FONDAZIONE ENI ENRICO MATTEI

# NOTA DI LAVORO

13.2013

## Trade of Woody Biomass for Electricity Generation under Climate Mitigation Policy

By **Alice Favero,** Yale University, FEEM and CMCC

**Emanuele Massetti**, Yale University, FEEM and CMCC

Climate Change and Sustainable Development
Series Editor: Carlo Carraro

# Trade of Woody Biomass for Electricity Generation under Climate Mitigation Policy

By Alice Favero, Yale University, FEEM and CMCC
Emanuele Massetti, Yale University, FEEM and CMCC

**Summary**

Bio-energy has the potential to be a key mitigation option if combined with carbon capture and sequestration (BECCS) because it generates electricity and absorbs emissions at the same time. However, biomass is not distributed evenly across the globe, and regions with a potentially high demand might be constrained by limited domestic supply. Therefore, climate mitigation policies might create the incentive to trade biomass internationally. This paper uses scenarios generated by the integrated assessment model WITCH to study trade of woody biomass from multiple perspectives: the volume of biomass traded, its value, the impact on other power generation technologies and on marginal abatement costs. The policy scenarios consist of three representative carbon tax policies (4.8 W/m2, 3.8 W/m2 and 3.2 W/m2 radiative forcing in 2100) and a cap-and-trade scheme (3.8 W/m2 in 2100). Results show that the incentive to trade biomass is high: at least 50% of biomass consumed globally is from the international market. Regions trade 13-69 EJ/yr of woody biomass in 2050 and 55-81 EJ/yr in 2100. In 2100 the value of biomass traded is equal to US$ 0.7-7.2 Trillion. Trade of woody biomass sensibly reduces marginal abatement costs. In the tax scenarios, abatement increases by 120-323 Gt $CO_2$ over the century. In the cap-and-trade scenario biomass trade reduces the price of emission allowances by 34% in 2100 and cumulative discounted policy costs by 14%.

**Keywords:** BECCS, Woody Biomass Trade, IAM, Negative Emissions, Carbon Market

**JEL Classification:** Q23, Q56, F18

*Emanuele Massetti gratefully acknowledges funding from the Marie Curie IOF Cli-EMA "Climate change impacts - Economic modeling and analysis".*

*Address for correspondence:*

Alice Favero
Yale University
195 Prospect Street
New Haven CT 06511
USA
Phone: +1 203 909 4443
E-mail: alice.favero@yale.edu

# Trade of woody biomass for electricity generation under climate mitigation policy

Alice Favero * Emanuele Massetti †

January 2013

**Abstract**

Bio-energy has the potential to be a key mitigation option if combined with carbon capture and sequestration (BECCS) because it generates electricity and absorbs emissions at the same time. However, biomass is not distributed evenly across the globe and regions with a potentially high demand might be constrained by limited domestic supply. Therefore, climate mitigation policies might create the incentive to trade biomass internationally. This paper uses scenarios generated by the integrated assessment model WITCH to study trade of woody biomass from multiple perspectives: the volume of biomass traded, its value, the impact on other power generation technologies and on marginal abatement costs. The policy scenarios consist of three representative carbon tax policies (4.8 W/m$^2$, 3.8 W/m$^2$ and 3.2 W/m$^2$ radiative forcing in 2100) and a cap-and-trade scheme (3.8 W/m$^2$ in 2100). Results show that the incentive to trade biomass is high: at least 50% of biomass consumed globally is from the international market. Regions trade 13-69 EJ/yr of woody biomass in 2050 and 55-81 EJ/yr in 2100. In 2100 the value of biomass traded is equal to US$ 0.7-7.2 Trillion. Trade of woody biomass sensibly reduces marginal abatement costs. In the tax scenarios, abatement increases by 120-323 Gt $CO_2$ over the century. In the cap-and-trade scenario biomass trade reduces the price of emission allowances by 34% in 2100 and cumulative discounted policy costs by 14%.

**Keywords**: BECCS, woody biomass trade, IAM, negative emissions, carbon market
**JEL classifications: Q23, Q56, F18**

*Alice Favero (corresponding author): Yale University, FEEM and CMCC; School of Forestry and Env Studies, 195 Prospect Street, New Haven, CT 06511, USA; Tel +1 203 909 4443; alice.favero@yale.edu.

†Emanuele Massetti: Yale University, FEEM and CMCC; emanuele.massetti@yale.edu. Emanuele Massetti gratefully acknowledges funding from the Marie Curie IOF Cli-EMA "Climate change impacts - Economic modeling and analysis".

# 1 Introduction

Reaching the long term 2°C target - the agreed goal of the UNFCCC Copenhagen Accord (UNFCCC 2010) to keep global average temperature increase below 2°C with respect to the pre-industrial level - represents a fundamental challenge to society. It is extremely ambitious and it might be impossible to achieve. Despite these apparent difficulties and the slow progress of international climate negotiations, there is growing pressure from policy makers and growing efforts within the research community to study very aggressive policies to contain global warming below 2°C.

The literature explored a large set of technology options to achieve the most aggressive targets. Without doubts, geoengineering is the most radical solution to reduce global temperatures. According to The Royal Society (2009) geoengineering can be divided into two classes. The first class includes solar radiation management techniques, which leave the stock of greenhouse gases (GHG) in the atmosphere unchanged but mitigate radiative forcing by absorbing less solar radiation. The second class includes all carbon dioxide removal techniques, which effectively reduce the stock of GHG in the atmosphere.

In particular, it is possible to remove $CO_2$ either through land use management to protect or enhance land carbon sinks (IPCC 2000; Sands and Leimbach 2003; Sohngen and Mendelsohn 2003) or by using ad hoc absorption techniques. Direct engineered capture of $CO_2$ from air relies on technologies whose primary goal is to absorb $CO_2$ from the atmosphere (Keith 2000; Kraxner, Nilsson, and Obersteiner 2003; Lackner 2003; Matthews and Caldeira 2007; Buesseler et al. 2008; Stolaroff, Keith, and Lowry 2008; Eisenberger et al. 2009). An alternative way to sequester $CO_2$ from the atmosphere is to use bio-energy with carbon capture and sequestration (CCS) for power generation. Carbon dioxide fixed in biomass through photosynthesis is captured when biomass is burned and it is then sequestered in underground deposits (Obersteiner et al. 2001; Rhodes and Keith 2005; Rhodes and Keith 2008; Azar et al. 2006; Azar et al. 2010; Chum et al. 2011). Bio-energy with CCS (BECCS) is attractive because it delivers two desired outputs at the same time: it generates carbon free electricity and it lowers the stock of $CO_2$ in the atmosphere. For these peculiar characteristics, BECCS plays a critical role in many scenarios of mitigation policies generated by integrated assessment models (IAM) (Clarke et al. 2009; Edenhofer et al. 2010; van Vuuren et al. 2011; Rose et al. 2012).

The IAM literature highlights three important benefits of BECCS.

First, the use of BECCS allows reaching stabilization target that would have been infeasible without it. Krey and Riahi (2009) find that the 2.6 W/m$^2$ overshoot scenario in the MESSAGE model is not achievable without BECCS. The 2.6 W/m$^2$ target was found to be unfeasible also in the IMAGE framework without BECCS (van Vuuren et al. 2010). Edenhofer et al. (2010) find that BECCS plays a crucial role in keeping GHG concentrations below 400 parts per million $CO_2$-equivalent (ppm $CO_2$-eq) in 2100. Thus, biomass potential is the main driver of mitigation costs in Edenhofer et al. (2010). Rose et al. (2012) stress that BECCS would be necessary to attain any level of radiative forcing below 3 $W/m^2$.

Second, BECCS makes it cost effective to delay until the second half of the century the adoption of more costly mitigation measures (Krey and Riahi 2009; van Vuuren et al. 2010; Thomson et al. 2011). Krey and Riahi (2009) find that emissions can peak in 2030; van Vuuren et al. (2010) show that the emission peak can be postponed up to 2060.

Finally, BECCS greatly reduce policy cost. In Azar et al. (2006) BECCS has the potential to reduce the stabilization cost by 80% in the case of a 350 ppm $CO_2$ target and by 42% in the case of a 450 ppm $CO_2$ target. Krey and Riahi (2009) find similar large gains from using BECCS.

Despite being attractive and promising, a large use of BECCS raises some important questions about biomass potential and cost, about CCS technological and economic viability and about availability of storage reservoirs.

With this work we focus on the role of international trade in granting access to biomass to regions that have low production potential and high demand. Trade has a potentially large role to play because biomass is unevenly distributed among world regions. Latin America and Sub-Saharan Africa have a very large production potential while some regions have very low potential (Berndes, Hoogwijk, and Van den Broek 2003; Rokityanskiy et al. 2007; Smeets et al. 2007; Heinim and Junginger 2009; Chum et al. 2011).

The importance of biomass trade under climate mitigation scenarios has already been recognized and discussed in the literature. Schlamadinger, Faaij and Daugherty (2004), Hansson and Berndes (2009) and Laurijssen and Faaij (2009) assess the relative advantages of the physical trade of biomass, the trade of bio-electricity and the trade of emissions permits using case studies or regional energy models. The IAMs IMAGE 2.3 (van Vuuren et al. 2007), MERGE (Magne, Kypreos, and Turton 2010) and REMIND (Popp et al. 2011) include trade of biomass among regions.

