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Is forest sequestration at the expense of bioenergy and forest products cost-effective in EU climate policy to 2050?

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Abstract

Forest management affects the quantity of CO_2 emissions in the atmosphere by carbon sequestration in standing biomass, carbon storage in forest products and production of bioenergy that replace fossil fuels. The main question in this paper is whether forest sequestration is worth increasing at the expense of bioenergy and forest products to achieve EU's emission reduction target to 2050 cost-effectively. The assessment is based on numerical calculations using a dynamic, partial equilibrium model of cost-effective solutions, where three abatement methods in the forest sector are included together with abatement in the fossil fuel sector. The results show that forest sequestration in standing biomass is cost-effective compared to bioenergy. When sequestration is taken into account, net present costs for meeting EU carbon targets can be reduced by 18%. This is achieved through an increase in annual carbon sequestration by 30-158 million ton CO_2. The overall cost of reaching the 80 per cent carbon reduction target amounts to 2,002 billion Euros when sequestration is included in the policy, but increases to 2,371 billion Euros without sequestration. Results suggest that forests can serve as a cost-efficient carbon sink over the considered time period.

Key words: bioenergy, cost-effectiveness, dynamic partial equilibrium, EU climate policy, forest carbon sequestration

1. Introduction

Forests are important in a climate perspective since carbon can be sequestered in standing biomass, or stored in forest products. Alternatively forest can produce bioenergy that can replace fossil fuels. In a cost-effective climate policy, it is, hence, important to recognize the abatement potentials in forests. Several studies show that sequestration account for 10-50 per cent of emission reductions globally in a cost-effective climate policy (Bosetti et al., 2009; Murray et al., 2009; Sohngen, 2009). Despite the high potential and relatively low cost of sequestration, it has only partially been included in international climate agreements such as the Kyoto Protocol.

EU's climate policy framework does not recognize emission reductions in the forest sector, apart from bioenergy. The main reasons are lack of appropriate and harmonized data due to measuring and monitoring problems as well as non-harmonized reporting methods across EU countries (European Commission, 2012a). However, forest sequestration is often viewed as a more effective method to reduce emissions than bioenergy (e.g. Holtsmark, 2012; Hudiburg et al., 2011; Johnson, 2009; Schulze et al., 2012). The main reason is that bioenergy is not necessarily carbon neutral in the short-term, albeit this is sometimes argued to be the case (Bright and Stromman, 2009; European Union, 2003; Petersen and Solberg, 2005; Sjolie et al. 2010). There are two explanations for the lack of carbon neutrality: *(i)* a long time-lag appears between biomass combustion, when emissions are emitted to the atmosphere, and forest regrowth, when emissions are sequestered; and *(ii)* a substantial amount of carbon is emitted to the atmosphere from harvesting, transporting and processing. As long as forest sequestration and bioenergy are not treated in a cost-efficient manner in EU climate policy, there is a risk that European forests become a carbon emission source rather than a sink in the future (Böttcher et al., 2012).

The European Commission (2012a,b) has acknowledged the importance of forest sequestration and has put forward three possible strategies to include the land use sectors in EU climate policy: (*i)* inclusion in the EU Emission Trading Scheme (ETS), (*ii)* inclusion in the non-trading sector, which covers most sectors not in the ETS, or (*iii)* through a new and separate target and commitment.

With a long-term perspective, the European Commission (2011) has proposed a roadmap for moving to a competitive, low carbon economy in 2050. This roadmap proposes reductions of greenhouse gases in the range of 80-95 per cent by 2050 compared to the level in 1990. The roadmap focuses on achieving this target range cost-effectively, implying that low cost abatement options such as forest sequestration could be accepted and cost-effective policy instruments could continue to dominate.

The main purpose of this study is to assess whether it is worth increasing the amount of forest sequestration at the expense of bioenergy and forest products to cost-effectively achieve the EU carbon emission reduction target to 2050. Forest sequestration in standing biomass, forest products and bioenergy are closely connected in physical terms, and their impacts on carbon release and uptake differ. The deployment of one of these abatement methods means an equivalent change in one or both of the other two. For the assessment, a dynamic partial equilibrium model is used in which abatement costs are minimized subject to the achievement of an 80 per cent reduction in CO_2 emissions by 2050, compared to the level in 1990. Abatement in the fossil fuel sector is also part of the model. The benefit of using a dynamic model is that it takes several years into account, which means that the non-linear natural growth of forests can be accommodated for. The analysis only considers the additional sequestration, which is here defined as the additional amount of sequestration achieved when forest harvests are reduced compared to current levels.

Our modeling approach is related to previous work in the field of cost-effective abatement strategies to reduce greenhouse gas emissions in the land use sectors and our empirical application is related to the choice between abatement methods in the forest sector. When modeling cost-effective abatement strategies, many studies take a static perspective (e.g. Dixon et al., 2008; Eliasch, 2008; Gren et al., 2012), while Van der Werf and Peterson (2009) highlight the importance of covering several decades to accommodate for the dynamic effects, since forest biomass follow a non-linear growth path at the stand level. Existing dynamic optimization models, covering different geographic areas at different levels of aggregation are found in Adams et al. (1996, 1999); Alig et al. (1997); Gielen et al. (2002); Lee et al. (2005); Rokityanskiy et al. (2007); Sathaye et al. (2005); Schneider et al. (2008); Sohngen and Mendelsohn (2003); Tavoni et al. (2007); Van Kooten (1999); Van't Veld and Platinga (2004).

These models incorporate forest sequestration by means of a non-linear forest biomass growth function, which vary in shape between models due to differences in functional form e.g. exponential, quadratic, etc. and accompanying parameter values. In this matter, our model follows van Kooten (1999) by using a specific exponential function for biomass growth that reflects natural growth. At any point in time, the level of sequestration in forests depends on the forest biomass growth and endogenously determined harvests i.e. harvests are quantified within the model. This harvest specification follows most of the models above, apart from Gielen et al. (2002) and Sathaye et al. (2005), which do not provide any details regarding harvest. Our specification of abatement costs follows Adams et al. (1996, 1999) and Alig et al. (1997), who calculated abatement costs as reductions in consumer and producer surplus in the agriculture and forestry markets. However, we only include the markets for some specific forestry products. Abatement in the fossil fuel sector is also possible in the models by Sohngen and Mendelsohn (2003), Tavoni et al. (2007) and Van't Veld and Platinga (2004). We follow this inclusion, but incorporate fossil fuels directly into our model instead of linking-the land use sector model to some integrated assessment model.

In our empirical application, we study the choice between bioenergy and sequestration in forest biomass or storage in forest products. This choice have previously been addressed by Gielen et al. (2002); Hedenus and Azar (2009) and Schneider and McCarl (2003) with diverging conclusions, which are described in the discussion in section 5. In that perspective, it is presently unclear how European forest resources should be used cost-effectively to contribute to carbon emission reductions. We therefore aim to add to the literature by modelling the choice between different forest abatement methods in Europe, where each country has a unique forest biomass volume function and where abatement options in the fossil fuel sector is also possible under the condition of cost-effectiveness. As far as we are aware, no previous models have incorporated these aspects together.

Our calculations show that the abatement cost can be reduced by recognizing additional sequestration as an abatement method in EU climate policy. This cost reduction is explained by the sequestration potential in both forests and forest products and a comparatively low cost of reducing bioenergy production in favour of sequestration. The level of additional sequestration is however quite small, which means that large reductions must be made in the fossil fuel sector as well. The results also show that additional sequestration increases until 2048 and then falls slowly, meaning that the saturation level where sequestration is nil or negative is never reached during the studied period.

The paper is organized as follows. Section 2 theoretically describes the dynamic partial equilibrium model used to analyse the contribution of sequestration to EU's climate change policy and section 3 presents the empirical model and the associated input data. The results are presented and analysed in section 4, followed by discussions and conclusions in section 5.

2. Method

Cost-effective solutions to reach the CO_2 emission reduction targets are calculated based on a non-linear, dynamic programming model. It is assumed that the ultimate objective of the EU policy maker is to achieve the emission target until 2050 at minimum cost. Four abatement strategies are available: 1) carbon sequestration in standing biomass; 2) incremental carbon storage in forest products; 3) bioenergy; and 4) reduction in fossil fuel consumption. Sequestration is achieved through reduced harvests. The model covers 27 EU member states and has five endogenous decision variables: the level of forest products, bioenergy, coal, oil and gas.

2.1 The model

The amount of forest sequestration is determined by the standing biomass volume, V_t^i, in country, i, with $i=1\ldots z$, at time, t, with $t= 1\ldots.T$ years. Standing biomass volume in the next year, V_{t+1}^{i} , is determined by the volume in the previous year, its growth, $G_t^i(V_t^i)$, and harvest, H_t^i, at the end of the previous year, as follows:

$$V_{t+1}^{i} = V_t^i + G_t^i(V_t^i) - H_t^i \tag{1}$$

$$V_0^i = \overline{V^i}$$

where, $\overline{V^i}$, is the actual standing biomass volume in each country in the first year. Growth in standing biomass volume, $G_t^i(V_t^i)$, is a continuous, concave function in V_t^i. Standing biomass volume, its growth and harvest are all measured in cubic meters per hectare (m^3/ha). By multiplying the harvest level with the total forest area, A^i, measured in ha, we get the total harvested volume in m^3 per country and year. The harvested volume is used for production of either bioenergy, B_t^i, or forest products, F_t^i:

$$A^i H_t^i = B_t^i + F_t^i \tag{2}$$

Forest products include all products made of wood, except bioenergy. Bioenergy and forest products are both measured in m^3. Without CO_2 emission reduction targets, it is assumed that the production level of bioenergy and forest products are constant over time.

Forest sequestration, S_t^i, measured in ton CO_2 removed from the atmosphere, is calculated as the difference in standing biomass volumes between years. This difference is multiplied with the area and the conversion parameter, η^i, which translates biomass volumes into CO_2 emissions:

$$S_t^i = \eta^i A^i (V_{t+1}^i - V_t^i) \tag{3}$$

It is assumed that forest products have the same carbon content per cubic meter as standing forest. Forest products, such as houses and furniture, can store carbon for a very long time, and we therefore assume that constitute a permanent carbon sink as is done in Adams et al. (1993).

