.9$. A decrease in input use has the opposite impact and reduces costs under all three carbon sink options. Moderate changes in other parameters have negligible effects on total and marginal costs.

6. Conclusions

The main purpose of this paper has been to evaluate the role of including stochastic forest carbon sink as an abatement measure in the EU ETS and to meet the national commitments. A simple partial equilibrium and chance constraint model was developed where control costs for reductions in energy uses for all EU27 were calculated as decreased in consumer surplus. These costs were calculated on the basis of country wise estimates of input price elasticities. Due to the lack of cost functions for conversion of land for promoting carbon sequestration, only sequestration as a side product from forest land use was included. The results showed that this carbon sequestration corresponds to 14 per cent of total carbon dioxide emissions from fossil fuel combustion in 2005, which is a reference year for the third period of the EU ETS. According to the results, total control cost for the EU ETS and national commitment can be reduced by 3/4 by inclusion of carbon sink. However, these cost decreases are counteracted by reliability concerns. For countries with large shares of forest sink and high uncertainty as measured by the coefficient of variation, the national commitment can not be met with high reliability. On the other hand, these countries are able to meet their national commitments only by carbon sequestration without any need for costly reductions in use of energy inputs.

The European Commission has expressed its concern regarding the inclusion of sinks in the ETS. These concerns are motivated by the non-permanence of the effects of sinks, the monitoring costs and the risk that the inclusion of sinks would imply that the market for allowance would shrink to the extent that an efficient market is no longer in place due to the reduction of the number of agents in the market. This study suggest that at least in the short run, there could be substantial savings in abatement costs when sinks are included, even when monitoring is limited and hence there is considerable uncertainty about sink effects. Only when the requirement for reliability is very high, cost savings become negligible. The paper does not address the problems that might arise due to the reduced size of the market, but as discussed in the paper, the size of the market is a factor that is determined by political decisions.

However, the costs depend on the given parameter values of prices and levels of fossil fuel use, price elasticities, and carbon sink capacities. Sensitivity analysis reveal that modest changes in BAU levels of fossil fuel energy uses have the largest impacts on total costs, which can increase by 2/3 for a 5 per cent increase in input use. Changes in the other parameters had modest effects on cost estimates. The partial equilibrium approach on cost estimates is likely to have significant effects since adjustments on the energy input markets are accounted for but not all dispersions and responses by sectors from the introduction of the ETS and the national commitments. Furthermore, the EU countries were regarded as price takers on the global energy markets, which may be questionable when considering that EU accounts for 15 per cent of total oil consumption. Nevertheless, the results are relatively robust with respect to changes in several parameters and point to considerable cost savings from the introduction of forest carbon sinks, but also to the cost of reliability for stochastic carbon sinks.

Appendix A: Derivation of control cost functions

Let P_{ijh} and X_{ijh} denote the consumer price and the quantity demanded in country i $(i = 1,..,27)$ of energy source j $(j = 1,...,10)$ for sector $h=1,2$. The input demand functions are then written as

$$X_{ijh} = a_{ijh} - b_{ijh} P_{ijh} \tag{A1}$$

where a_{ijh} is a constant, which represents the intercept of the demand curve and b_{ijh} is the coefficient, which represents the slope of the demand curve. An estimate of the coefficient b_{ijh} is derived from the definition of the price elasticity of each energy input as

$$b_{ijh} = \frac{X_{ijh}' \varepsilon_{ijh}}{P_{ijh}'} \tag{A2}$$

where X_{ijh}' and P_{ijh}' are the input use and price under BAU as illustrated in figure 1. When inserting (A2) in the expression for the intercept in (A1) we obtain

$$a_{ijh} = (1 + \varepsilon_{ijh}) X_{ijh}'$$

The price function is given by the inverse demand function

$$P_{ijh} = c_{ijh} - d_{ijh} X_{ijh} \tag{A3}$$

where the intercept $c_{ijh} = \frac{a_{ijh}}{b_{ijh}}$ and the coefficient $d_{ijh} = \frac{1}{b_{ijh}}$. By using (A1) and (A2) we obtain an expression for P_{ijh} in terms of X_{ijh} and the exogenous parameters ε_{ijh}, X_{ijh}' and P_{ijh}' as

$$P_{ijh} = \frac{P_{ijh}'}{\varepsilon_{ijh}} \left((1 + \varepsilon_{ijh}) - \frac{X_{ijh}}{X_{ijh}'} \right) \tag{A4}$$

The cost function, i.e. decrease in consumer surplus, for reductions in X_{ijh} is obtained by integrating (A4) over X_{ijh} and deducting by $P_{ijh}'(X_{ijh}'-X_{ijh})$ as written in eq. (5) in the main text.