However, none of these studies has assessed the economic effect of introducing trade of biomass on optimal abatement or on the cost of achieving a given mitigation target.

With this study we aim at filling this gap in the literature by examining the characteristics of a potential global market for woody biomass, the impact of trade on biomass demand and on the optimal power mix and the impact of trade on GHG emissions, using three representative tax scenarios. We then test the impact of trade on mitigation costs by assuming that the long-term radiative forcing target obtained by the central value of the carbon tax is attained using a cap-and-trade policy scheme.

We develop a new version of the integrated assessment model WITCH (Bosetti et al. 2006; 2007; 2009) that includes international trade of biomass. We use the regional biomass supply curves obtained from the Global Biosphere Optimization Model (GLOBIOM) developed by IIASA (Havlk et al. 2011). The supply curves consist of second generation woody biomass coming from conventional plantations and short rotation forests for each region. The GLOBIOM model also provides the maximum biomass endowment for each region at any time period that guarantees the carbon neutrality of biomass.

This paper is organized as follows. Section 2 and 3 describe the method and the assumptions used for the analysis. Section 4 presents scenarios of international trade of woody biomass using three representative taxes on all GHG emissions and the effect of trade on the optimal power generation mix. Section 5 presents the effect of biomass trade on mitigation policy costs under a cap-and-trade policy scenario. Section 6 presents results of sensitivity analysis. Conclusions follow with a summary of our findings. The Appendix presents a detailed list of equations of the model not included in the main text.

## 2 The model

WITCH — World Induced Technical Change Hybrid — is a regional integrated assessment model structured to provide normative information on the optimal responses of world economies to climate damages (cost-benefit analysis) or on the optimal responses to climate mitigation policies (cost-effectiveness analysis) (Bosetti et al. 2006; 2007; 2009).

WITCH has a peculiar game-theoretic structure that allows modeling both cooperative and non-cooperative interactions among countries. As in RICE (Nordhaus and Yang, 1996), the non-cooperative solution is the outcome of an open-loop Nash game: thirteen world regions interact non-cooperatively on the environment (GHG emissions), fossil fuels, energy R&D, and on learning-by-doing in renewables. Investment decisions in one region affect investment decisions in all other regions, at any point in time. In this paper the non-cooperative solution is used to build both the Reference and the policy scenarios. Since we work in a cost-effectiveness framework, we do not include the feedback of climate change on the economy, which is instead present when the model is used for cost-benefit analysis.

The economy of each region is modeled along the lines of a Ramsey-Cass-Koopmans optimal growth model. The model is solved numerically assuming that a central planner governs the economy.[1] In this Section we briefly sketch the general structure of the model and we illustrate equations that describe the power generation and the biomass production sectors. The final good and the oil sectors, together with other equations governing the model, are described in the Appendix.

## 2.1 The economy

The economy is composed of four different sectors $s \in S$: (i) the sector that produces the final consumption good $C(fg)$, (ii) the oil extraction sector ($oil$), (iii) the power generation sector ($el$) and (iv) the forestry sector that grows and collects woody biomass ($wbio$). The standard WITCH model considers only the final good sector and the power sector. We use a more recent version of the model in which the oil sector is separated from the final good sector (Massetti and Sferra, 2010), we introduce the forestry sector and we explicitly illustrate the role of government in managing carbon tax revenues. We do not use backstop energy technologies that are instead part of the standard version of the model.[2]

**The final good sector.** The final good sector uses capital $K_g$, an R&D knowledge stock $K_{rd}$, electricity $EL$, fuels $F$, labor $L$ and technology $\psi$ to generate output $GY_{fg}$:

$$GY_{fg} = G\left[K_g,\ K_{rd},\ EL,\ F,\ L,\ \psi\right], \tag{1}$$

where we omit time and region indexes when no ambiguity arises. $\psi$ represents total factor productivity, which is exogenous and grows at the rate $g\left(n,t\right)$. Labor and capital cannot move across regions. Labor is equal to population. The exact functional form used in the model and further detail on the R&D sector are provided in the Appendix.[3]

Electricity is purchased from firms that operate in the power sector using nine different generation technologies indexed with $j$. The final good sector purchases each electricity type separately. Different types of electricity are mixed using nested CES functions to simulate different degrees of substitutability. The final good sector also directly use coal ($F_{fg,coal}$), oil ($F_{fg,oil}$), gas ($F_{fg,gas}$) and bio-fuels for transport ($F_{fg,bf}$). Oil is purchased from the international market. The expenditure

[1] Since there are no externalities within each region, the centrally planned and the competitive solution are identical (Barro and Sala-i-Martin, 2003).

[2] Test runs have shown that backstops are not used and unnecessarily complicate the numerical solution of the model.

[3] WITCH has a damage function that translates global mean temperature in productivity impacts to the final good sector. In this paper we do not include the damage function and we focus on climate policy costs net of environmental benefits.

for fuels other than oil is modeled as a sunk cost for the economy. The price of the final good is used as numeraire: $\phi_{fg} = 1$ . Net output is equal to:

$$Y_{fg} = GY_{fg} - \sum_j p_{EL_j} EL_j - p_{F_{coal}} F_{fg,coal} - p_{F_{oil}} F_{fg,oil} - p_{F_{gas}} F_{fg,gas} - p_{F_{bf}} F_{fg,bf}, \tag{2}$$

where $p_{EL_j}$ is the price of electricity generation of type $j$, $p_{F_coal}$, $p_{F_oil}$, $p_{F_gas}$, are the international price of fossil fuels and $p_{F_{bf}}$ is the domestic price of bio-fuels.[4]

**The oil sector.** Firms in the oil sector extract oil using eight different technologies, depending on the oil type (from light crude oil to extra heavy tar sands) indexed with $v \in V\{1, ..., 8\}$. Total production of oil is $Q_{oil} = \sum_v Q_{oil,v}$. Oil is sold on a global world market. By denoting domestic aggregate consumption with $F_{oil} = F_{el,oil} + F_{fg,oil}$ we have that $Q_{oil} = F_{oil} + \widetilde{Q}_{oil}$, where $\widetilde{Q}_{oil}$ indicates net export of oil. The international market of oil must be balanced at every time period: $\sum_n \widetilde{Q}_{oil}(n,t) = 0$. $p_{F_{oil}}$ is the market clearing price. Output of the oil sector is valued using the price of oil $p_{F_{oil}}$ and is equal to:

$$Y_{oil} = p_{F_{oil}} Q_{oil} \ . \tag{3}$$

**The power sector.** Firms in the power sector generate electricity using nine different technologies: oil ($EL_{oil}$), coal ($EL_{coal}$), gas ($EL_{gas}$), nuclear ($EL_{nuclear}$), wind ($EL_{wind}$), hydro-power ($EL_{hydro}$), coal with carbon capture and storage (CCS) ($EL_{coalccs}$), gas with CCS ($EL_{gasccs}$), biomass with CCS ($EL_{beccs}$). We index power generation technologies with $j \in J$. The choice of investments in power generation capacity determines demand of fuels from the power sector: coal ($F_{el,coal}$), oil ($F_{el,oil}$), gas ($F_{el,gas}$), uranium ($F_{el,uranium}$) and biomass ($F_{el,wbio}$). All fuels are indexed with $f \in F\{coal, oil, gas, uranium, bf, wbio\}$. Further detail on the power generation technology is given below, where we provide information on biomass electricity generation with CCS (BECCS). Output of the power sector is valued using the price of each electricity type $p_{EL_j}$ and is net of CCS cost used by coal, gas and beccs power plants: $CCS = CCS_{coal} + CCS_{gas} + CCS_{beccs}$. The cost of CCS ($C_{n,ccs}$) is region-specific, depends on cumulative storage ($TCCS(n,t) = \sum_{s=0}^{t-1} CCS(n,s)$) and is considered as a sunk cost for the economy:

[4] WITCH considers first generation biofuels (ethanol, bio-diesel) that are not traded internationally. The final good sector in developing regions also uses traditional biomass as a direct source of energy. Traditional biomass demand is exogenous and the price of traditional biomass is set equal to zero.

$$Y_{el} = \sum_j p_{EL_j} EL_j - \sum_f p_{F_{el,f}} F_{el,f} - C_{ccs}\left(TCCS\right) \ . \tag{4}$$

**The forestry sector.** The forestry sector grows and harvests biomass $Q_{wbio}$ at the region-specific cost ($C_{n,wbio}(Q_{wbio})$) subject to the constraint $Q_{wbio}(n,t) \leq \overline{Q}_{wbio}(n,t)$. The cost function and the upper threshold to biomass production ($\overline{Q}_{wbio}$) are derived from the model GLOBIOM (Havlik et al., 2011) and are discussed in Section 3.2. Here we note that $Q' > 0$ and $Q'' > 0$. The forestry sector sells biomass to BECCS power plants domestically and abroad: $Q_{wbio} = F_{el,wbio} + \widetilde{Q}_{wbio}$, where $\widetilde{Q}_{wbio}$ denotes net export of woody biomass. This implies that negative values of $\widetilde{Q}_{wbio}$ represent net imports. The international market of woody biomass must be balanced at every time period: $\sum_n \widetilde{Q}_{wbio}\left(n,t\right) = 0$. The market clearing price of woody biomass is $p_{F_{wbio}}$.[5]

Profits in the forestry sector are $\pi_{wbio} = p_{F_{wbio}} Q_{wbio} - C_{wbio}\left(Q_{wbio}\right)$ and optimality conditions require that $p_{F_{wbio}} \geq \partial C\left(Q_{wbio}\right)/\partial Q_{wbio}$, where the latter holds with a strict equality if biomass cannot be traded internationally. The output of the forestry sector is valued using the international price of woody biomass $p_{F_{wbio}}$:

$$Y_{wbio} = p_{F\,wbio} Q_{wbio} \ . \tag{5}$$

Trade allows countries with a high availability and low cost of biomass to increase profits by selling biomass abroad. Trade reduces profits of the forestry sector in regions with low availability of biomass if $p_{F_{wbio}} < \partial C\left(\overline{Q}_{wbio}\right)/\partial Q_{wbio}$.