Emissions of CO_2 to the atmosphere stem from consumption of fossil fuels and production of bioenergy. Fossil fuel emissions stem from the combustion of fuels and are determined by the quantities consumed, X_t^{ij}, by fossil fuel type, *j*, with *j=1…w*. Fossil fuels are measured in ton oil equivalents (toe). Bioenergy emissions stem from harvest, transport, processing and combustion of bioenergy and are determined by the quantities produced. Bioenergy is assumed to replace fossil fuels. Hence, the quantity of bioenergy produced is first subtracted from the quantity of fossil fuels consumed, given that also bioenergy is converted to toe by a parameter, γ. Emissions to the atmosphere are then calculated by converting the net quantity of fossil fuels into emissions, measured in ton CO_2, by the conversion factors, α^j. Secondly, emissions from bioenergy are added to the net emission equation. The parameter, φ , is used to calculate net CO_2 emissions, in ton per m^3, emitted to the atmosphere when forests are harvested, transported, processed and burnt.

Total net emissions to the atmosphere must be lower or equal to the emission target, E_t^{MAX} , each year. These yearly targets are determined by EU climate policy to 2050 regarding the maximum amount of emissions to the atmosphere:

$$E_t = \sum_i (\sum_j \alpha^j (X_t^{ij} - \gamma B_t^i) + \varphi B_t^i - \eta^i F_t^i - S_t^i)) \leq E_t^{MAX} \qquad (4)$$

where $\partial E_t / \partial X_t^{ij} > 0$, $\partial E_t / \partial B_t^i >< 0$, $\partial E_t / \partial F_t^i < 0$ and $\partial E_t / \partial S_t^i < 0$

The abatement cost incurred by forest owners for reduction in bioenergy and forest products is denoted, $C_t^{iB}(\hat{B}^i - B_t^i)$, and, $C_t^{iF}(\hat{F}^i - F_t^i)$, respectively, where $\hat{B}^i$ and $\hat{F}^i$ are the Business As Usual (BAU) levels, assumed constant over the time period considered. These reductions will lead to an increased level of sequestration in forests. The cost functions are both assumed to be continuous, decreasing and convex in B_t^i and F_t^i , respectively. The abatement cost related to fossil fuel reductions is denoted, $C_t^{ij}(\hat{X}^{ij} - X_t^{ij})$, where $\hat{X}^{ij}$ is the BAU levels, assumed constant over the time period considered. This cost function is assumed to be continuous, decreasing and convex in X_t^{ij} .

The decision problem of the policy maker under the EU 2050 scenario is then formulated as the minimization of total abatement costs in present value terms:

$$\underset{B_t^i, F_t^i X_t^{ij}}{Min} \quad TC = \sum_t \sum_i \rho^t \left(C_t^{iB} (\hat{B}^i - B_t^i) + C_t^{iF} (\hat{F}^i - F_t^i) + \sum_j C_t^{ij} (\hat{X}^{ij} - X_t^{ij}) \right) \tag{5}$$

subject to (1)-(4) and

$$0 \le B_t^i \le \hat{B}^i, \qquad \forall i,t$$

$$0 \le F_t^i \le \hat{F}^i, \qquad \forall i,t$$

$$0 \le X_t^{ij} \le \hat{X}^{ij}, \forall i,j,t$$

where $\rho = \dfrac{1}{(1+\delta)}$ is the discount factor and, δ , is the discount rate. The conditions imply that bioenergy, forest products and fossil fuels must be positive and not increase beyond the BAU level.

In order to solve the decision problem defined by (1)-(5), assuming an interior solution, the Lagrangian for discrete time is set up:

$$L=\sum_t\sum_i \rho^t\left[\begin{array}{l} C_t^{iB}(\hat{B}^i-B_t^i)+C_t^{iF}(\hat{F}^i-F_t^i)+\sum_j C_t^{ij}(\hat{X}^{ij}-X_t^{ij})- \\ \rho\mu_{t+1}^i(V_t^i+G_t^i(V_t^i)-H_t^i-V_{t+1}^i)- \\ \lambda_t(-\sum_j \alpha^j(X_t^{ij}-\gamma B_t^i)-\varphi B_t^i+\eta^i F_t^i+S_t^i+E_t^{MAX}) \end{array}\right] \tag{6}$$

Equations (1)-(5) define a non-convex optimization problem. The cost-effective allocation of emission reductions can be determined from the solution to (5). We derive the necessary first order conditions for cost minimization (Appendix A shows the stepwise derivation), which give the optimal allocation of B_t^i, F_t^i, X_t^{ij} and V_t^i:

$$\frac{\partial L}{\partial B_t^i}=\rho^t\left[\frac{\partial C_t^{iB}(\hat{B}^i-B_t^i)}{\partial B_t^i}+\rho\mu_{t+1}^i\frac{1}{A^i}-\lambda_t(\sum_j \alpha^j\gamma-\varphi)\right]=0 \tag{7}$$

$$\frac{\partial L}{\partial F_t^i}=\rho^t\left[\frac{\partial C_t^{iF}(\hat{F}^i-F_t^i)}{\partial F_t^i}+\rho\mu_{t+1}^i\frac{1}{A^i}-\lambda_t\eta^i\right]=0 \tag{8}$$

$$\frac{\partial L}{\partial X_t^{ij}}=\rho^t\left[\frac{\partial C_t^{ij}(\hat{X}^{ij}-X_t^{ij})}{\partial X_t^{ij}}+\lambda_t\alpha^j\right]=0 \tag{9}$$

$$\frac{\partial L}{\partial V_t^i} = \rho^t \left[\mu_t^i - \rho \mu_{t+1}^i (1 + \frac{\partial G_t^i}{\partial V_t^i}) + \eta^i A^i (\lambda_t - \rho \lambda_{t+1}) \right] = 0 \qquad (10)$$

where μ_{t+1}^i and λ_t are the Lagrange multipliers, where the first is positive and the second negative. These multipliers are the shadow prices for the stock of standing biomass volume and the emission reduction target, respectively. In a cost minimization problem, a positive μ_{t+1}^i means that a unit increase in the stock of standing biomass volume would reduce the objective value, the total abatement cost in optimum, with that amount and vice versa. A negative λ_t means that an unit increase in the emission target would decrease the objective value with that amount in optimum and vice versa. The shadow price for the emission target can be used to illustrate cost-effective design of economic instruments since it is equal to the efficient carbon tax, or, equivalently, the allowance price under a cap-and-trade system.

Equation (7) and (8) can be rewritten in terms of marginal cost of a unit reduction in bioenergy and forest products in period, *t,* respectively:

$$\frac{\partial C_t^{iB} (\hat{B}^i - B_t^i)}{\partial B_t^i} = \lambda_t (\sum_j \alpha^j \gamma - \varphi) - \rho \mu_{t+1}^i \frac{1}{A^i} \qquad (11)$$

$$\frac{\partial C_t^{iF}(\hat{F}^i - F_t^i)}{\partial F_t^i} = \lambda_t \eta^i - \rho \mu_{t+1}^i \frac{1}{A^i} \tag{12}$$

Cost-efficient production of bioenergy and forest products are thus determined by the shadow price for the emission reduction target and the discounted shadow price in the next period of not harvesting an additional unit today, multiplied by their respective impacts. The impacts in the first terms on the right-hand side of (11), $\sum_j \alpha^j \gamma - \varphi$, and (12), η^i, are the net emissions per unit of bioenergy and the incremental carbon stored per unit of forest products, respectively. The effects in the second terms of (11) and (12), $\frac{1}{A^i}$, imply that the next period's shadow price of not harvesting an additional unit today is divided by the forest area, A^i.

Equation (9) can be rewritten in terms of marginal cost of an additional unit of fossil fuel reduction in period, *t:*

$$\frac{\partial C_t^{ij}(\hat{X}^{ij} - X_t^{ij})}{\partial X_t^{ij}} = -\lambda_t \alpha^j \tag{13}$$

The marginal cost is determined by the Lagrange multiplier of the emission reduction target, λ_t and the impact, α^j, on this target from a marginal reduction in fossil fuel consumption, which is determined by the carbon content of fossil fuels.

Conditions (11) to (13) show that the marginal cost differs across abatement methods.

Condition (10) can be rewritten and show dynamic effectiveness:

$$\mu_t^i + \lambda_t \eta^i A^i = \rho \mu_{t+1}^i (1 + \frac{\partial G_t^i}{\partial V_t^i}) + \rho \lambda_{t+1} \eta^i A^i \tag{14}$$

The left-hand side of (14) shows the shadow prices of standing biomass volume and the emission target, respectively. The right-hand side of (14) shows the discounted shadow price of the next period's standing biomass volume and the emission target, respectively. Here the change in biomass volume growth from a marginal change in biomass volume, $\frac{\partial G_t^i}{\partial V_t^i}$, is taken into account. When condition (14) holds we have found the optimal management of forests and there is no room for net cost savings by reallocating abatement between years, since the marginal cost of achieving the target is equal across time, as expressed in present value terms.

Everything else equal, a larger impact on emissions implies higher use of an abatement measure. With regards to forest resources, this means that if we take a static view on the problem, sequestration in forests should not be increased at the expense of forest products, since that carries a cost, and both have the same climate impact. However, due to the dynamics in forest sequestration it can potentially be worth increasing sequestration at the expense of forest products, provided that this increases future forest growth. Hence, it can be cost-effective to increase sequestration in forests through costly reductions in both bioenergy and forest products.

3. Empirical model and data

The empirical model is built in the GAMS software, using the CONOPT3 solver for all calculations (Brooke et al., 1998). The model is divided into yearly time periods, starting in 2010 and ending in 2050, where all costs are discounted with a three per cent annual discount rate. The literature regarding the choice of discount rate in the field of economics of climate change is vast and the issue has been debated intensively following the Stern review (Stern, 2008) by e.g. Dasgupta, (2008); and Weitzman, (2007, 2010). From this debate it is possible to argue for both a high and a low discount rate, which may also vary between countries. We thus make a simplification here by using a uniform, constant discount rate for all countries.