Appendix B: Tables

Figure B1: Schematic overview of Eurostat energy data. Eurostat data code in brackets. Framed boxes are used as data sources in the model.

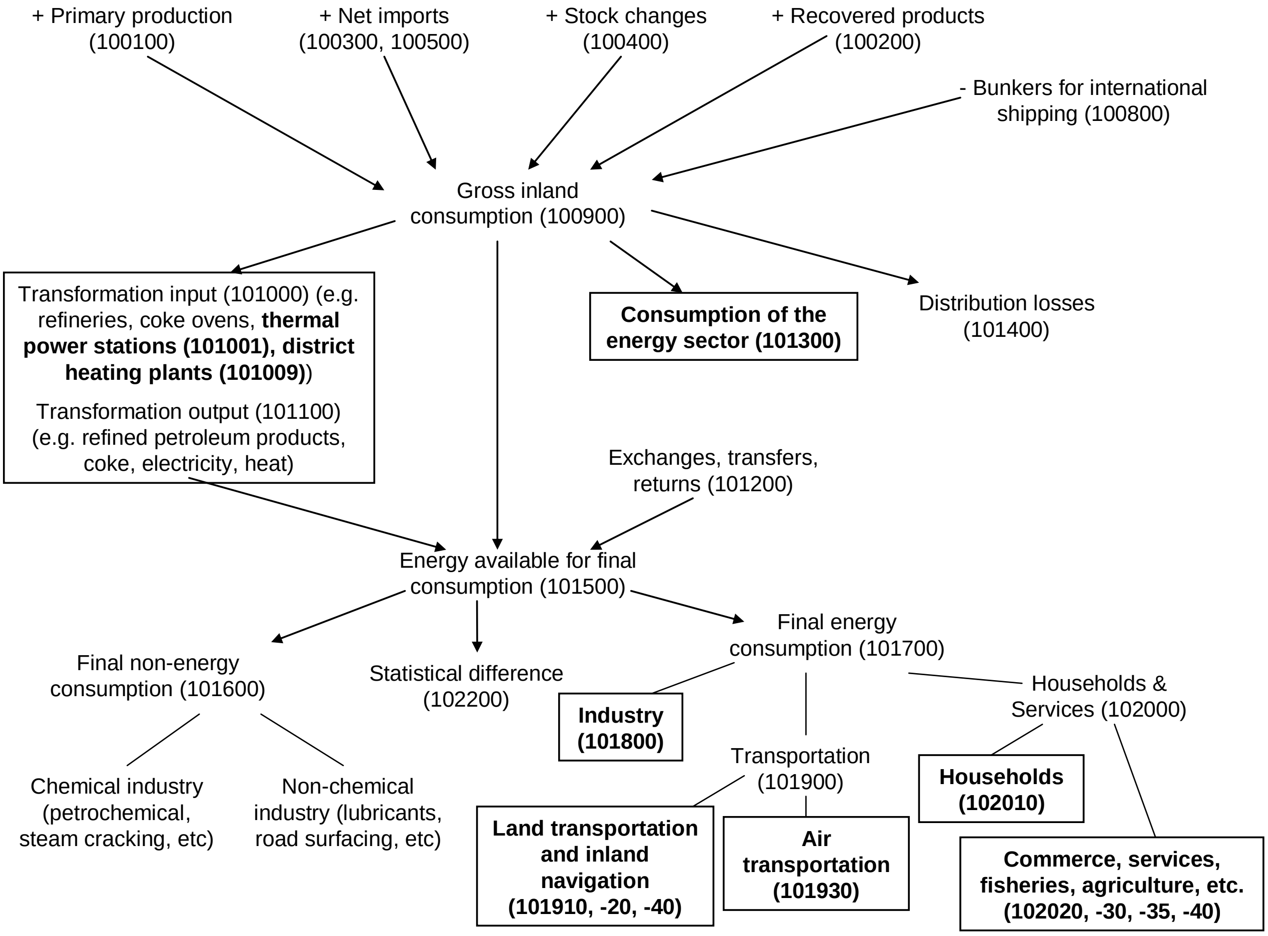

Table B1: Sectors included in the ETS and their corresponding Eurostat data sheets