**Aggregate output.** Aggregate output is determined by summing the output of the four sectors:

$$\begin{aligned} Y &= Y_{fg} + Y_{oil} + Y_{el} + Y_{wbio} \\ &= GY_{fg} + p_{F_{oil}}\widetilde{Q}_{oil} + p_{F_{wbio}}\widetilde{Q}_{wbio} - \sum_{f=coal,gas,bf,uranium}\ \sum_{s=fg,el} p_{F_f} F_{s,f} - C_{ccs}\left(TCCS\right). \end{aligned} \tag{6}$$

**The social planner problem.** In each region a benevolent social planner maximizes aggregate discounted utility of households subject to the economy-wide budget constraint. Population in region $n$ at time $t$ is denoted with $L\left(n,t\right)$; total consumption is denoted with $C\left(n,t\right)$; consumption per capita is then defined as $c\left(n,t\right) \equiv C\left(n,t\right)/L\left(n,t\right)$. Discounted utility is then equal to:

[5] The market clearing price of oil and woody biomass is found iteratively solving the model until when the sum of global excess demand is below a minimum threshold for both markets.

$$U = \sum_{t=0}^{\infty} u \left\{ log \left[ c\left(t,n\right) \right] \right\} L\left(t,n\right) R\left(t\right), \tag{7}$$

where the discount factor $R(t)$ reflects a declining rate of pure time preference $\rho_v(t)$: $R(t) \equiv \prod_{v=0}^{t} \left(1+\rho_v(t)\right)^{-t}$.[6]

The social planner chooses investments in final good capital ($I_{fg,g}$), investments in energy efficiency R&D ($I_{fg,rd}$), expenditure on coal ($F_{fg,coal}$), oil ($F_{fg,oil}$), gas ($F_{fg,gas}$) and bio-fuels for transport ($F_{fg,bf}$) within the final good sector.

In the power sector the social planner determines investments in power generation capacity for nine different technologies ($I_j$). The choice of investments in power generation capacity determines demand of fuels from the power sector and expenditures in operation and maintenance ($OM_j$).

In the forestry sector the social planner chooses supply of biomass ($Q_{wbio}$). Finally, in the oil sector, the social planner determines investments in extraction capacity for all oil categories ($I_{oilcap,v}$). The budget constraint of the economy thus reads as follows:

$$C = Y - I_{fg,g} - I_{fg,rd} - \sum_j I_{el,j} - \sum_j OM_j - \sum_v I_{oilcap,v} - C_{wbio}\left(Q_{wbio}\right) \ . \tag{8}$$

### 2.1.1 Bioenergy with CCS power generation

Woody biomass is used only in integrated gasification coal (IGCC) power plants with CCS.[7] As for all other power generation technologies, BECCS electricity generation is governed by a Leontief type production function:

$$EL_{beccs} = min \left\{ \beta_{beccs} F_{wbio} \ ; \ \sigma_{beccs} CCS_{wbio} \ ; \ \varsigma_{beccs} OM_{beccs} \ ; \ \gamma_{beccs} K_{beccs} \right\} \ , \tag{9}$$

where $0 < \beta < 1$ is an efficiency parameter that determines the amount of biomass (measured in energy units) needed to generate one kWh of BECCS electricity. Henceforth we omit the technology subscript when no ambiguity arises. Demand of woody biomass is then:

$$F_{el,wbio} = \frac{1}{\beta} EL_{beccs}. \tag{10}$$

[6] The model is solved numerically using 30 five-year time periods without terminal conditions. The last ten time periods are discarded.

[7] Several test runs have shown that there is no incentive to use biomass in standard pulverized coal power plant without CCS. For this reason we describe the model assuming that biomass is used only in IGCC power plants with CCS.

$CCS_{wbio}$ is the storage capacity needed to sequester $CO_2$ from BECCS. The total amount of $CO_2$ removed and stored depends on the carbon content of woody biomass, denoted with $\omega_{wbio}$, and on the capture rate at the power plant, denoted with $e$: $CCS = e\omega_{wbio}F_{wbio}$. By using equation (10) it is possible to show that $\sigma \equiv e\omega/\beta$.

K measures BECCS generation capacity in power units. $\eta$ is an efficiency parameter that regulates the number of hours of operation of BECCS power plants. Power generation capacity grows as follows:

$$K(t+1,n) = (1-\delta)\,K(t,n) + I_{el}(t,n)/\phi \ , \tag{11}$$

where $I_{el}$ is the investments in BECCS in region $n$ at time $t$, $\delta$ is the depreciation rate of power plants and $\phi$ is the investment cost of BECCS generation capacity.[8] Finally, operation and maintenance costs ($OM$) are needed to run power plants and their demand is regulated by $\varsigma$.

If the country is a net importer of biomass, BECCS power plants also pay a cost for transporting biomass $TC$ proportional to distance $D$ from major production regions. Transportation cost is paid on the share of imported biomass over total consumption, denoted with $\gamma$: $\gamma = 0$ if the country is a net exporter, $\gamma = 1$ if a country has zero domestic production of biomass.[9]

The cost of generating one unit of electricity with BECCS is thus equal to:

$$C(EL) = \left[\frac{1}{\beta}p_{F_{wbio}} + \frac{1}{\beta}\gamma\, TC\cdot D + \frac{1}{\sigma}C_{ccs}(TCCS) + \frac{1}{\varsigma} + \frac{1}{\eta}(r+\delta)\,\phi\right]EL. \tag{12}$$

BECCS firms maximize profits $\pi_{EL_{beccs}} = p_{EL_{beccs}}EL_{beccs} - C_{beccs}(EL_{beccs})$. Optimality conditions require that $\partial\, C_{beccs}(EL^*_{beccs})/\partial\, EL^*_{beccs} = p_{el_{beccs}}$. Thus:

$$p_{EL} = \frac{1}{\beta}p_{F_{wbio}} + \frac{1}{\beta}\gamma\, TC\cdot D + \frac{1}{\sigma}C_{ccs}(TCCS) + \frac{1}{\varsigma} + \frac{1}{\eta}(r+\delta)\,\phi \ . \tag{13}$$

Optimality conditions in the final good sector require that the marginal product of electricity is equal to its price. In particular, the optimal power mix depends on the relative convenience of the $j$ power technologies. Thus, the following condition must hold: $(\partial GY/\partial EL_{beccs})/(\partial GY/\partial EL_j) = p_{EL_{beccs}}/p_{EL_j}\ \forall j$.

[8] Investment cost in other technologies may vary across regions and time: $\phi_{el_j}(t,n)$.

[9] Transportation costs enter the BECCS version of equation (4) as a sunk cost.

### 2.2 GHG emissions and climate policy

WITCH considers emissions of $CO_2$ from fossil fuels and international transport of woody biomass, from oil extraction, from land use, land use change and deforestation (LULUCF) and emissions of other non-$CO_2$ gases. $CO_2$ emissions from fuel combustion are a function of the carbon content ($\omega$) of each fuel $F_i$. $CO_2$ emissions from transport of woody biomass (MTR) are determined by the carbon intensity of maritime transport ($\xi$) and the distance from major centers of production ($D$).[10] Emissions from oil extraction ($MOIL$) are obtained summing emissions from the extraction of each oil type. LULUCF emissions ($LU$) and emissions of other non-$CO_2$ gases ($M_{ghg}$) (methane, nitrous oxide, sulfur dioxide, short- and long-lived fluorinated gases) are exogenous. Abatement of $CO_2$ emissions from fuel combustion is endogenously determined by changing the energy mix. Abatement of both LULUCF emissions and other GHGs is also endogenous but relies on abatement cost curves. By denoting abatement of LULUCF emissions with $ALU$ and abatement of non $CO_2$ GHG with $AM_{ghg}$ with $ghg \in G\,\{CH_4, N_2O, S_2O, SLF, LLF\}$, and by recalling that power sector firms that use coal, gas or biomass can capture and store $CO_2$ underground (CCS), total GHG emissions are:

$$M = \sum_i \omega_i F_i + MTR + MOIL + LU + \sum_{ghg} M_{ghg} - CCS - ALU - \sum_{ghg} AM_{ghg}. \tag{14}$$

Emissions of GHG are fed into a three-box climate model that delivers GHG concentration in the atmosphere, radiative forcing and temperature increase with respect to the pre-industrial level (see Bosetti, Massetti and Tavoni, 2007).