3.1 Abatement in the forest sector

The forest sector is restricted to the carbon pools of standing biomass volume, forest products and bioenergy in each country. There is no distinction between tree species due to lack of data. The calculation of standing biomass volume, V_t^i, is based on the so called Chapman-Richard (C-R) function (Bjornstad and Skonhoft, 2002; Van Kooten, 1999), which is an exponential, s-shaped function that measures cumulative standing biomass volume in m^3/ha over the age, y_t^i, of the forest, as follows:

$$
\begin{aligned}
V_t^i(y_t^i) &= k^i (y_t^i)^{m^i} e^{-n^i y_t^i} \\
V_0^i(y_0^i) &= \overline{V}(\overline{y^i})
\end{aligned}
\tag{15}
$$

where, k^i, m^i, and n^i, are positive parameters that are country specific and determined by tree species, soil fertility, temperature and forest management. We assume that this function can be applied to the average-aged forest stand in the different countries. Parameters have been calibrated for each country based on Bjornstad's and Skonhoft's (2002) estimated C-R function for Norwegian spruce, grown in unmanaged forests i.e. non-harvested. These estimates are used because that would avoid double counting of harvests in our model.

For the calibration, we use the average standing biomass volume per hectare and associated average forest age in 2010. We also assume that standing biomass volume in all countries has the same maximum volume as in (Bjornstad and Skonhoft, 2002), 849 m3/ha, but that they can reach this at different age of the average stand. A comparison with estimates in Christensen et al. (2005), shows that our assumption of a maximum volume of 849 m3/ha is within the range found in beech reserves in Belgium, Czech Republic, Germany, Slovakia and Slovenia that have a living wood volume between 772 and 876 m^3/ha. The parameters k^i and n^i are calibrated for the functions to fit these data. The annual increment per hectare in 2010 (Eurostat, 2011) is used to evaluate the fitted C-R functions, and this comparison shows that reasonable estimates of annual growth are obtained. The growth in standing biomass volumes are also within reasonable limits of those reported in Nabuurs and Lioubimov (2000). Their maximum net annual increment for spruce is approximately 7 m^3/ha per year, at an age of 95. Our estimates are varying between 6 and 13 m^3/ha for ages 60-110 years, with most countries at the lower end of this range.

The 27 individual C-R functions so obtained reflect that forests generally grow faster in temperate than boreal forests, which is supported by the literature (e.g. Holtsmark, 2012; McKechnie et al., 2011. The average age, standing biomass volume, forest area, real increment and calibrated increment in 2010 can be found in Appendix C, Table C1. The calibrated C-R parameters are found in Table C2. Due to the large influence of age and volume on the shape of the growth functions, sensitivity analysis is carried out in the results section.

The growth, $G_t^i(V_t^i)$, in standing biomass volume is calculated by taking the derivative of the volume function with respect to age:

$$G_t^i(V_t^i) = \frac{\partial V_t^i(y)}{\partial y_t^i} = m^i \frac{V_t^i(y_t^i)}{y_t^i} - n^i V_t^i(y_t^i) \quad (16)$$

The average age of the forest is varying over time due to forest growth and harvests and is calculated from (15).

The increase between consecutive years in standing biomass volume is converted to CO_2-sequestration, by the parameter, η^i , for which data is obtained from IPCC, (2006), see Appendix B.

Bioenergy in the form of fuel wood, pellets and wood chips, are often used for space heating and power generation in Europe and hence replace fossil fuels. Following, e.g., Holtsmark (2012), Kirchbaum (2002) and Van Kooten (1999), we assume that bioenergy will replace coal in Combined Heat and Power (CHP) plants, since coal has the highest carbon content, which implies that such replacement reduces emissions the most. The calculation of net emissions from bioenergy is based on the substitution for fossil fuels as well as emissions stemming from harvesting, transporting, processing and burning bioenergy (Petersen, 2006; Holtsmark, 2012), as is explained in Appendix B.

3.2 Cost functions for reducing bioenergy and forest products

The cost of reducing the production of bioenergy and forest products, for the benefit of increased forest sequestration, is defined as reductions in producer surplus from foregone sales of these products on their respective markets. The producer surplus is the area above the inverse supply function, bounded by the observed market price of the product. The inverse supply functions of bioenergy and forest products are calculated in a similar manner; hence we only show the calculation for bioenergy in Appendix A.

Restrictions are imposed on bioenergy and forest product production, which imply that they must be positive and lower/equal to the 2010 BAU level. The sum in volume, of bioenergy and forest products is equivalent to total harvest volumes, data can be found in Appendix C, Table C3. It is assumed that the prices of bioenergy and forest products are the same each time period and that the producers are price takers on the markets for these products. Most countries do not provide prices, therefore it is assumed that the price of forest products and bioenergy in all countries amount to 43 €/m^3 and 39 €/m^3, respectively, which are the average Swedish prices in 2010 (Swedish Forest Agency, 2013).

Supply elasticities for bioenergy and forest products have not been estimated in all EU countries. However, there are estimates for fuel wood, sawn wood and pulp wood products in Sweden, where sawn wood has an elasticity of 0.28, pulp wood 0.14 and fuel wood 0.55 (Geijer et al., 2010). Some previous studies (Buongiorno et al., 2003; Lauri et al., 2012; Solberg et al., 2003) assumed that the elasticity is the same in all European countries. We assume that the supply elasticities in EU countries are the same as in Sweden and use 0.55 for bioenergy and 0.21 for forest products, the average of sawn wood and pulp wood.

3.3 Cost functions for reducing fossil fuels

Costs of fossil fuel reductions are calculated as the costs of foregone consumption of fossil fuel products, which is defined as decreases in consumer surplus of these products. Decreases in consumer surplus are derived from inverse fossil fuel demand functions for three main classes of fossil fuel products; oil, coal and natural gas. Inverse demand functions are calculated in a corresponding manner as the inverse supply functions, Appendix A.

It is assumed that the EU is a price taker on the world market of fossil fuels and cannot influence prices. Restrictions are imposed in terms of an upper bound, equal to current consumption, and a lower bound equal to zero. Quantities of fossil fuels consumed are from Eurostat database (Eurostat, 2013b) for the year 2010. Prices of oil are for the year 2006 and are the average of different oil products calculated in Gren et al. (2009). The prices of natural gas are for 2010 and are obtained from Eurostat's database (Eurostat, 2013c). Data on the price of coal products are not available in official statistics, and have therefore been obtained from Gren et al. (2009). The price used in the model is the average price of steam coal and hard coal coke of 62.5 €/toe. All numbers for quantities and prices used in the model can be found in Appendix D, Tables D1 and D2. The elasticities for oil, coal and gas are from Holtsmark and Maestad, (2002) and found in Appendix D, Table D3.

3.4 Emission targets

Total model emissions from fossil fuel combustion in Europe are calculated to approximately 4.0 billion ton CO_2 in 2010, based on the amount of fossil fuel consumed and their conversion factors from toe to ton CO_2. This is close to the real amount of 4.7 billion ton CO_2 (Eurostat, 2012). The difference can be due to so called process emissions that occur when processing certain raw materials.

The calculation of the required emission reduction target for the year 2050 is based on an 80 per cent reduction of emissions from the real 1990-level. Intermediate targets, equal percentage reduction each year, are calculated based on a stepwise reduction from real emissions in 2010 to the target level in 2050. The required reduction in emissions, each year, then becomes approximately 3.5 per cent and is used in the two scenarios analysed[1]. In order to only consider additional sequestration in the model, the BAU sequestration in forest and incremental carbon storage in forest products are deducted from the total amount of sequestration. The reason for only deducting sequestration and not emissions from bioenergy, is due to the fact that sequestration is currently not part of EU policy, whereas bioenergy is. If carbon sequestration will be included in the policy in the future, only the additional amount should be accounted for. The reason is that the BAU sequestration would happen without any incentives to forest producers and can thereby be viewed as a free abatement resource, while the additional sequestration occur at the expense of either bioenergy or forest products when sequestration is recognized as an abatement method.

4. Results of cost-effective solutions

Two scenarios for achieving the EU 2050 emission reduction target cost-effectively are examined: with and without additional sequestration. The scenario with sequestration includes four abatement options; carbon sequestration in forests, incremental carbon storage in forest products, bioenergy and reductions in fossil fuel consumption. The scenario without sequestration only includes reductions in fossil fuels.

The development of sequestration in forests and storage in forest products are shown in Figure 1 as total sequestration and BAU sequestration. The difference between the two lines is the additional sequestration. We note that both lines are increasing over time and that the difference between them is rather low, in the range of 30-158 million ton CO_2 per year, which corresponds to a maximum of 4.9 per cent of the total emission reductions to be achieved to 2050.

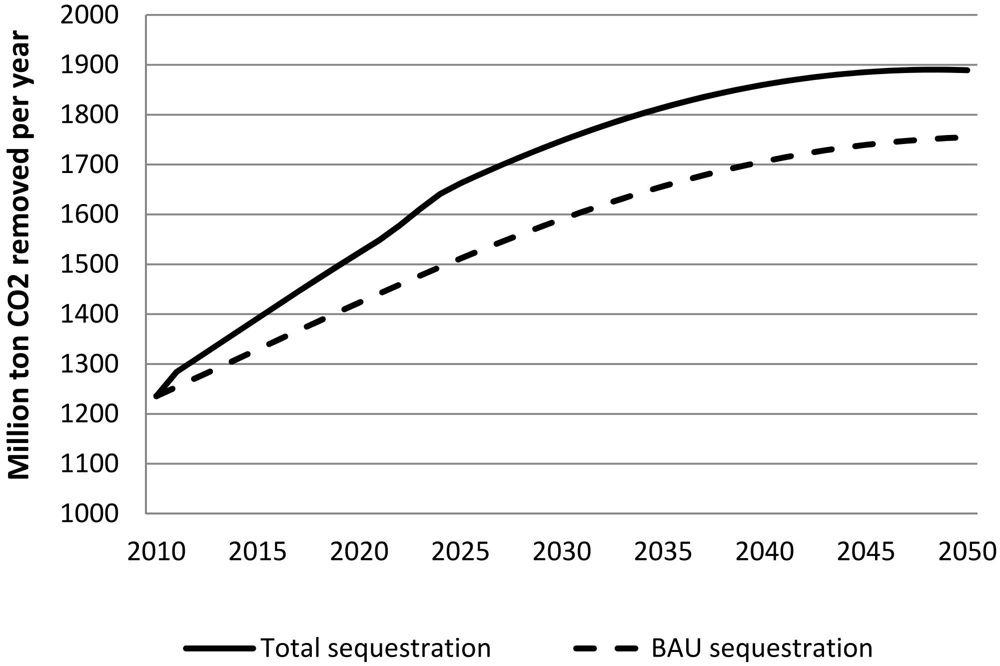

Figure 1. Development of cost-efficient total and Business as Usual sequestration in forests and forest products in million ton CO_2 removed from the atmosphere per year

This means that a large amount of emission reduction must come from expensive reductions in fossil fuels.