ETS sectors	**Eurostat data sheet** (Data code)
Power and heat	Thermal power plants (101001) Distrct heating plants (101009)
Trading industries	Coke-oven & gas-works plants (101304) Refineries (101307) Iron & Steel (101805) Non-ferrous metal (101810) Chemical (101815) Non-metallic mineral products (101820) Paper & printing (101840)
Air transportation	Air transportation (101930)

Table B2: Sectors not included in the ETS and their corresponding Eurostat data sheets

Non-ETS sectors	**Eurostat data sheet** (Data code)
Non-trading industries & services	Electricity generation sector (101301) Mines & patent fuel/briquetting plants (101303) Oil & gas extraction (101305) Oil & gas pipelines (101306) Nuclear industry (101308) Ore extraction (except fuel) industry (101825) Food, drink & tobacco industry (101830) Textile, leather & clothing industries (101835) Engineering and other metal industry (101845) Other non-classified industries (101850) Fisheries (102020) Agriculture (102030) Services (102035) Other sectors (102040)
Households	Households (102010)
Land transportation & inland navigation	Road transportation (101920) Rail transportation (101910) Inland navigation (101940)

Table B3: Classification of petroleum fuels for different sectors

Sectors	**Petroleum fuel classification**	**Petroleum products in Eurostat** (Data code)
Power and heat Energy sector, Industry & Services	Light fuel oil/ Heating oil	Motor spirit/Gasoline (3230) Gas/Diesel oil (3260) LPG & Refinery gas (3205) Kerosene (3240)
	Heavy fuel oil	Residual fuel oil (3270) Naphtha (3250) Other petroleum products (3280)
Households	Light fuel oil/ Heating oil	All petroleum products (3200)
Land transportation & inland navigation	Gasoline	Motor spirit/Gasoline (3230)
	Diesel	Gas/Diesel oil (3260) Residual fuel oil (3270) LPG & Refinery gas (3205) Kerosene (3240)
Air transportation	Jet fuel	Motor spirit/Gasoline (3230) Kerosene (3240)

Table B4: Fossil fuel consumption in ETS sectors in 2006, 1000 tonnes of oil equivalent

ETS Sectors	Hard coal & derivatives		Lignite & derivatives		Natural & Derived gases		Light fuel oil/ Heating oil		Heavy fuel oil		Jet fuel
	C POWER	C TRIND[1]	L POWER	L TRIND 1	NG POWER	NG TRIND 1	HEAT POWER	HEAT TRIND 1	HEAVY POWER	HEAVY TRIND[1]	JET AIR[2]
EU27	148 570	37 367	90 001	2 866	144 529	75 768	4 366	31 241	23 632	35 549	51 856
AT Austria	1 328	1 328	149	2	2 706	2 271	5	511	352	564	705
BE Belgium	1 618	1 652	0	152	4 680	4 117	24	616	303	1 170	1 179
BG Bulgaria	1 614	581	4 166	15	1 036	974	13	335	106	518	204
CY Cyprus	0	37	0	0	0	0	7	0	1 093	128	308
CZ Czech	1 952	1 951	12 229	920	1 816	2 163	8	167	163	264	350
DE Germany	31 236	7 222	36 297	1 172	20 473	15 675	498	5 687	1 167	4 102	8 743
DK Denmark	5 297	170	0	0	2 182	283	69	381	350	266	919
EE Estonia	3	23	2 160	46	506	57	7	6	64	0	32
ES Spain	14 224	1 374	1 357	0	13 531	9 527	1 656	3 157	2 836	5 397	5 579
FI Finland	3 857	637	1 942	269	2 819	1 408	34	818	427	1 003	615
FR France	5 353	4 517	0	0	6 414	6 916	96	3 244	1 579	5 723	7 075
GR Greece	0	285	7 974	109	1 889	288	522	889	1 558	1 509	1 295
HU Hungary	286	435	1 707	0	3 696	1 116	40	197	130	349	272
IE Ireland	1 266	114	436	0	2 412	291	90	152	750	660	870
IT Italy	10 122	4 184	0	2	28 874	9 747	518	3 187	8 744	5 989	3 981
LT Lithuania	7	129	3	0	1 273	124	3	314	211	248	53
LU Luxembourg	0	107	0	3	550	195	0	9	0	0	405
LV Latvia	5	31	1	0	864	165	1	5	28	41	67
MT Malta	0	0	0	0	0	0	13	0	566	0	77
NL Netherlands	5 030	1 284	0	4	11 515	4 808	444	4 541	134	586	3 703
PL Poland	27 565	3 555	12 578	1	1 897	4 335	27	1 107	190	1 316	429
PT Portugal	3 276	26	0	0	2 121	752	21	135	1 085	1 246	924
RO Romania	250	1 347	6 833	115	4 244	3 546	63	918	711	809	139
SE Sweden	376	1 084	236	7	478	612	102	1 077	401	789	870
SI Slovenia	205	77	1 239	0	126	359	9	28	9	71	26
SK Slovakia	921	1 454	696	48	1 120	1 293	1	475	106	292	43
UK	32 779	3 728	0	0	26 728	7 495	88	3 319	570	2 516	12 992