We consider two policy tools: a tax on emissions and a cap-and-trade scheme, both covering all GHG emissions. In both cases we assume that world regions credibly commit to reduce GHG emissions from 2015.

**Carbon tax.** In the carbon tax policy framework all countries agree on a uniform global tax $T(t)$. All users of fossil fuels pay a tax proportional to the $CO_2$ content of each fuel and receive a credit if they capture and store $CO_2$. We assume that firms in the final good sector pay taxes on and manage abatement technologies of land use emissions and non-$CO_2$ GHGs. Tax revenues are collected by the government and recycled lump-sum ($LS$). When the policy tool is a carbon tax the public budget constraint reads as follows:

$$G\left(n,t\right) = T\left(t\right) M\left(n,t\right) - LS\left(n,t\right). \tag{15}$$

[10] $\widetilde{Q}_{wbio} > 0 \Rightarrow MTR = 0$.

The government must run a balanced budget in every period: $G(n,t) = 0\ \forall\, t$ and $\forall\, n$.

Output of the final good sector and the budget constraint of the economy are transformed as follows:

$$
\begin{aligned}
Y_{fg} = GY_{fg} - \sum_j p_{EL_j} EL_j - p_{F_{coal}} F_{fg,coal} - p_{F_{oil}} F_{fg,oil} - p_{F_{gas}} F_{fg,gas} - p_{F_{bf}} F_{fg,bf} - \\
- T\left( LU + \sum_{ghg} M_{ghg} - ALU - \sum_{ghg} AM_{ghg} \right) - C_{lu}(LU) - \sum_{ghg} C_{ghg}(AM_{ghg}) \ , \quad (16)
\end{aligned}
$$

$$
C = Y - I_{fg,g} - I_{fg,rd} - \sum_j I_{el,j} - \sum_j OM_j - C\left(Q_{wbio}\right) + LS \ , \tag{17}
$$

where $C_{lu}(LU)$ is the abatement cost of LULUCF emissions and $C_{ghg}(AM_{ghg})$ is the abatement cost of non-$CO_2$ GHGs.

**Cap-and-trade.** In the cap-and-trade policy tool governments agree on a global maximum level of emissions $\overline{GM}(t)$ that is consistent with the long term climate target and distribute emission allowances internationally so that $\sum_n \overline{M}(n,t) = \overline{GM}(t)$, where the upper bar indicates an upper limit. We assume that governments manage emission allowances endowed to the country. Governments auction emission allowances both domestically and internationally - on an global market for emission allowances - at the price $P_{ep}(t)$. If demand of permits from the domestic economy is higher than the emission allowances, the government buys credits from the international market. Any surplus from emission permits sales is recycled lump sum. With a global cap-and-trade scheme the government budget constraint reads as follows:

$$
G(n,t) = P_{ep}(t)\, M(n,t) + P_{ep}(t)\left[\, \overline{M}(n,t) - M(n,t) \,\right] - LS(n,t)\,. \tag{18}
$$

In WITCH $P_{ep}(t)$ is found by iteratively solving the model until the international market of emission allowances is in equilibrium at every time period: $\sum_n \left[\, \overline{M}(n,t) - M(n,t) \,\right] = 0\ \forall\, t$. Also in this case governments must always run balanced budgets.

**BECCS under climate policy.** It is standard convention to assume that biomass has zero net emissions because the trees recently absorbed its carbon content from the atmosphere. This does not mean that the use of biomass does not cause GHG emissions: emissions arise when collecting, processing and transporting biomass and due to side effects, including effects on other land uses.

However, once at the power plant, biomass should be exempt from carbon taxes. This implies that power plant that produces BECCS electricity receives a subsidy equal to the value of the tax for capturing and storing $CO_2$ and pays a tax only on emissions associated to international transport of biomass. The price of BECCS electricity is obtained by modifying equation (13) as follows:

$$p_{EL} = \frac{1}{\beta} p_{F_{wbio}} + \frac{1}{\beta} \gamma\, TC \cdot D + \frac{1}{\sigma} C_{ccs}(TCCS) + \frac{1}{\varsigma} + \frac{1}{\eta}\,(r+\delta)\,\phi - e\omega \frac{1}{\beta} T + \frac{1}{\beta} \gamma\, \xi D \cdot T\ . \tag{19}$$

BECCS power generation firms are willing to demand biomass subject to the optimality condition imposed by equation (19). This implies that, for a given price of electricity, when the tax increases they are willing to pay biomass more. The price of biomass increases proportionally to the carbon tax: $\partial p_{F_{wbio}} / \partial T = e\omega + \gamma\, \xi D$. This also implies that if global demand of biomass exceeds global maximum output, regional social planners are willing to pay a price higher than the global marginal cost of biomass production. As the carbon tax increases the marginal production cost of biomass remains the same, but the value of biomass increases with the carbon tax and thus BECCS firms are willing to pay a higher price on the international market. Firms in the forestry sector will capture the rent.

This is a peculiar outcome of our non-cooperative solution. A cartel of biomass importing regions would be able to extract part of the rents from the forestry sectors of exporting regions.

# 3 Assumptions

## 3.1 The economy

WITCH is calibrated to reproduce the observed value of GDP and other energy variables in 2005. All monetary values are expressed in 2005 USD, using market exchange rates. Population is exogenous and is equal to 9.2 billion in 2050 and to 9.1 billion in 2100; total factor productivity $\psi$ grows endogenously — faster in developing countries — but at a declining rate. World regions are: USA, WEURO (Western Europe), EEURO (Eastern Europe), KOSAU (Australia, South Africa and South Korea), CAJAZ (Canada, Japan and New Zealand), TE (Transition Economies), MENA (Middle East and Northern Africa), SSA (Sub-Saharan Africa), CHINA, INDIA, SASIA (South Asia), EASIA (East Asia), LACA (Latin America and the Caribbean).

We provide here also a brief description of the Reference scenario, in which there is no climate policy: average global GDP per capita grows from 6,900 USD per capita in 2005 to 18,000 USD in 2050 and to 39,634 USD in 2100; global total primary energy supply is equal to 436 EJ/yr in 2005, 830 EJ/yr in 2050 and 1013 EJ/yr in 2100. GHG emissions are equal to 44 Gt $CO_2$ in 2005, 80 Gt

$CO_2$ in 2050 and 101 Gt $CO_2$ in 2100; in 2100 GHG concentration in the atmosphere is equal to 951 ppm and radiative forcing is equal to 6.6 W/m$^2$ inducing a temperature increase of 4°C above the pre-industrial level.

### 3.2 BECCS

In this section we explain how we model BECCS power plants and we describe the assumptions on cost and availability of biomass. There are many uncertainties associated to the BECCS technology. First, it is unclear the cost of large-scale power plants with CCS and the cost of storing carbon underground in safe, long-term deposits (Metz et al. 2005; Gough and Upham 2011). Second, the cost and potential of biomass supply are largely unknown. In particular, it is unclear if a large scale production of bio-energy supply would affect other competing uses of land (e.g. food production and ecosystem), what would be the demand of water for irrigation purposes and, most importantly, the emission balance (Berndes 2002; Rhodes and Keith 2008; van Vuuren et al. 2010; Gough and Upham 2011).

We are therefore forced to make some discretionary choices in our modeling exercise. The implication of these choices on main results is tested by means of sensitivity analysis in Section 6.

**Power plants.** We assume that biomass is burned in IGCC power plants with CCS with efficiency equal to 35%. The capital cost for biomass-fired IGCC power plants is 4170 USD/kW. [11] The capture rate of carbon dioxide is equal to 90%. Both the efficiency and the capture rate are consistent with other studies in the literature (Luckow et al. 2010, Krey and Riahi, 2009). [12]

The cost of storing $CO_2$ underground is region-specific in WITCH. The cost varies according to the estimated size of reservoirs and it increases exponentially as cumulative storage increases. [13]

**Biomass.** For this study we consider only woody biomass from conventional plantations and short rotation forests. Regional biomass supply cost functions are derived from the Global Biosphere Optimization Model (GLOBIOM) (Havlk et al. 2011). In particular, GLOBIOM provides the marginal cost supply functions as step functions and we converted them in second degree func-

[11]Efficiency of coal IGCC power plants is equal to 40% and the investment cost is equal to 3170 USD/kW.

[12]In Luckow et al. 2010 the efficiency of IGCC power plants is assumed to be 42.6% while for a biomass IGCC plant is equal to 41.6%. Luckow et al. (2010) assume a CCS capture rate of 91% in 2020, growing to 94% in 2095 while Krey and Riahi (2009) assume a capture rate of 90%.

[13]Capturing and storing 20 Gt $CO_2$ underground costs around 4 USD/t$CO_2$ for LACA, 5 USD/t$CO_2$ for EASIA, 6.7 USD/t$CO_2$ for the USA, WEURO, KOSAU, India and China, 7.3 USD/t$CO_2$ for SSA, 12.8 USD/t$CO_2$ for MENA and TE and 21.6 USD/t$CO_2$ for CAJAZ.