In the last two years, the additional sequestration is falling. This is due to the fact that the ageing European forest has reached its growth peak, where it is unable to sequester an increasing amount of carbon. Thus, beyond the considered policy period, there may be limited scope for further increases in sequestration.

The additional sequestration is largely occurring at the expense of bioenergy, which is shown on the right axis in Figure 2. The level of bioenergy is falling dramatically in the beginning when the level of sequestration is increasing rapidly. Then it is falling more slowly until 2023 when coal is phased out. In 2025 bioenergy is also completely phased out.

The development of fossil fuel consumption is also shown in Figure 2, in the scenario with sequestration.

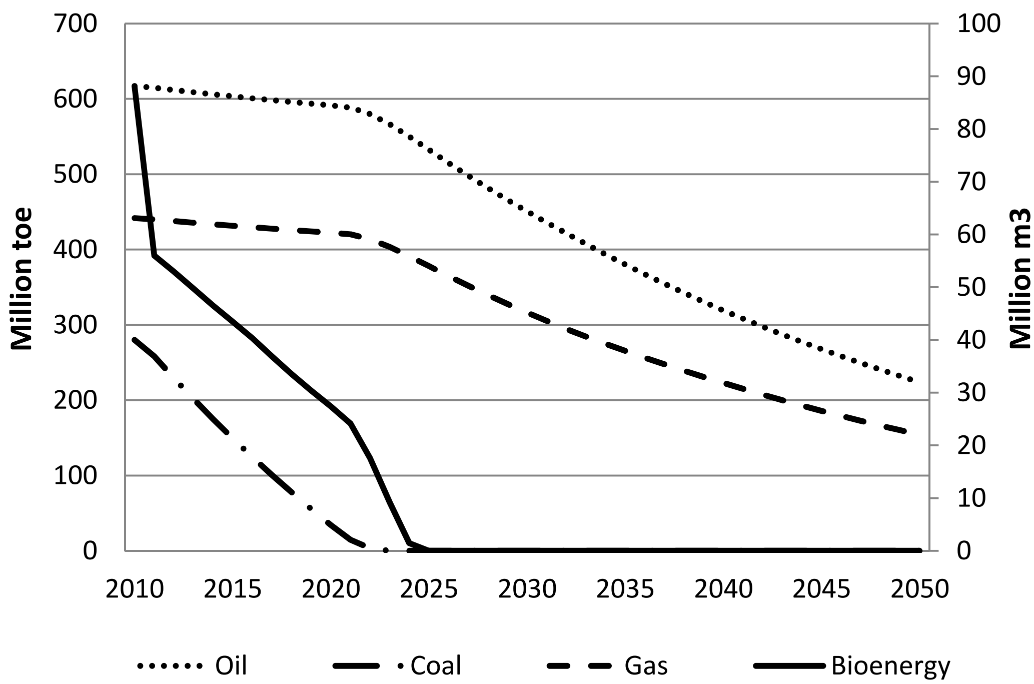

Figure 2. Development of fossil fuels and bioenergy

Oil is reduced the most in absolute terms, followed by natural gas and coal. When coal is phased out, more expensive abatement methods, per unit emission reduction, must be used. Gas, oil and bioenergy therefore experience a steeper fall when there are no more coal abatement opportunities.

The developments in Figure 1 and 2 lead to an overall abatement cost of 2,002 billion Euros when reducing emissions by 80 per cent to 2050 in the EU, with intermediate targets every year. If sequestration is not recognized as an abatement method, the cost of achieving the target is increased to 2,371 billion Euros. Hence, there is a cost saving of approximately 18 per cent when recognizing additional sequestration.

Figure 3 shows total discounted abatement cost, summed over all EU countries, of achieving the emission target every year. In both scenarios, the cost is first increasing slowly and then more rapidly from 2025, as the emission target becomes successively more stringent. Towards the end of the time period, the cost is increasing at a decreasing rate, due to the fact that costs are discounted.

The difference between the two scenarios is not large. In the scenario with sequestration, the cost is slightly higher in the beginning, but then becomes lower after 2022 compared to the scenario without sequestration.

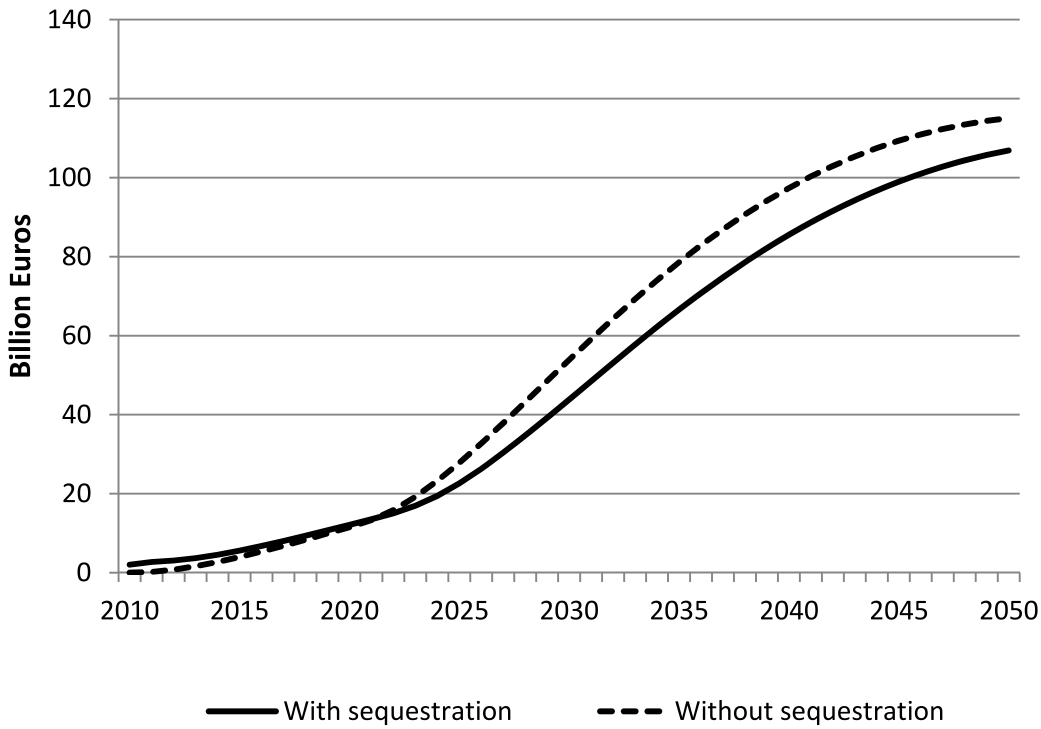

Figure 3. Total discounted abatement cost of all European countries

The explanation for the higher cost in the scenario with sequestration in the beginning is that bioenergy and forest products are reduced not only in order to sequester carbon in the same year but also to increase the future sequestration, as for several countries a higher biomass volume implies more rapid growth.

The annual costs in the scenario without sequestration can be compared to estimates in Capros et al. (2012). They calculated average annual cost in 2011-2050 to be 2659-3090 billion, depending on the scenario. Their emission reduction target is the same as in this study. These costs are in line with our total abatement cost to 2050 rather than the annual costs. The reason for this large discrepancy is explained by at least two factors: *1)* energy demand in their model is determined exogenously, implying that the demand must be met by comparatively expensive energies. We, however, allow demand to be determined endogenously, which means that it can be reduced to nil if that is cost-efficient; *2)* fossil fuel prices in their model for the EU are determined by global supply and demand and incorporate the EU carbon price, which imply comparatively high fossil fuel prices. For the EU this means that the energy demand must be met by comparatively expensive energies or technologies in order to meet the emission reduction target.

Results from den Elzen et al. (2005) can be compared to our scenario with sequestration, where they calculated the abatement cost in Europe to be approximately 1-2 per cent of GDP in 2050 for three different emission reduction targets in the range of 60-95 per cent compared to a baseline level in 2050. This is about 168-337 billion Euros according to GDP forecast from European Commission (2012c) and is lower than our estimates. The difference can be explained by two main factors: *1)* their cost results are determined by the global equilibrium price for CO_2 permits, where the supply curve stem from marginal abatement cost curves. These curves are derived from different general and partial equilibrium models, for different world regions and are likely to be lower than those we have for the EU countries; 2) incorporation of comparatively cheap abatement options such as CDM-credits[2], carbon sequestration due to forest management as well as afforestation and reforestation. These methods can contribute to reductions in the overall cost of reaching the targets and can explain their lower cost.

Figure 4 shows the cost share of fossil fuel, bioenergy and forest products in all countries. The difference between countries can be explained by taking two extreme cases such as Germany and Sweden. The cost share related to reductions in bioenergy and forest products are higher in Sweden than in Germany. This is due to the possibility in Sweden to reduce bioenergy and forest products in favor of sequestration during the studied period. Such strategy implies a cost advantage, which is possible because forest growth can continue to increase throughout the period. This is not the case in Germany, which initially has an older forest, which implies that it reaches its growth peak in just a few years. In that respect, there is no advantage for Germany to reduce bioenergy and forest products in favor of sequestration since that would only lead to slower forest growth. Instead a large proportion of the emission reductions must come from reduced consumption of fossil fuels.