1: Trading industries; 2: Air transportation

Table B5: Fossil fuel consumption in Non-ETS sectors in 2006

Non-ETS Sectors 1000 tonnes of oil equivalent	Hard coal & derivatives		Lignite & derivatives		Natural & Derived gases			Light fuel oil/ Heating oil		Heavy fuel oil	Gasoline	Diesel
	C IND&S[3]	C HOUSE[4]	L IND&S[3]	L HOUSE 4	NG IND&S[3]	NG HOUSE[4]	NG TRAN[5]	HEAT IND&S[3]	HEAT HOUSE 4	HEAVY IND&S[3]	GAS TRAN[5]	DIES TRAN[5]
EU27	5 318	7 970	1 093	1 786	100 988	120 050	646	53 036	53 190	8 125	110 058	196 187
AT Austria	15	101	8	20	1 763	1 295	0	2 106	1 587	425	2 034	4 560
BE Belgium	86	140	0	5	3 126	3 457	12	1 910	3 150	481	1 540	6 758
BG Bulgaria	84	133	11	143	607	24	25	347	25	179	636	1 868
CY Cyprus	0	0	0	0	0	0	0	126	175	38	339	279
CZ Czech	93	89	189	731	2 707	2 275	12	485	33	131	2 112	3 639
DE Germany	423	180	590	428	17 180	28 813	0	10 866	18 187	193	22 981	26 720
DK Denmark	94	0	0	0	1 415	682	0	941	558	184	1 895	2 489
EE Estonia	5	15	14	3	136	46	0	132	10	39	323	436
ES Spain	123	195	0	0	4 428	3 043	0	4 078	3 786	1 105	7 281	27 329
FI Finland	1	4	27	11	120	34	3	1 336	625	184	1 956	2 323
FR France	519	356	15	0	11 706	14 614	62	8 750	9 321	979	10 461	31 537
GR Greece	0	1	7	0	279	139	13	1 973	2 958	306	4 131	2 998
HU Hungary	8	213	8	46	2 733	3 644	3	181	181	20	1 615	2 675
IE Ireland	46	210	11	288	610	631	0	1 002	1 218	122	1 967	2 526
IT Italy	10	7	0	0	13 106	17 047	413	3 734	5 342	1 676	13 274	25 529
LT Lithuania	80	38	2	13	308	140	0	93	55	16	360	1 065
LU Luxembourg	0	0	0	0	241	247	0	86	243	2	472	1 744
LV Latvia	30	19	0	0	266	103	2	200	39	29	390	706
MT Malta	0	0	0	0	0	0	0	0	24	0	80	137
NL Netherlands	**0**	6	13	0	9 667	7 371	1	994	88	43	4 381	7 351
PL Poland	3 362	5 729	67	52	3 087	3 314	0	3 298	799	203	4 251	8 394
PT Portugal	1	0	0	0	460	203	10	1 121	665	379	1 757	4 336
RO Romania	3	0	90	10	3 191	2 548	0	1 088	452	344	1 511	2 594
SE Sweden	109	0	2	0	284	57	23	961	249	201	3 931	3 306
SI Slovenia	2	0	0	0	208	93	0	417	377	20	667	842
SK Slovakia	41	3	43	44	2 138	1 283	5	124	16	41	635	1 059
UK	265	528	0	0	18 932	28 211	0	6 932	3 026	769	19 068	23 001

3: Non-trading industries and services; 4: Households; 5: Inland navigation, rail and road transportation