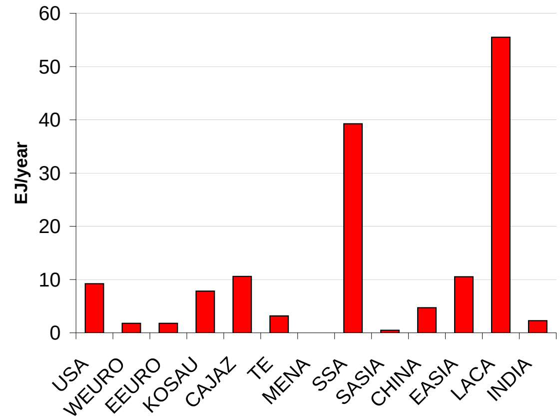



Figure 1: Regional biomass potential in 2050

tions.[14] GLOBIOM also provides the maximum biomass production potential for each region at any time period until 2050. The maximum potential is defined as the amount of biomass that can be produced only on available land areas which is the land remaining after satisfying regular demand for forestry products. These land use change restrictions guarantee the carbon neutrality of biomass. Therefore, there are no emissions from land use change due to the demand of biomass.[15]

According to GLOBIOM biomass potential varies significantly across regions from a minimum of 0 EJ/yr in Middle East and North Africa to a maximum of 56 EJ/yr in Latin America in 2050 (Figure 1). The global biomass potential is equal to 158 EJ/yr in 2010 and decreases to 147 EJ/yr in 2050. After 2050 we assume that the potential is fixed to 2050s values. The literature presents a substantial variation in the estimates of the biomass production potentials with a range of 70-420 EJ/yr in 2050 and 140-600 EJ/yr (Reilly and Paltsev 2007; Gillingham, et al. 2008; Calvin et al. 2009; Luckow et al. 2010; Magne, Kypreos, and Turton 2010; Popp et al. 2011). The divergence in the estimates is mainly due to the types of biomass included (residue, grass, plants, trees) and the assumptions on land use change. [16]

Marginal production costs range from a minimum of 3 USD/GJ to a maximum of 40 USD/GJ. The maximum cost is reached when the biomass sector supplies all the biomass available per year. The literature uses lower assumptions on cost: Magne, Kypreos, and Turton (2010) estimates a

[14]GLOBIOM provides biomass supply cost functions until 2050 with little variation over time. After 2050 we assume that cost functions are fixed to 2050s values.

[15]The neutrality constraint only accounts for $CO_2$ emissions from land-use change (i.e. deforestation), but ignores $N_2O$ emissions from increased fertilizer use.

[16]Hoogwijk et al. (2003) are quite optimistic compared to other studies and estimate the biomass maximum potential to be 650 EJ/yr in 2050 and 1400 EJ/yr in 2100.

maximum feedstock cost of 10 USD/GJ; in van Vuuren et al. (2007) the biomass production cost ranges between 4 and 10 USD/GJ; finally, Popp et al. (2011) uses a cost of 7 USD/GJ.

**Transportation costs.** Following Hansson and Berndes (2009), we assume transportation costs of 0.00025 euro/GJ per kilometer for all regions. Transportation costs are measured using the average distance from the main port of each region and range between 0.005 and 0.01 USD/kWh.[17] Emissions from transportation are a function of the carbon intensity of maritime transport and of the energy intensity of biomass, which determines overall cargo volume needs.[18]

# 4 Carbon tax scenarios

We assume that world regions credibly committ to reduce all GHG emissions from 2015. In the carbon tax policy framework[19] all countries agree on a uniform global tax $T(t)$. Taxes are equal to 2, 7 and 14 USD/t$CO_2$ in 2015 and reach 158, 576 and 1161 USD/t$CO_2$ in 2100.[20] We label the three scenarios as $t1$, $t2$ and $t3$, in increasing order. In 2100, without trade of biomass, radiative forcing is equal to 4.8, 3.8 and 3.2 W/m$^2$. This corresponds to a level of GHG concentrations equal to 680, 560 and 500 ppm $CO_2$-eq and to 3.2, 2.5 and 2.2 °C of warming with respect to pre-industrial times.

In order to assess the impact of trade of biomass we run the tax scenarios with and without trade.

[17] Main harbours were defined according to World port rankings - 2009 at http://aapa.files.cms-plus.com/PDFs/WORLD%20PORT%20RANKINGS%202009.pdf. The distance for ship transportation is retrieved from Port to port distances at http://www.searates.com/reference/portdistance/. Last viewed in December 2011.

[18] We assume that the $CO_2$ intensity for maritime transport is equal to 3 g $CO_2$-eq/tkm according to Transport, energy and $CO_2$ at http://www.iea.org/textbase/nppdf/free/2009/transport2009.pdf and the density of energy chips is 380 kg/m$^3$ according to Units, conversion factors and formula for wood for energy at http://www.coford.ie/media/coford/content/publications/projectreports/cofordconnects/ht21.pdf. Last viewed in September 2012.

[19] For convenience we refer to the tax on all GHG emissions as the "carbon tax" even if this tax is on all GHG emissions

[20] We solve the model using a cap-and-trade policy tool with borrowing and banking for a 460 ppm $CO_2$-eq target in 2100. With both when and where flexibility, we find the optimal level and growth rate of the carbon price. The growth rate of the carbon price is then used to determine the three tax trajectories starting from the three representative carbon tax levels in 2015. By focusing on carbon taxes we avoid unnecessary assumptions on the distribution of emission allowances and thus separate efficiency from equity considerations.

### 4.1 International trade of biomass

Results show that the incentive to trade biomass is large. Thanks to trade, world regions efficiently distribute woody biomass and significantly alter the energy mix, thus increasing the efficiency of carbon taxes. The market of woody biomass emerges as a major global commodity market, both in terms of volumes and value traded.

Regions start trading biomass between 2025 and 2050, depending on the tax level, as illustrated in the left panel of Figure 2. The market starts in 2025 when the carbon tax is equal to 36 USD/t$CO_2$ in t3, in 2030 when the carbon tax is equal to 28 USD/t$CO_2$ in t2 and in 2050 when the carbon tax is equal to 32 USD/t$CO_2$ in t1. In 2050 regions trade 13-69 EJ/yr depending on the scenario. The volume of the market reaches its peak at about 83 EJ/yr. The ceiling on the market emerges as a direct consequence of the cap on global biomass potential and because exporting countries have greater and greater incentive to use BECCS domestically as the tax increases the attractiveness of BECCS electricity compared to other technologies. As the tax reaches very high levels exporting countries reduce supply from its maximum level to accommodate domestic demand. By pooling all observations from the three tax scenarios we obtain a useful insight on the relationship between carbon price and market volume (right panel of Figure 2).

Biomass traded in the global market covers 50-60% of global consumption in all time periods. This figure possibly underestimates the importance of trade for global consumption of biomass because we use regional aggregates instead of single countries.

There is very little information on the possible size of biomass trade in the literature. Only Vuuren et al. (2007) provide quantitative estimations on the international market of biomass. They show that the most stringent stabilization target (450 ppm $CO_2$-eq, thus somehow comparable with our t3 scenario) drives approximately 50 EJ/yr in 2050. However, they use a different regional aggregation and the carbon price in 2050 might be different from ours.

The international price of woody biomass (net of transportation costs) emerges in WITCH endogenously as the market clearing price of global biomass market. When the market starts the price of biomass can be as low as 0.0004 USD/kWh, thus revealing a substantial excess of production capacity in countries with large production potential. In 2050 the price is equal to 0.002-0.06 USD/kWh. In 2100 it reaches 0.05-0.34 USD/kWh with an average annual growth rate of 4-6% depending on the scenario (Figure 3). By pooling all observations from the three tax scenarios we see that there is a clear linear relationship between the carbon tax and the price of biomass: a 100 USD tax increase corresponds to approximately 0.03 USD/kWh increase in the price of biomass. This roughly corresponds to $\partial p_{F_{wbio}}/\partial T = e\omega + \gamma\, \xi D$, as noted above. The price of