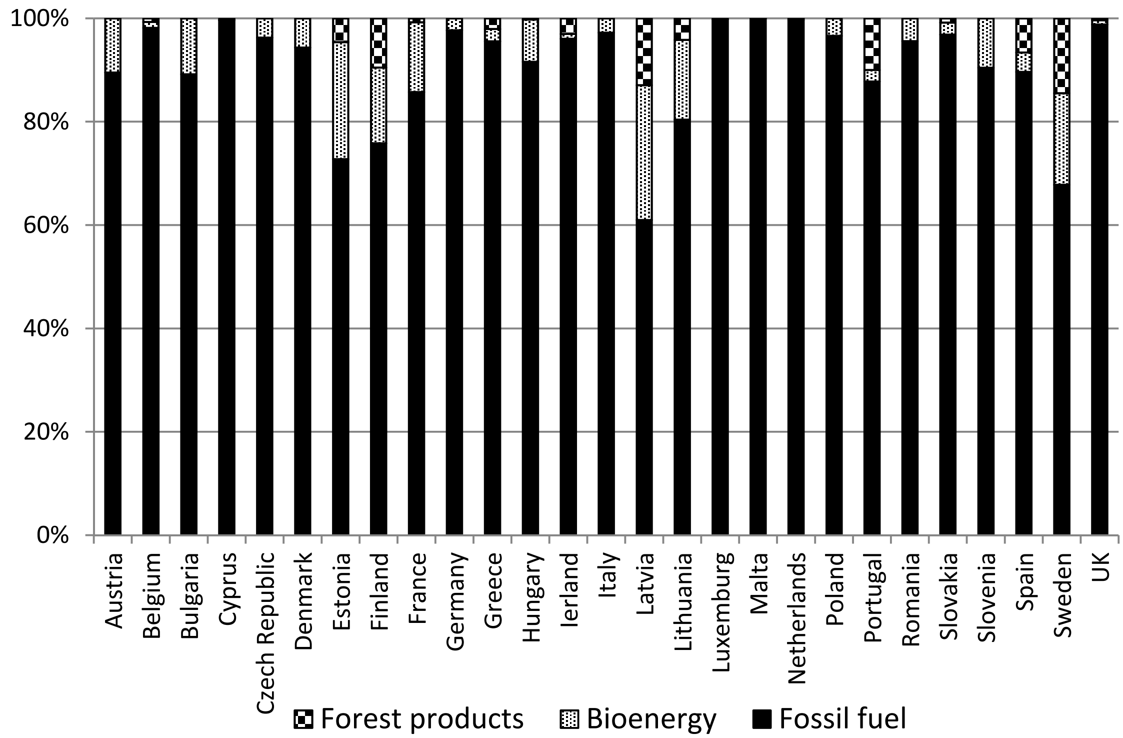

Figure 4. Cost shares per country for reductions in fossil fuels, bioenergy and forest products

The total abatement cost in the scenario with and without sequestration can be found in Appendix E, Figure E1.

Figure 5 shows how additional sequestration is developing in the countries with the highest level of sequestration during the entire period. The other countries are found in Appendix E, Figure E2 and E3. The development is varying between countries and can be explained by two main factors: *1)* The shape of the biomass volume function as well as the average age in the initial year varies between countries. This means that the annual biomass increment, which is the same as the sequestration level, will also vary during the policy period.

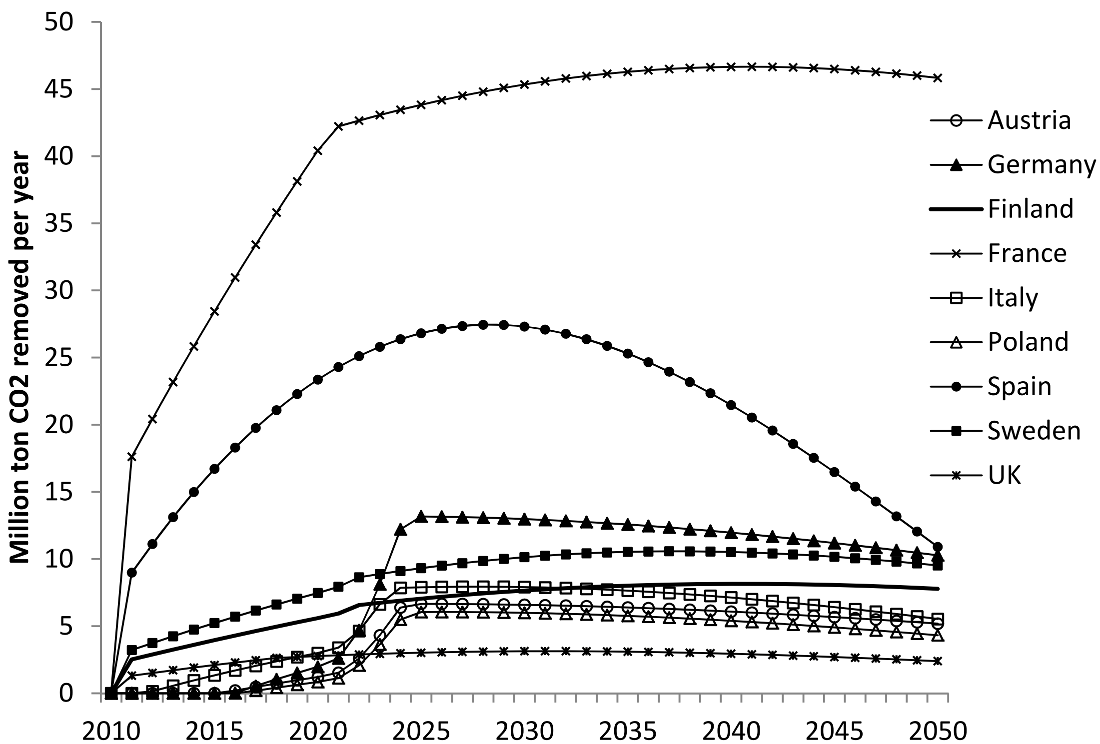

Figure 5. Development of additional sequestration in forest and forest products

Countries with a low initial average age have higher potentials to increase sequestration than countries with an initial high age, since there is a limit to increasing sequestration. *2)* The variation in sequestration is also determined by the differences in cost of reducing in particular bioenergy, and in some cases also forest products, in favour of sequestration. The explanation for reducing forest products in favour of sequestration in some countries is the dynamics in forest growth. It is sometimes an advantage to keep the forest and thereby increase the forest age, to reach a higher level of sequestration in the future.

4.1 Sensitivity analysis

The level of forest sequestration in both standing biomass and forest products are largely influencing the overall results of the model. Therefore, the model is also run with a linear function for standing biomass to see what effect that has. A linear function implies a constant growth rate, for which we use the mean annual increment in European forests in 2010 (Appendix C, Table C1). Figure 6 shows that the total abatement cost of achieving the target is only 67 per cent with the linear function compared to the exponential function. The explanation for this is a higher level of additional sequestration with a linear function. This is shown in the second and third bar in Figure 6, where the additional sequestration is 97 per cent of the BAU sequestration in 2050 with the linear function and only 8 per cent of the BAU sequestration with the exponential function. This is expected, since a constant growth rate implies no slowdown in growth when forests become old. Figure 6 also shows that there is a higher level of fossil fuels in 2050 with a linear function, 135 per cent, compared to the exponential. This is because fewer fossil fuel reductions have to be made when the sequestration level is higher.

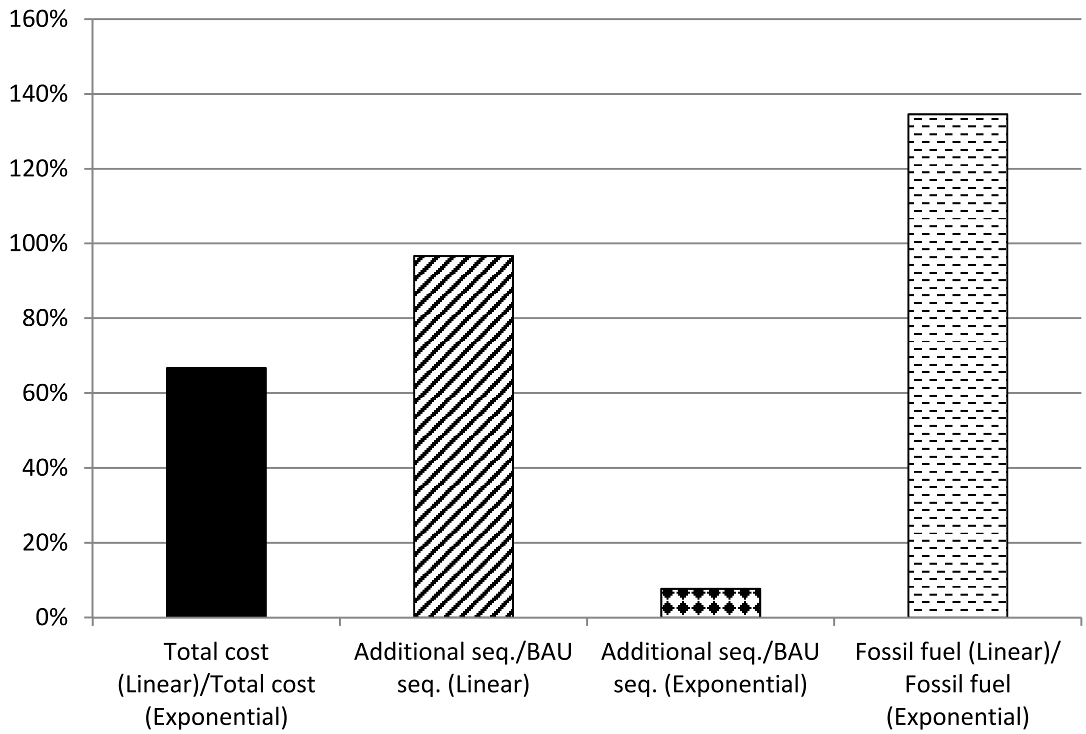

Figure 6. Comparison of total cost, sequestration (seq.) and fossil fuel consumption in 2050, when using either the linear function for standing biomass in forests or the exponential function

As stated in the data section, sequestration potential in each country build on data for average forest age and standing biomass volumes as well as forest area in 2010. If these data are erroneously estimated that will affect the overall cost of achieving the targets. Therefore, sensitivity analysis is carried out for changes in initial average age and forest area.

We also analyze the effects of changing the price elasticities and product prices. The reason is that forest product elasticities are assumed to be the same for all EU countries based on the Swedish estimates and fossil fuel elasticities are quite old. Similarly, prices of fossil fuels and forest products are quite difficult to retrieve since companies are reluctant to report them.