Table B6: thousand tons CO2 per thousand ton of oil equivalent

Heavy fuel oil	3,279
Light fuel oil/Heating oil	3,019
Gasoline	2,901
Diesel	3,090
Jet fuel	2,994
Hard coal	3,961
Lignite	4,237
Natural gas	2,349

(Based on values for ton C per TJ from Garg, Kazunari & Pulles, 2006. Weighted averages have been calculated for fuel categories consisting of more than one type of fuel)

Table B7: **Factors for converting all prices to Euros per ton of oil equivalent (toe)**

Fuel	Euros per unit (in data source)	Ton per unit	toe per ton, tce or GJ(GCV)	Conversion factor [1/(toe/unit)]
Heavy fuel oil	Euro/ton		0,937	1,067
Heating oil	Euro/1000 l	0,842	1,030	1,153
Gasoline	Euro/1000 l	0,765	1,051	1,243
Diesel	Euro/1000 l	0,851	1,013	1,160
Jet fuel	Euro/USgallon	0,00307	1,027	317,169
Steam coal and lignite	Euro/tce		0,697	1,435
Hard coal coke	Euro/ton		0,681	1,468
Natural gas	Euro/GJ(GCV)		0,0215	46,512

(Fuel mass densities supplied by IEA 2007. Estimates of tons of oil equivalent per GJ (GCV - Gross calorific value) of natural gas and per ton of petroleum fuel and hard coal coke are obtained from Eurostat 2008.)

Table B8: Average input prices in 2006, mill Euro/ thousand TOE

	Gasoline	*Diesel,*	*Res. oil*	*Heating oil*	*Natural gas:*	
					Industry	*Household*
AT, Austria	1.42	1.12	0.35	0.771	0.45	0.66
BE, Belgium	1.75	1.16	0.28	0.59	0.35	0.70
BG, Bulgaria[3]	1.03	0.89	0.31	0.52	0.20	0.32
CY, Cyprus[4]	1.23	1.00	0.31	0.80	0.21	0.42
CZ, Check republic	1.35	1.12	0.28	0.66	0.30	0.46
DE, Germany	1.70	1.24	0.30	0.64	0.38	0.85
DK, Denmark	1.71	1.23	0.68	1.07	0.42	1.54
EE, Estonia[3]	1.15	0.97	0.3§	0.58	0.13	0.26
ES, Spain	1.37	1.07	0.37	0.64	0.35	0.61
FI, Finland	1.69	1.14	0.47	0.69	0.27	0.42
FR, France	1.63	1.20	0.33	0.67	0.35	0.65
GR, Greece	1.30	1.07	0.36	0.83	0.21	0.42
HU, Hungary[3]	1.39	1.15	0.32	1.07	0.31	0.26
IE, Ireland	1.44	1.22	0.42	0.73	0.42	0.86
IT, Italy	1.70	1.31	0.38	1.16	0.34	0.73
LT, Lithuania[3]	1.21	1.00	0.31	0.56	0.19	0.30
LU, Luxembourg	1.44	1.02	0.31	0.55	0.32	0.57
LV, Latvia[3]	1.16	0.98	0.31	0.65	0.16	0.25
MT, Malta[5]	1.44	1.09	0.31	0.61	0.21	0.42
NL, Netherlands	1.89	1.21	0.35	0.92	0.40	0.79
PO, Poland	1.32	1.09	0.29	0.65	0.26	0.42
PT, Portugal	1.64	1.14	0.40	0.70	0.36	0.73
RO, Romania[3]	1.03	0.89	0.31	0.52	0.24	0.32
SE, Sweden	1.65	1.30	0.80	1.07	0.55	1.19
SI, Slovenia[3]	1.26	1.05	0.38	0.64	0.33	0.69
SK, Slovakia[3]	1.38	1.18	0.27	0.68	0.30	0.66
UK, United Kingdom	1.74	1.55	0.43	0.59	0.39	0.38
Steam coal price: 0.167 Jet fuel: 0.504						

Table B9: Own price elasticities in absolute terms of oil, coal, natural gas and gasoline