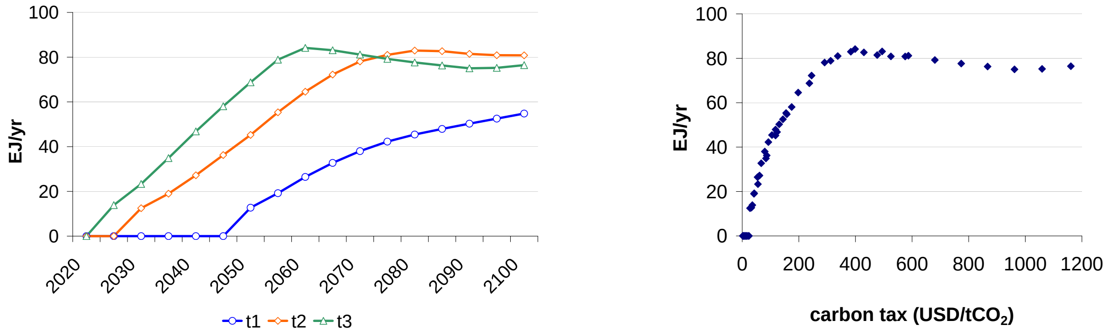



Figure 2: Biomass international market volume

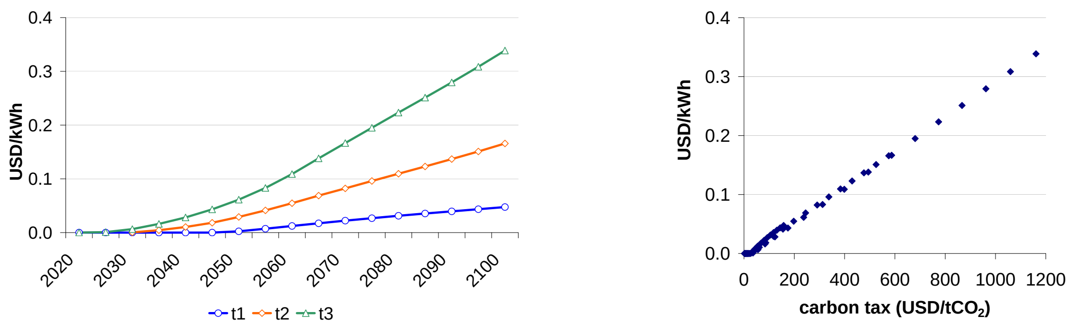



Figure 3: International price of biomass

biomass is mainly driven by the value of its carbon content. When biomass demand exceeds global production possibilities, BECCS power generation firms are willing to pay an increasing price for biomass even if the marginal cost of production remains unchanged (see equation 19) and firms in the forestry sector gain pure rents.[21]

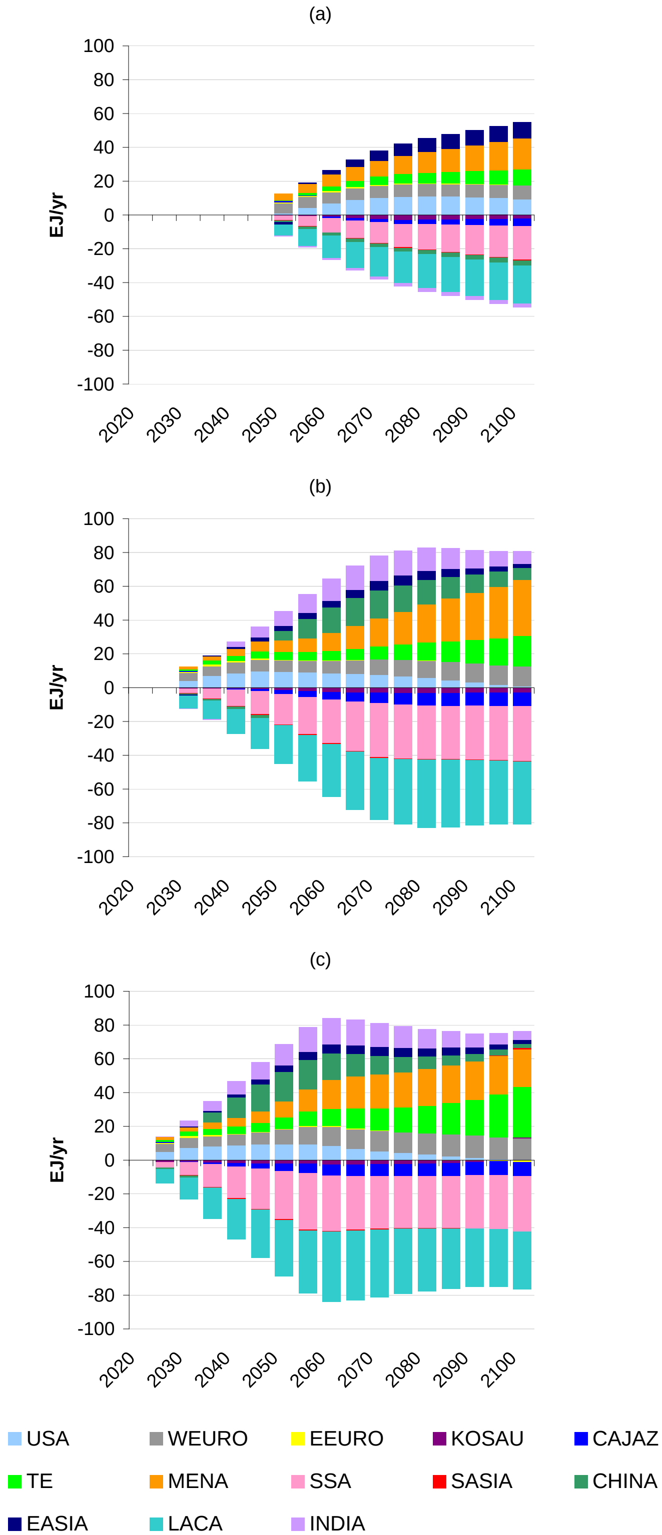
Financial transactions connected to biomass trade will increase in value due to either larger exchange of biomass (scenario t2) or growing prices (scenario t3). In 2100 the value of biomass traded in the global market ranges between 0.7 and 7.2 USD Trillion, which corresponds to 0.2% - 2% of global output. As noted above, this figure underestimates the potential value of global trade because we consider aggregate regions instead of single countries. Interestingly, the value of biomass traded in the global market becomes similar to the value of oil traded in the oil market at the end of the century: 1.4-1.7% of global output. The oil market follows a downward trend because carbon taxes discourage oil consumption and lowers the equilibrium price.

At regional level, trading dynamics can be explained by the endowment of biomass, biomass

[21]Firms in the forestry sector are competitive. The cap on total production acts as a cartel mechanism that allow to restrict global output.

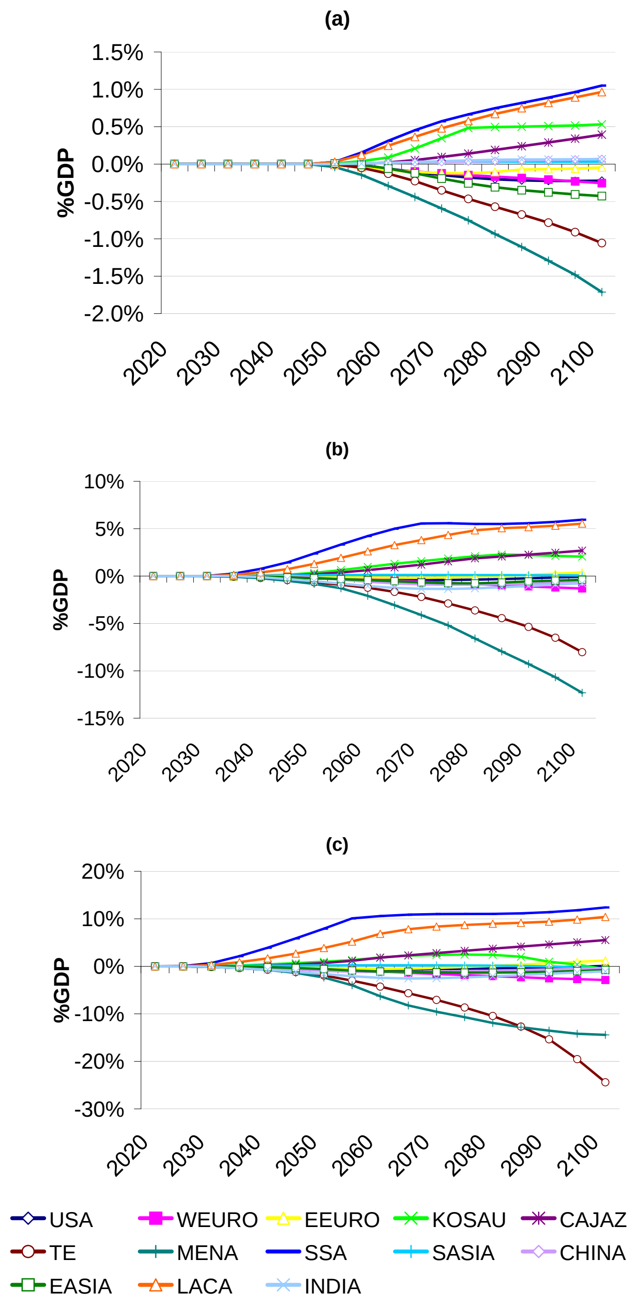
production cost and the carbon intensity of the economy. On the one hand, exporters are countries with the largest biomass potential, lowest production costs and relatively small domestic demand. Latin America (LACA) and Sub-Saharan Africa (SSA) are the two largest biomass suppliers, representing almost 85% of exports in 2100 in all scenarios. On the other hand, biomass importers have either zero domestic capacity to meet their national demand (e.g. MENA), low biomass potential (e.g. WEURO) or high production costs (e.g. TE). These three regions represent together 53-78% of biomass international demand by 2100, depending on the scenario. The regional distribution of exporters and importers does not change significantly under different tax scenarios (Figure 3).