The effects on total abatement cost of reducing or increasing these parameters by 10% in the sequestration scenario are shown in Table 1. The results indicate that the total costs are most sensitive to changes in forest area, with an increase in cost by 18.4 per cent, or a decrease by 16.4 per cent, when the area is shifted upwards or downwards, respectively. The reason for this high sensitivity is that the area determines the overall availability of forest sequestration opportunities in a country. The cost is much more sensitive to an upward than a downward shift in forest age. An increase in forest age implies that we reach maximum sequestration faster, which in turn implies a slower forest growth earlier in the time period. This implies higher costs, since more reductions have to be carried out in the fossil fuel market.

The abatement cost is not particularly sensitive to changes in forest related elasticities or prices, neither to changes in fossil fuel elasticities or prices. The results show that the abatement cost is more sensitive to changes in bioenergy than forest product elasticities and prices. This is most likely due to the fact that forest products hardly change during the whole time period, since that carries a cost for achieving the same amount of sequestration as in forests. The abatement cost is also more sensitive to changes in oil elasticities and prices, compared to the same changes in gas and coal. This is most likely due to the comparatively high cost and large consumption quantities of oil.

Table 1. Changes in total costs in percentages of achieving the emission targets to 2050 in the scenarios with sequestration, when the parameters are changed downwards or upwards by 10%

	Down	*Up*
Forest age	-0.4%	3.2%
Forest area	18.4%	-16.4%
Forest product elasticities	0.1%	-0.1%
Bioenergy elasticities	0.3%	-0.2%
Forest product prices	-0.1%	0.1%
Bioenergy prices	-0.3%	0.3%
Coal elasticities	1.5%	-1.2%
Gas elasticities	3.1%	-2.9%
Oil elasticities	5.7%	-5.0%
Coal prices	-1.3%	1.3%
Gas prices	-3.2%	2.8%
Oil prices	-5.5%	5.1%

5. Discussion and conclusion

We set out to analyze if forest sequestration should be increased at the expense of bioenergy and forest products in a cost-effective EU climate policy to 2050. By comparing two different scenarios; with and without additional sequestration, i.e. the level of sequestration above the BAU level, we found a cost saving of 18 per cent when recognizing sequestration, bioenergy and forest products. The results also showed that the cost-efficient level of sequestration increased during the studied period, with variations between countries in both level and rate of increase. This increase came at the expense of reductions in bioenergy in particular. Forest sequestration was also increased in a few countries at the expense of forest products despite our assumption that forest product constitute a permanent carbon sink. This is explained by the dynamics in forest sequestration, where it is sometimes optimal to incur a higher cost today in order to reach a higher sequestration level in the future. Our results also showed that the level of yearly additional sequestration in the EU corresponds to a maximum of 4.9 per cent out of the total required reduction in CO_2 emissions, which means that large reductions in either fossil fuels or alternative abatement methods such as renewable energies or agricultural sequestration are still needed. Finally, it is worth pointing out that European forests are far from being saturated during the studied period, meaning that sequestration is still positive beyond 2050, however the rate is falling slowly.

Our results are in line with the general literature results that points towards cost-effectiveness in using forest sequestration as an abatement method (e.g. Bosetti et al., 2009; Kindermann et al., 2008; Murray et al., 2009; Richards and Stokes, 2004; Sohngen, 2009; Van Kooten et al., 2004). The dynamic models that compared the cost-effectiveness of bioenergy and sequestration however drew contrasting conclusions. Hedenus and Azar (2009) found that forest resources should rather be used for bioenergy production than sequestration in a cost-effective climate policy, when strict long-term targets are applied, while Gielen et al. (2002) and Schneider and McCarl (2003) found that sequestration is more cost-effective than bioenergy. The main explanations for the diverging results in Hedenus and Azar (2009) are due to the fact that they use an energy system model, with exogenously given energy demand. This can imply that comparatively low cost bioenergy is used to meet this demand, at the expense of forest sequestration. Additionally, they assume that bioenergy is carbon neutral, which gives an advantage to bioenergy compared to studies such as this, where it is assumed that bioenergy implies net emissions. Their assumption of carbon neutrality is however not supported by the recent literature that focuses on this issue (e.g. Holtsmark, 2012; Hudiburg et al., 2011; Johnson, 2009; Schulze et al., 2012).

The implications of our results for policy development is in particular that forest sequestration should be recognized as an abatement option in EU's climate policy, since that could reduce the overall costs of reaching the ambitious target set for the long-term. There are a number of possibilities available to take in sequestration in EU's climate policy, including an inclusion in the existing framework of ETS and member state targets or in a separate framework. Kuikman et al. (2011) propose a separate framework for carbon sequestration in the EU and discuss different policy instruments closely related to the Common Agriculture Policy (CAP), which could be used to cover the land use sector as a whole. The economic literature (e.g. Alig et al., 2010) generally propose market based instruments such as emission trading; taxes or carbon offset schemes for the agricultural and forestry sectors' emissions and sinks. However, more research is needed to find the most appropriate instrument for forest sequestration in the EU. Any such research should take into consideration that sequestration is accompanied with uncertainties and dynamic effects that affect their overall potential. Furthermore, any policy instrument for incentivising forest sequestration must fit into the existing frameworks and policy instruments for reducing carbon emissions and incentivising ecosystem services in the land use sector.

The model underlying these results has both strengths and weaknesses. The strengths are in particular related to the level of detail in estimating forest sequestration potentials, where each European country has an individually estimated forest growth function. The weaknesses are related to the inclusion of only forest related and fossil fuel abatement options. The inclusion of other options, such as renewable energies and carbon sequestration in the agricultural sector could affect the results, as well as inclusion of the possibility to convert land to and from forestry. The latter seems particularly important given our findings in the sensitivity analysis. Also, sequestration might be further increased through the choice of forest management measures. Due to these limitations, the results should be interpreted with some care.

Footnotes

1 Calculation of overall emission reduction target to 2050:

Emissions1990 * 0.2 = Emissions2050;

Calculation of yearly emission reduction targets:

Emissions2010 * 0.965 = Emissions2011

Emissions2011 * 0.965 = Emissions2012

……

……

Emissions2049 * 0.965 = Emissions2050

2 CDM credits stem from Clean Development Mechanism projects. These are emission reduction projects that are carried out in so called Annex 1 countries to the Kyoto Protocol, which have no binding emission reduction targets according to this Protocol. The CDM-credits are traded on the European carbon market and are cheaper than EU carbon allowances.

Appendix A. Derivation of abatement cost functions

Let P^i and B^i denote the producer price and the quantity supplied in country, *i,* of bioenergy. The supply functions of bioenergy are assumed to be linear and are then written as:

$$B^i = a^i + b^i P^i \tag{A1}$$

Where, a^i, is a constant that represents the intercept of the supply curve and, b^i, is the coefficient that represents the slope of the supply curve. An estimate of the coefficient is derived from the definition of the supply elasticity of bioenergy as:

$$b^i = \frac{\widehat{B}^i \varepsilon^i}{\widehat{P}^i} \tag{A2}$$

where $\widehat{B}^i$, $\widehat{P}^i$ and ε^i are the observed bioenergy output and price under BAU as well as the supply elasticity of bioenergy, respectively. When inserting (A2) in (A1) and solving for the intercept we obtain:

$$a^i = (1-\varepsilon^i)\widehat{B}^i \tag{A3}$$

The cost function is given by the inverse supply function:

$$P^i = \frac{B^i - a^i}{b^i}$$

Where the intercept is $\frac{a^i}{b^i}$, and the coefficient $\frac{1}{b^i}$. By using (A1) and (A2) we obtain an expression for P^i in terms of B^i and the exogenous parameters: $\widehat{B}^i$, $\widehat{P}^i$ and ε^i *as:*

$$P^i = \frac{\widehat{P}^i}{\varepsilon}\left(\frac{B^i}{\widehat{B}^i} - (1-\varepsilon^i)\right) \quad \text{(A4)}$$

The cost function, decreases in producer surplus, for reductions in B^i is obtained by integrating (A4) over B_t^i and deducting that from $\widehat{P}^i$ as follows:

$$C_t^i(\hat{B}^i - B_t^i) = \widehat{P}^i(\hat{B}^i - B_t^i) - \int_{B_t^i}^{\hat{B}^i} \frac{\widehat{P}^i}{\varepsilon^i}\left(\frac{B^i}{\widehat{B}^i} - (1-\varepsilon^i)\right)dB_t^i \quad \text{(A5).}$$

The cost functions of reductions in fossil fuels are derived in the same fashion as the cost functions for reduction in bioenergy, except that we calculate reductions in consumer surplus and use the demand functions for fossil fuels instead of supply functions. This cost function is calculated as follows:

$$C_t^{ij}(\hat{X}^{ij} - X_t^{ij}) = \int_{X_t^{ij}}^{\hat{X}^{ij}} \frac{\widehat{P}x^{ij}}{\varepsilon^{ij}}\left((1+\varepsilon^{ij}) - \frac{X_t^{ij}}{\widehat{X}^{ij}}\right)dX - \widehat{P}x^{ij}(\widehat{X}^{ij} - X_t^{ij}) \quad \text{(A6)}$$

Derivation of the first order conditions from the Lagrange function (6):

Where, $H_t^i = \dfrac{B_t^i + F_t^i}{A^i}$ and $S_t^i = \eta^i A^i(V_{t+1}^i - V_t^i)$

$$\frac{\partial L}{\partial B_t^i} = \rho^t\left[\frac{\partial C_t^{iB}(\hat{B}^i - B_t^i)}{\partial B_t^i} + \rho\mu_{t+1}^i\frac{1}{A^i} - \lambda_t\sum_j \alpha^j\gamma + \lambda_t\varphi)\right]$$

$$= \rho^t\left[\frac{\partial C_t^{iB}(\hat{B}^i - B_t^i)}{\partial B_t^i} + \rho\mu_{t+1}^i\frac{1}{A^i} - \lambda_t(\sum_j \alpha^j\gamma - \varphi)\right] = 0 \quad \text{(A7)}$$

$$\frac{\partial L}{\partial F_t^i} = \rho^t \left[\frac{\partial C_t^{iF}(\hat{F}^i - F_t^i)}{\partial F_t^i} + \rho\mu_{t+1}^i \frac{1}{A^i} - \lambda_t \eta^i \right] = 0 \tag{A8}$$

$$\frac{\partial L}{\partial X_t^{ij}} = \rho^t \left[\frac{\partial C_t^{ij}(\hat{X}^{ij} - X_t^{ij})}{\partial X_t^{ij}} + \lambda_t \alpha^j \right] = 0 \tag{A9}$$

$$\frac{\partial L}{\partial V_t^i} = \rho^t \left[-\rho\mu_{t+1}^i - \rho\mu_{t+1}^i \frac{\partial G_t^i}{\partial V_t^i} + \mu_t^i + \lambda_t \eta^i A^i - \rho\lambda_{t+1}\eta^i A^i) \right]$$

$$\rho^t \left[\mu_t^i - \rho\mu_{t+1}^i (1 + \frac{\partial G_t^i}{\partial V_t^i}) + \eta^i A^i (\lambda_t - \rho\lambda_{t+1}) \right] = 0 \tag{A10}$$

Appendix B. Conversion parameters

The parameter, η^i, is calculated according to the IPCC (2006) method as follows:

$$\eta^i = BCEF^i * CF * ER$$

Where $BCEF^i$ is the biomass conversion and expansion factor that varies between boreal and temperate forests; CF is the carbon fraction of dry matter with a standard value of 0.5 and ER is CO_2 emissions removed from the atmosphere with a standard value of 44/12. Both forest sequestration and forest products are converted into CO_2 emissions removed from the atmosphere by means of, η^i. Table B1 shows the parameter values used for, η^i in temperate and boreal forests.