	Oil[1]	*Coal*[1]	*Natural gas*[1]	*Gasoline*[2]
AT, Austria	0.45	0.41	0.46	0.59
BE, Belgium	0.63	0.40	0.37	0.71
BG, Bulgaria[3]	0.80	0.59	0.58	0.50
CY, Cyprus[4]	0.51	0.62	0.55	1.12
CZ, Check republic	0.60	0.49	0.39	0.50
DE, Germany	0.58	0.61	0.35	0.57
DK, Denmark	0.47	0.68	0.45	0.64
EE, Estonia[3]	0.80	0.59	0.58	0.50
ES, Spain	0.45	0.60	0.54	0.30
FI, Finland	0.58	0.58	0.64	1.23
FR, France	0.52	0.37	0.30	0.70
GR, Greece	0.51	0.62	0.55	1.12
HU, Hungary[3]	0.80	0.59	0.58	0.50
IE, Ireland	0.58	0.67	0.53	1.68
IT, Itlay	0.44	0.42	0.37	1.15
LT, Lithuania[3]	0.80	0.59	0.58	0.50
LU, Luxembourg	0.63	0.40	0.37	0.71
LV, Latvia[3]	0.80	0.59	0.58	0.50
MT, Malta[5]	0.44	0.42	0.37	0.71
NL, Netherlands	0.42	0.49	0.33	2.29
PO, Poland	0.43	0.57	0.38	0.50
PT, Portugal	0.58	0.57	0.50	0.67
RO, Romania[3]	0.80	0.59	0.58	0.50
SE, Sweden	0.56	0.35	0.51	0.46
SI, Slovenia[3]	0.80	0.59	0.58	0.50
SK, Slovakia[3]	0.80	0.59	0.58	0.50
UK, United Kingdom	0.39	0.58	0.32	0.45
Jet air: 0.05[6]				

1) Holtsmark and Maestad (2002)
2) Graham and Gleister (2002)
3) regarded as ‘economies in transition’ in Holtsmark and Maestad (2002)
4) assumed to be the same as for Greece
5) assumed to be the same as for Italy
6) Wohlgemut (1997)

Table B10: Forest land, emission factors and total carbon sink

A. Total Forest Land	Forest land area (kha)			Emission Factors; Net CO2 emissions(+)/removals(-); Mg C/ha						Total (Gg)
	Total	Mineral	Organic	Living biomass	Dead organic matter	Soil, Mineral	Soil, Organic	Aggregate, Mineral	Aggregate, Organic	Net CO2 emssions/ removals
EU 24	155 544,80	143 465,10	12 079,69							-561 325,24
EU 15	121 286,86	110 431,27	10 855,59	-0,85	0,01	-0,14	0,18	-0,98	-0,65	-421 040,35
Austria	3 619,89	3 619,89		-1,31	-0,05	-0,13		-1,49	-1,35	-19 729,23
Belgium	620,98	620,98		-1,18	0,00	-0,04		-1,22	-1,18	-2 776,94
Bulgaria	4 076,46	4 076,46		-0,47				-0,47	-0,47	-6 996,04
Czech Republic	2 592,95	2 574,29	18,67	-0,48	0,00	0,00	0,00	-0,48	-0,48	-4 591,19
Denmark	475,60	457,97	17,63	-1,57		-0,01		-1,58	-1,57	-2 757,66
Estonia	2 251,90	1 480,28	771,62	-0,81			1,09	-0,81	0,28	-3 591,63
Finland	22 145,69	16 104,75	6 040,94	-0,52	-0,03	-0,06	0,33	-0,61	-0,22	-40 879,01
France	16 384,23	16 384,23	0,00	-1,59	0,22	-0,05	0,00	-1,41	-1,36	-84 745,64
Germany	10 798,94	10 798,94		-2,00				-2,00	-2,00	-79 049,75
Greece	6 560,21	6 560,21	0,00	-0,19	0,01	0,00	0,00	-0,18	-0,18	-4 432,02
Hungary	1 805,80	1 805,80		-0,70				-0,70	-0,70	-4 661,00
Ireland	554,00	543,15	10,84	-0,69	-0,01	0,14	3,95	-0,56	3,25	-978,20
Italy	11 261,38	11 261,38		-1,08	-0,20	-1,02		-2,30	-1,28	-94 883,76
Latvia	2 929,00	2 929,00		-1,66	-0,01			-1,67	-1,67	-17 935,82
Lithuania	2 030,00	2 030,00		-1,14				-1,14	-1,14	-8 487,01
Netherlands	478,80	478,80		-1,24	-0,19			-1,43	-1,43	-2 509,28
Poland	8 990,62	8 752,24	238,38	-1,22		-0,44		-1,66	-1,22	-54 266,11
Portugal	3 475,78	3 475,78		-0,47	0,00	-0,01		-0,48	-0,46	-6 062,78
Romania	6 754,70	6 754,70		-1,51				-1,51	-1,51	-37 520,68
Slovakia	1 932,00	1 927,11	4,89	-0,36	-0,07			-0,44	-0,44	-3 096,83
Slovenia	1 173,85	1 173,85		-1,10				-1,10	-1,10	-4 733,09
Spain	14 190,94	14 190,94		-0,64				-0,64	-0,64	-33 473,62
Sweden	27 946,73	23 235,51	4 711,22	-0,27	-0,03	-0,06	0,44	-0,36	0,15	-27 925,15
United Kingdom	2 494,35	2 228,84	265,50	-1,23	-0,13	-0,27	-0,54	-1,64	-1,91	-15 242,81