We find that trading biomass generates large financial inflows in Sub-Saharan Africa and Latin America, where most of global production is concentrated, and large outflows in MENA, responsible for most of global demand (Figure 4). Sub-Saharan Africa and Latin America receive revenues from exports equal to 0.6-3.6% and 1.1-7.6% of annual regional GDP in 2050 and equal to 1-13% and 1.2-14% in 2100, respectively. In Sub-Saharan Africa, selling biomass would become a major economic activity. The highest financial outflows come from the Middle East and North Africa (MENA) the largest importer of biomass. In the highest carbon tax scenario, the financial outflow is equal to almost 30% of the regional GDP (4 USD Trillion) in 2100. While it is easy to understand why MENA would find it optimal to spend such a large fraction of GDP in our scenarios, it is hard to imagine that the policy would be easily accepted by the MENA region.




Notes: Positive values indicate importing regions while negative values refer to exporting regions.

Figure 4: Net import of biomass (EJ per year) under different carbon tax scenarios: (a) t1, (b) t2, (c) t3




Notes: Positive values indicate revenue of exporting regions while negative values refer to expenditure of importing regions.

Figure 5: Revenue and expenditure from the international market of biomass as a % of the GDP under different carbon tax scenarios: (a) t1, (b) t2, (c) t3

## 4.2 The impact of trade on biomass demand and on the power mix

In this Section we compare the carbon tax scenarios with trade to those without trade, for the corresponding level of taxation.

The introduction of international trade of biomass increases the amount of biomass available at global level. This raises the amount of biomass production from 16-64 EJ/yr to 27-112 EJ/yr in 2050 and from 64-81 EJ/yr to 99-147 EJ/yr in 2100. These results fall within the range found in the literature (Gillingham, Reilly and Paltsev 2007; Smith and Sands 2008, Calvin et al. 2009; Hoogwijk et al. 2009; Luckow et al. 2010; Magne, Kypreos, and Turton 2010).

The introduction of trade significantly changes regional production and demand decisions. Regions with a relatively low cost and/or large endowment of biomass see a surge of demand from other regions. This leads to an increase of the price of biomass and thus to a contraction of domestic consumption. For instance, in 2050, trade changes the optimal supply of biomass from 5-18 EJ/yr to 11-40 EJ/yr in Latin America; in Sub-Saharan Africa from 3-10 EJ/yr to 5-32 EJ/yr, depending on the carbon tax scenario. As a consequence, Latin America cuts domestic demand by 64% in the t2 scenario and by 73% in the t3 scenario; Sub-Saharan Africa reduces demand by 54% and 69%, respectively.

We find opposite results in regions with relatively low cost and/or small endowment of biomass. However, trade does not necessarily reduce the price of biomass in those regions. In some cases the new price of biomass might be higher than the price in autarky because domestic production might be constrained by the domestic endowement and $\partial GY/\partial EL_{wbio} > \partial C_{wbio}(\overline{Q})/\partial Q$ when $Q^* > \overline{Q}$. One example is Western Europe. In 2050 production decreases from 0.7 to 0.3 EJ/yr with the t1 carbon tax, from 1.8-1.5 EJ/yr with the t2 carbon tax and remains instead equal to 1.8 EJ/yr — its maximum potential — with the t3 scenario. After 2050 the price of woody biomass increases in Western Europe while at the same time BECCS consumption increases due to the large imbalance between demand and supply in the scenario without trade.

Middle East and Northern Africa is a special case because the region has no endowment of biomass. Trade opens the possibility to exploit an extremely powerful mitigation option that is otherwise precluded.

The above described dynamics create a substantial variation in the regional distribution of biomass use (Figure 6). Trade increases total biomass use and it moves biomass where its marginal product is higher.

Trade of biomass obviously changes the optimal mix of power generation technologies (Figure 7). In 2050 the share of electricity from BECCS increases from 4-16% to 6-29% while the share of electricity from IGCC coal with CCS decreases from 8-10% to almost zero. In 2100 the gap between the two technologies widens: while IGCC coal drops to zero, BECCS covers more than a quarter of total power supply in all scenarios. This is the result of both greater availability of BECCS and of the competition for the same $CO_2$ storage sites, which increase the price of IGCC coal with CCS. Also the share of gas with CCS declines, but to a lesser extent.[22] Demand of nuclear power decreases in regions that import woody biomass but it increases in exporting regions. For instance, in both TE and WEURO demand of nuclear power declines by 11% in 2050 in the t3 scenario; in LACA demand of nuclear power increases instead by 7%. Nuclear and BECCS are close substitute because they are able to provide base-load power with zero or negative $CO_2$ emissions.

[22]The model does not include unconventional gas resources. The new recent developments in "'fracking"' technologies have quickly and dramatically changed the future prospect for natural gas. We might therefore underestimate the role of natural gas in our mitigation scenarios.

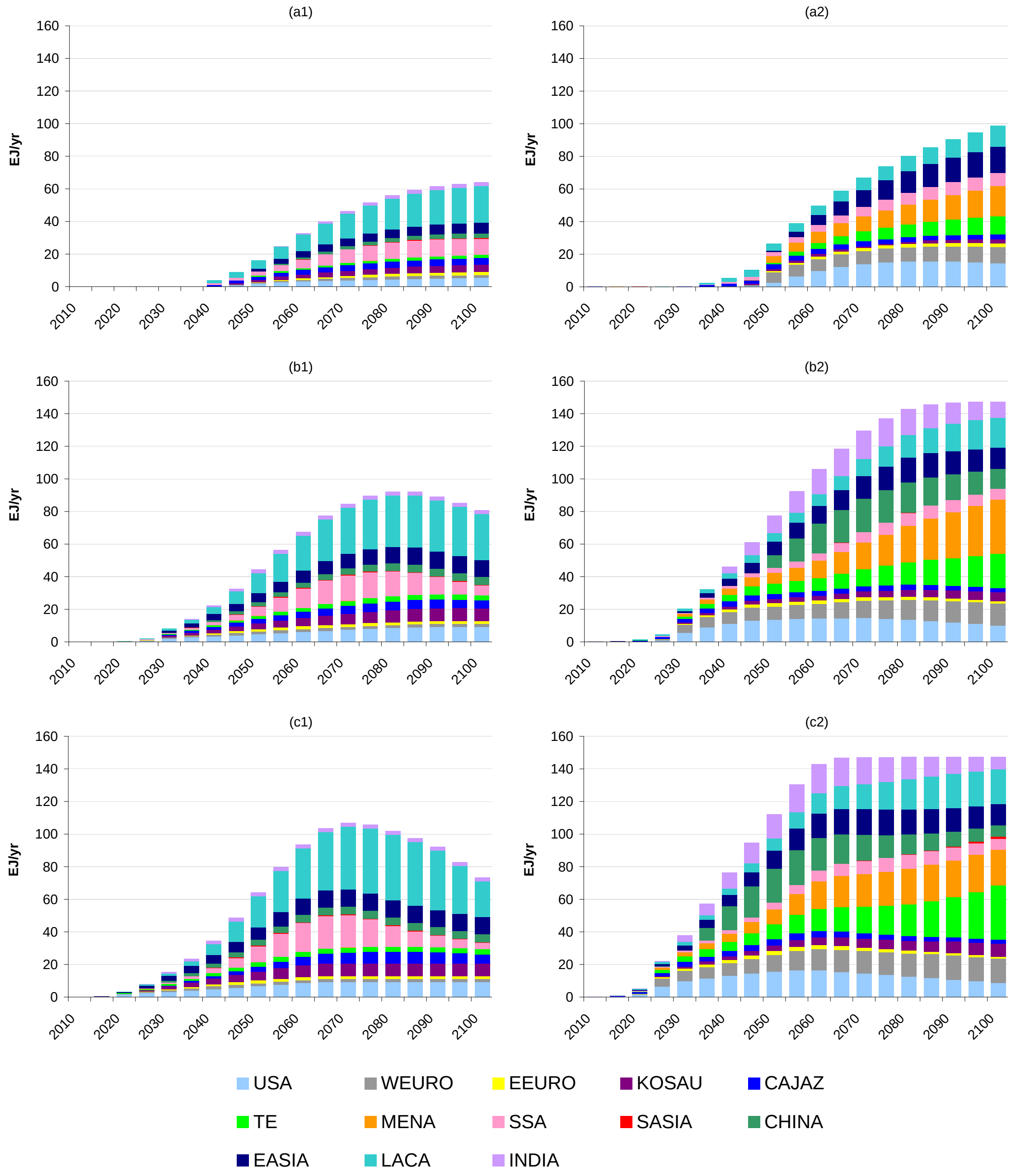



Figure 6: Regional consumption of woody biomass under three carbon tax scenarios: (a1) t1 w/o biomass trade; (a2) t1 w biomass trade; (b1) t2 w/o biomass trade; (b2) t2 w biomass trade; (c1) t3 w/o biomass trade; (c2) t3 w biomass trade.