The calculation of net emissions from bioenergy is carried out in two steps. First, the level of bioenergy (m^3) is converted by the factor, γ, which is 0.18 (Forest Sweden, 2012), into the same unit of measurement as coal (toe) in order to be deducted from the coal consumption. The net coal use is then converted into emissions by the conversion factor for coal, α^j, where *j=coal.* Second, emissions from harvesting, transporting, processing and combusting bioenergy, defined as, φ, are added in the emission equation. The parameter, φ, consist of emissions from harvesting, transporting processing and combustion of bioenergy. Table B1 contains the numbers and source of the conversion factors.

Table B1. Conversion parameters used in the model

	Forest related parameters		Oil[4]	Coal[4]	Natural Gas[4]
	ton CO_2/m^3	toe/m^3	ton CO_2/toe	ton CO_2/toe	ton CO_2/toe
η^i	1.459[1]				
φ	0.798[2]				
γ		0.18[3]			
α^j			3.019	4.1	2.349

[1] In all countries with temperate forests. In countries with boreal forest the number is 0.913.
The calculation of the BCEF in η^i is the average of pine, other coniferous and hardwood species in temperate forests and the average of pine, firs, spruces and hardwood in boreal forests.
The numbers stem from Table 4.5 in IPCC (2006).
The following countries have boreal forest: Estonia, Lithuania, Latvia, Finland and Sweden.

[2] This includes harvest, transport and processing emissions of 0.024 ton CO_2/m^3 (Petersen,2006) and combustion emissions of 0.774 ton CO_2/m^3 (Holtsmark, 2012)

[3] This is the conversion factor translating m^3 into toe (Forest Sweden, 2012)

[4] Gren et al. (2009)

Appendix C. Data related to forest resources

Table C1. Average age, biomass volume, forest area and increment in 2010

	Average age *years* [1]	Model age *years*	Forest volume *m^3/ha* [2]	Model volume *m^3/ha*	Real increment *m3/ha/yr*	Model increment m3/ha/yr	Forest area *ha*
Austria	65	65	292	292	7,5	9,8	3851
Belgium[3]	35	56	248	176	7,9	7,8	678
Bulgaria	55	55	167	167	5,1	7,6	3927
Cyprus[4]	-	15	51	4	0,9	0,9	173
Czech Rep	64	64	289	289	9,9	9,9	2657
Denmark	40	40	193	193	10	11,8	587
Estonia	45	45	200	200	5,6	6,0	2203
Finland	67	67	100	100	4,6	4,6	22084
France	76	76	162	162	6,2	5,4	15954
Germany	68	68	315	315	10,1	9,9	11076
Greece[4]	-	17	47	7	1,3	1,3	3903
Hungary[5]	40	57	174	141	6,4	6,4	2039
Ireland[6]	16	44	101	93	5,8	5,8	738
Italy	47	47	151	151	4	8,2	9149
Latvia[7]	48	44	189	94	5,8	5,8	3354
Lithuania[7]	51	43	221	88	5,7	5,7	2165
Luxemburg	89	89	299	299	7,5	7,3	87
Malta[4]	-	11	-	2	0	0,5	0.3
Netherlands	58	58	192	192	7,6	8,1	365
Poland	54	54	247	247	8	10,5	9319
Portugal	27	27	54	54	10,5	5,7	3437
Romania	58	58	212	212	6,5	8,7	6391
Slovakia	64	64	189	189	7,4	7,3	2713
Slovenia	90	90	301	301	7,8	7,2	1243
Spain[8]	27	20	50	21	3,1	3,2	18173
Sweden	59	59	113	113	4,7	5,2	28605
UK	50	50	132	132	8,6	6,9	2881

Forest age, volume and area from UNECE (2013) and real increment from Eurostat (2011)
[1] Initial age is calculated from data on forest area by age class for 2010, where the age class form weights. For Austria, Luxemburg, Portugal, Romania, Slovenia 2005 age and volume is used.

[2] Initial volumes per hectare are calculated from data on total volume and forest area for 2010.

[3] The C-R function is the same as for Netherlands, age and volume adjusted to real increment

[4] The C-R function is the same as for Italy, age and volume adjusted to real increment

[5] The C-R function is the same as for Slovakia, age and volume adjusted to real increment

[6] The C-R function is the same as for UK, age and volume adjusted to real increment

[7] The C-R function is the same as for Estonia, age and volume adjusted to real increment

[8] The C-R function is the same as for Portugal, age and volume adjusted to real increment

Table C2. Calibrated parameters of the Chapman-Richards function

	k^i	m^i	n^i
Austria	0.000173	3.824	-0.025
Belgium[1]	0.0000374	3.824	-0.0168
Bulgaria	0.000134	3.824	-0.0234
Cyprus[2]	0.000211	3.824	-0.0264
Czech Rep.	0.0001825	3.824	-0.0254
Denmark	0.000567	3.824	-0.03415
Estonia	0.000137	3.824	-0.0235
Finland	0.0000372	3.824	-0.01675
France	0.0000374	3.824	-0.0168
Germany	0.0001672	3.824	-0.0248
Greece[2]	0.000211	3.824	-0.0264
Hungary[3]	0.0000912	3.824	-0.0212
Ireland[4]	0.0001356	3.824	-0.02351
Italy	0.000211	3.824	-0.0264
Latvia[5]	0.000137	3.824	-0.0235
Lithuania[5]	0.000137	3.824	-0.0235
Luxemburg	0.0000544	3.824	-0.01851
Malta[2]	0.000211	3.824	-0.0264
Nethelands	0.000135	3.824	-0.0234
Polands	0.000267	3.824	-0.0281
Portugal	0.000425	3.824	-0.0316
Romania	0.0001586	3.824	-0.0245
Slovakia	0.0000912	3.824	-0.0212
Slovenia	0.000053	3.824	-0.0184
Spain[6]	0.000425	3.824	-0.0316
Sweden	0.00005835	3.824	-0.01885
UK	0.0001356	3.824	-0.02351

The three parameters of the Chapman-Richard function are calibrated based on Bjornstad and Skonhoft (2002)

[1] same as France, [2] same as Italy, [3] same as Slovkia,
[4] same as UK, [5] same as Estonia, [6] same as Portugal

Table C3. Production quantities of forest products and bioenergy in 2010

Country	Ind. roundwood (thousand m3)	Fuelwood (thousand m3)
Austria	13 281	4 550
Belgium	4 114	714
Bulgaria	3 011	2 657
Cyprus	5	4
Czech Rep.	14 771	1 965
Denmark	1 590	1 080
Estonia	5 256	1 944
Finland	45 977	4 975
France	29 634	26 174
Germany	45 388	9 031
Greece	336	711
Hungary	2 746	2 994
Ireland	2 437	181
Italy	2 647	5 197
Latvia	10 222	2 312
Lithuania	5 154	1 943
Luxemburg	258	17
Malta	0	0
Netherlands	791	290
Poland	31 343	4 124
Portugal	9 048	600
Romania	10 548	2 564
Slovakia	9 089	510
Slovenia	1 841	1 104
Spain	10 969	5 120
Sweden	66 300	5 900
UK	8 337	1 381

Source: Eurostat database (2013a).
Forest products are industrial roundwood and bioenergy is fuelwood.

Appendix D. Data related to fossil fuels

Table D1. Total consumption in all sectors of fossil fuel products in 2010

	Natural Gas (1000 toe)	Oil products (1000 toe)	Coal products (1000 toe)
Austria	8214	13091	3397
Belgium	16960	25630	3186
Bulgaria	2241	4027	6887
Cyprus	0	2592	17
Czech Rep.	8019	9335	18474
Germany	73406	114204	77120
Denmark	4437	6886	3809
Estonia	563	1055	3917
Finland	3837	10271	6878
France	42540	83925	12046
Greece	3234	15064	7863
Hungary	9815	6832	2730
Ireland	4696	7604	2095
Italy	68057	70513	14170
Lithuania	2492	2587	205
Luxemburg	1197	2875	66
Latvia	1462	1293	109
Malta	0	911	0
Netherlands	39309	35067	7596
Poland	12807	26400	54608
Portugal	4489	12381	1657
Romania	10788	9247	7009
Slovakia	5006	3689	3897
Slovenia	863	2573	1458
Spain	31221	60616	7828
Sweden	1331	14509	2492
UK	84814	73919	30457
All countries	*441798*	*617096*	*279971*

Source: Eurostat, 2013b

Table D2. Fossil fuel prices

Country	Oil (€/toe)	Gas (€/toe)
Austria	820	543
Belgium	863	489
Bulgaria	682	390
Cyprus	784	589
Czech Republic	785	474
Denmark	1023	783
Estonia	697	376
Finland	905	773
France	882	510
Germany	901	541
Greece	821	589
Hungary	900	500
Ierland	878	462
Italy	1042	572
Latvia	719	376
Lithuania	714	432
Luxemburg	780	491
Malta	811	589
Netherlands	1004	531
Poland	761	453
Portugal	894	532
Romania	682	246
Slovakia	797	451
Slovenia	759	589
Spain	804	477
Sweden	1045	773
United Kingdom	996	470
Average	843	519

The price of oil products is the average of light and heavy fuel oil, petrol and diesel with and without taxes and VAT for 2006 (Gren et al., 2009).