Source: UNFCCC national inventory submissions Common Reporting Format (CRF) spreadsheets, as reported per February 2009*
http://unfccc.int/national_reports/annex_i_ghg_inventories/national_inventories_submissions/items/4303.php

Appendix C: Brief presentation of the BAU emissions in 2020

PRIMES (as described in Capros et al 2008a) is a partial equilibrium model of energy supply and demand in the European Union for the medium and long term running up to 2030. Energy demand and supply, prices and investments are determined endogenously. The projections depend on existing stocks of capital and investment in new plants or equipment is driven by economic optimization, with the exception of diverging national energy policies (e.g. on nuclear) and plants already planned or under construction. Technical-economic characteristics of existing and new technologies evolve according to exogenously given trends. Discount factors involve risk premiums and vary from 8% for large utilities up to 20% for individual households. New technologies are subject to additional risk premiums at their early stages of development before they get sufficiently mature.

Policies supporting or regulating energy technologies (mainly nuclear power, renewable energies and cogeneration) are extrapolated from past trends without assuming any new initiatives. Legislation that was in place up to year 2006, including EU directives that are adopted but yet implemented by the Member States, is assumed to be effectively implemented. Tax rates are, in real terms, kept constant at 2006 levels, unless otherwise stated in the Energy Taxation Directive. The ETS is assumed to operate under the current setting, with a carbon price of 20€/tCO_2 in 2010 rising smoothly to 24€/tCO_2 in 2030 (real prices in 2005 terms).

The PRIMES model Baseline scenario is put in a global context through a global energy scenario based on the POLES and Promotheus models. Global GDP is assumed to increase with 3.3% per year, while global energy intensity decreases by 1.7% per year. In 2020 primary energy consumption is projected to be about 20% lager than in 2010 and 50% larger than in 2001. Consumption of fossil fuels rises with 70%, 40% and 60% for natural gas, oil and coal (lignite) respectively from 2001 to 2020, from 2010 to 2020 the projected increases are 35%, 20% and 15%. World fossil fuel prices are projected to evolve as in Table C1.

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- **Table C1. Fossil fuel price projections in Capros et al 2008a**

- $[1](2005)/boe[2]	- 2005	- 2010	- 2015	- 2020
- Oil	- 54.5	- 54.5	- 57.9	- 61.1
- Gas	- 34.6	- 41.5	- 43.4	- 46.0
- Coal	- 14.8	- 13.7	- 14.3	- 14.7

- 1) At 1.25$/€; 2) barrel of oil equivalent

In the EU27 population is assumed to remain stable but, given declining household size, the number of households will increase. GDP is expected to grow at 2.2% per year over the period. GDP per capita in the Member States is expected to partly converge, with annual growth rates at 2.0% in EU15 and 4.1% in the 12 new Member States. Structural change in the EU economy is assumed, with value added in industrial sectors growing at around 1.9% per year while service sectors have a growth rate of 2.3%. Transportation activity growth gradually decouples from GDP growth. Freight transport is expected to grow 1.7% per year, while passenger transport increase at an annual rate of 1.4%, with a shift towards air transportation which is expected to grow at 3.1%.

Given all assumptions, the base line emissions in 2020 are calculated as presented in Table C2

Table C2: Baseline emissions in 2020

GHGs Mton CO2-equivalents	*2020 (Baseline)*
All GHGs	5496
All CO_2	4610
ETS	2557
- ETS without aviation	2339
- Aviation	218
Non-ETS	2940
- Energy related Non-ETS	2054
- Non CO2 GHGs	886

Source: Capros et al 2008b, tables 2 & 4.

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