The price of natural gas is the average of domestic consumers with and without taxes in 2010 (Eurostat, 2013c).

Table D3. Price elasticities for fossil fuel products

	Oil products	Coal products	Natural gas
Austria	-0.45	-0.41	-0.46
Belgium	-0.63	-0.40	-0.37
Bulgaria[3]	-0.80	-0.59	-0.58
Cyprus[1]	-0.51	-0.62	-0.55
Czech Rep.	-0.60	-0.49	-0.39
Germany	-0.58	-0.61	-0.35
Denmark	-0.47	-0.68	-0.45
Estonia[3]	-0.80	-0.59	-0.58
Finland	-0.58	-0.58	-0.64
France	-0.52	-0.37	-0.30
Greece	-0.51	-0.62	-0.55
Hungary[3]	-0.80	-0.59	-0.58
Ireland	-0.58	-0.67	-0.53
Italy	-0.44	-0.42	-0.37
Lithuania[3]	-0.80	-0.59	-0.58
Luxemburg	-0.63	-0.40	-0.37
Latvia[3]	-0.80	-0.59	-0.58
Malta[2]	-0.44	-0.42	-0.37
Netherlands	-0.42	-0.49	-0.33
Poland	-0.43	-0.57	-0.38
Portugal	-0.58	-0.57	-0.50
Romania[3]	-0.80	-0.59	-0.58
Slovakia[3]	-0.80	-0.59	-0.58
Slovenia[3]	-0.80	-0.59	-0.58
Spain	-0.45	-0.60	-0.54
Sweden	-0.56	-0.35	-0.51
UK	-0.39	-0.58	-0.32

Source: Holtsmark and Maestad, (2002).
[1] Assumed to be the same as for Greece
[2] Assumed to be the same as for Italy
[3] Defined as economies in transition with the same elasticities

Appendix E. Results

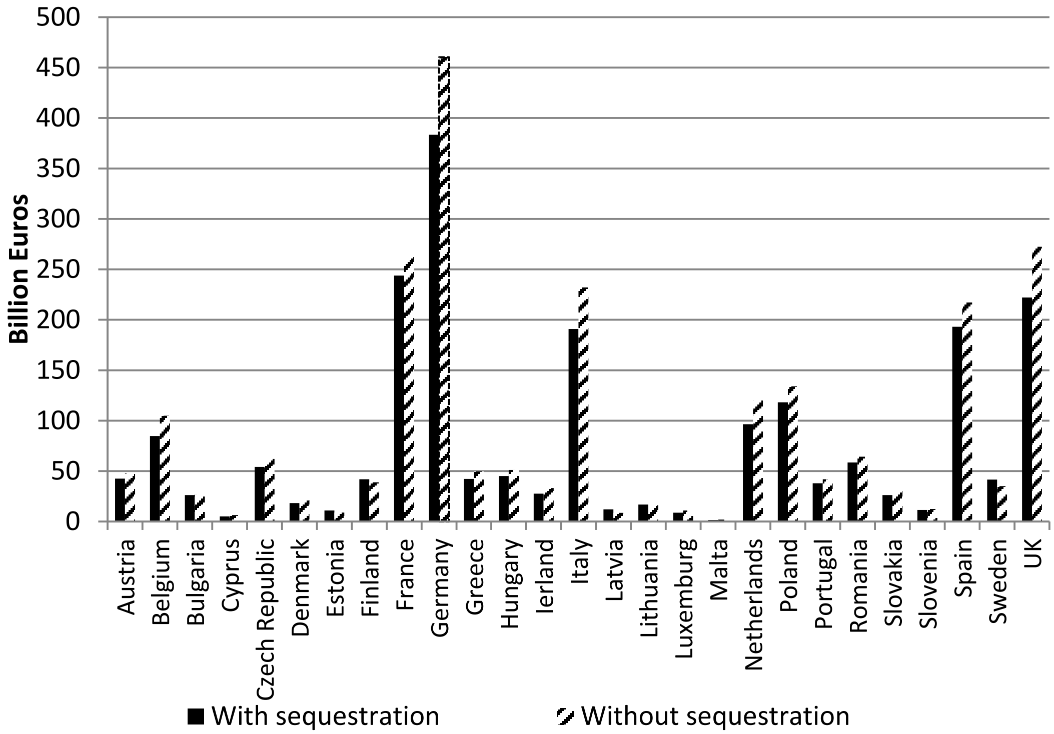

Figure E1. Total discounted abatement cost with and without sequestration, divided according to country, in billion Euros

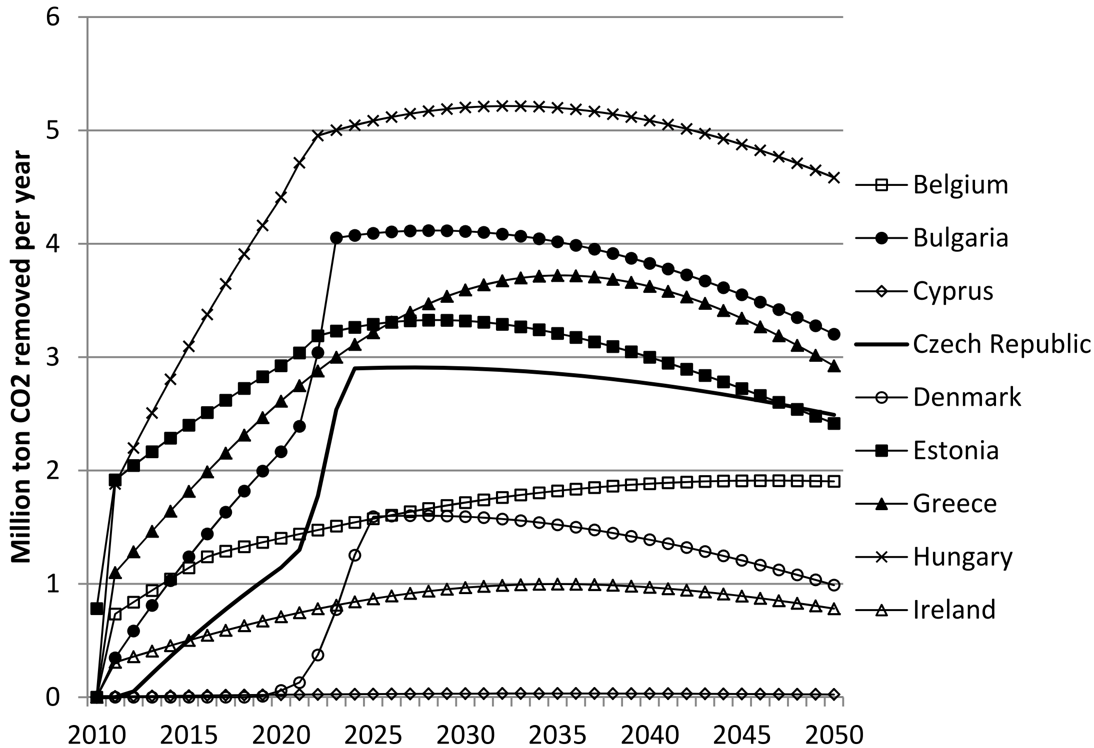

Figure E2. Development of sequestration in forests and forest products in some European countries in million ton CO_2 removed per year

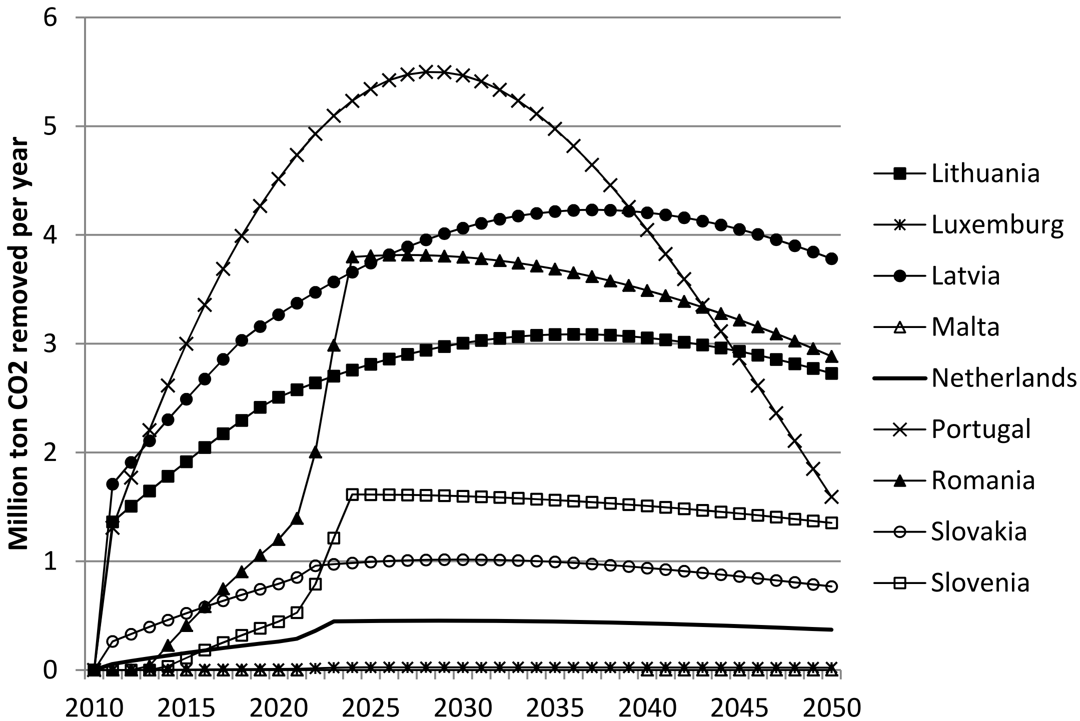

Figure E3. Development of sequestration in forests and forest products in some European countries in million ton CO_2 removed per year

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