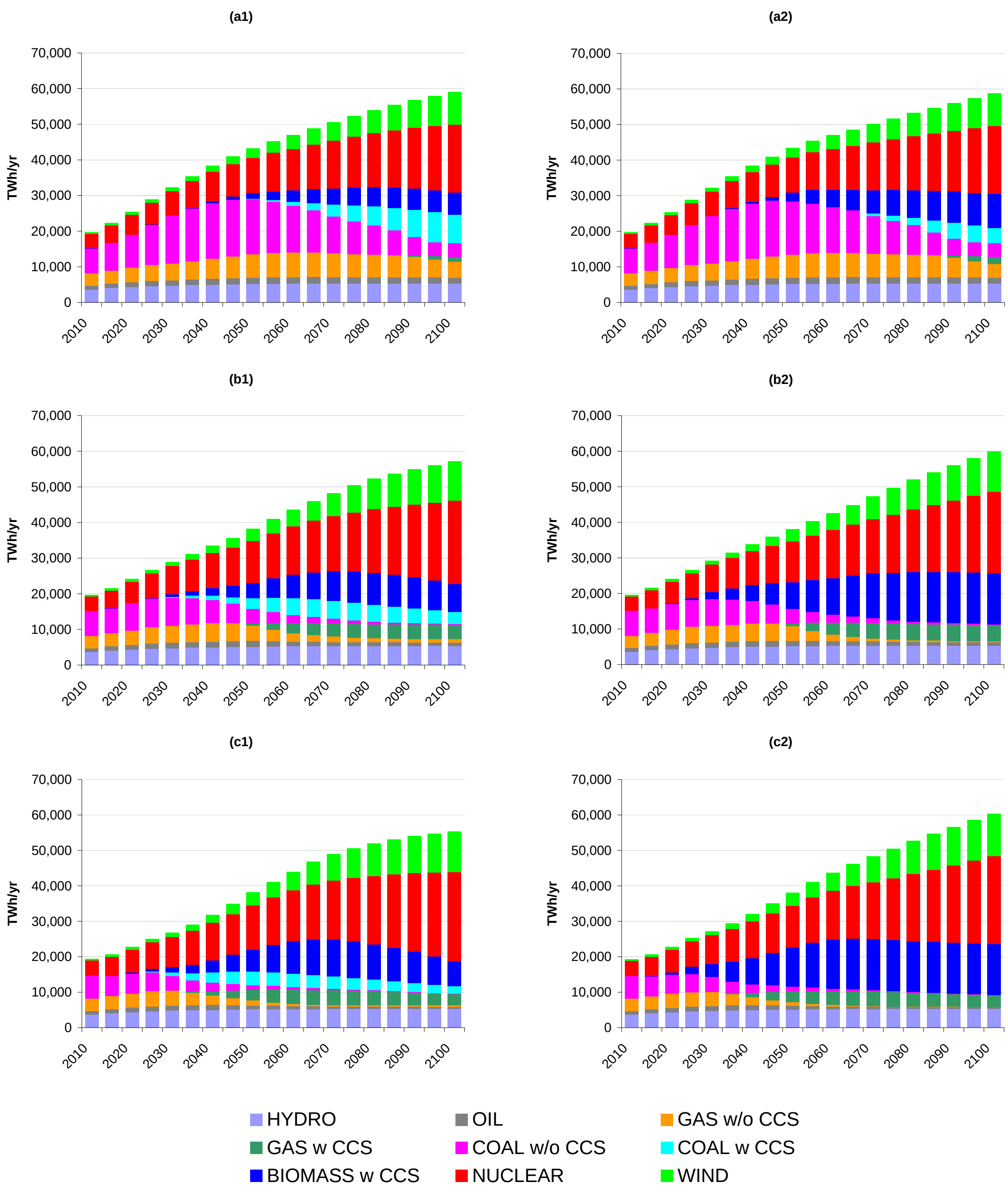



Figure 7: Electricity generation by technology under three carbon tax scenarios: (a1) t1 w/o biomass trade; (a2) t1 w biomass trade; (b1) t2 w/o biomass trade; (b2) t2 w biomass trade; (c1) t3 w/o biomass trade; (c2) t3 w biomass trade.

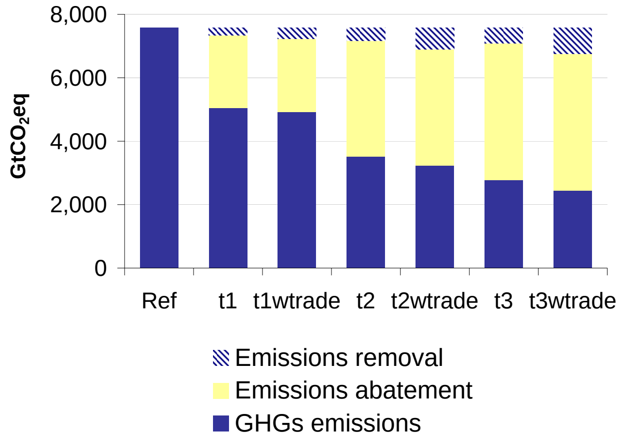



Figure 8: 2010-2100 cumulative GHGs emissions abatement with and without the trade of biomass under three carbon tax scenarios.

## 4.3 The impact of trade on emissions

Trade of biomass enlarges the choice set in each region, shifts the aggregate regional marginal abatement cost curve to the right and therefore increases the efficiency of mitigation policy. The overall cost of the policy remains unchanged while optimal abatement increases. However, the question is not if but rather by how much trade of biomass reduces GHG emissions at global level.

Figure 8 compares cumulative GHG emissions over the period 2010-2100 under the three tax scenarios, with and without trade of biomass. Results confirm the key role played by BECCS in climate mitigation scenarios found in the literature and highlight the importance of allowing an efficient global distribution of biomass. Trade reduces cumulative emissions by 120 Gt $CO_2$-eq in the t1 scenario, by 284 Gt $CO_2$-eq in the t2 scenario and by 323 Gt $CO_2$-eq in the t3 scenario. Between 93% and 98% of this additional reduction is due to an increase of emission removal from the atmosphere (the area with diagonal lines) while the remaining share is due to the shift from fossil fuel power technologies to BECCS.

An analysis of the carbon intensity of output in 2100 reveals the importance of trade in a mitigation scenario. At global level trade reduces the carbon intensity of output by 4%, 30% and 38% in the three tax scenario, respectively. Also global energy intensity of output decreases at the end of the century, because trade increases the efficiency of the power mix. Importers reduce their carbon intensity more than exporters as they substitute fossil fuels with bio-energy and store more $CO_2$ with CCS. For instance, in 2050 TE and MENA reduce their carbon intensity by 55% and by 45%, respectively, in the t3 scenario.

This has a long-term effect on GHGs concentrations: they are reduced by 10 ppm $CO_2$-eq

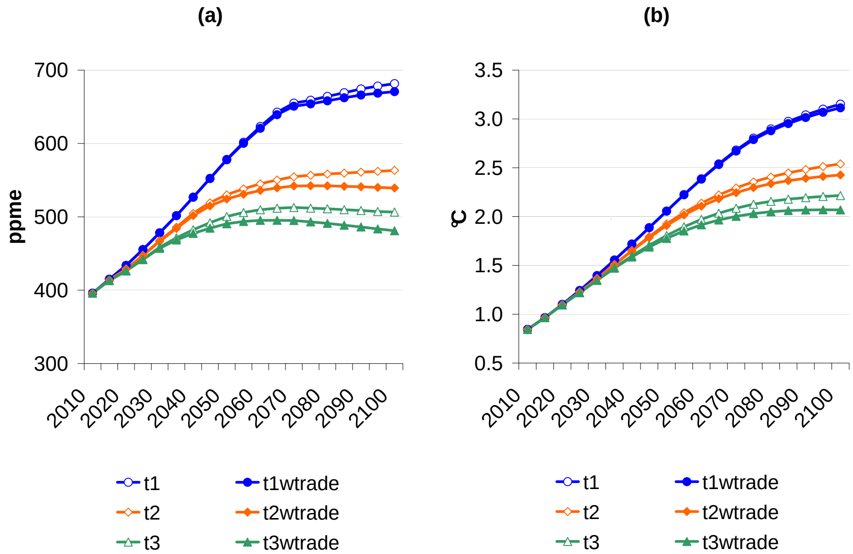



Figure 9: (a) GHGs concentration and (b) increase in Temperature with respect to pre-industrial levels under three carbon taxes with and without biomass trade.

(from 680 ppm to 670 ppm) in t1 and by 20 ppm $CO_2$-eq (from 560 ppm to 540 ppm and from 500 ppm to 480 ppm) in the t2 and t3 scenarios (Figure 9a) inducing a decrease in the temperature of 0.1°C by 2100 in all scenarios (Figure 9b).

# 5 Results: Emission trading

The aim of this Section is to provide an estimate of the economic value of the trade option in a mitigation scenario. We use a cap-and-trade policy scheme in which all regions agree to achieve a global level of radiative forcing equal to 3.8 w/m$^2$. This is equivalent to the level of radiative forcing achieved by the t2 carbon tax. They also agree to reduce emissions from 2015. Regions can trade emission permits on a global market.[23] The level of GHG emissions per year is fixed to the level found in the t2 scenario. Greater efficiency is thus reflected into a lower price of emission permits and lower mitigation permits. In order to provide an estimate of the option value of trade we compare a stabilization scenario with trade to a scenario without trade of biomass.

While the global option value of woody biomass trade does not depend on the distribution of emission permits, the regional economic impact changes under different allocation rules. Different allocation rules would also change the net position of regions on the international market of carbon

[23]Banking and borrowing of emissions allowances are not allowed, but there is no restriction to international trade of permits.

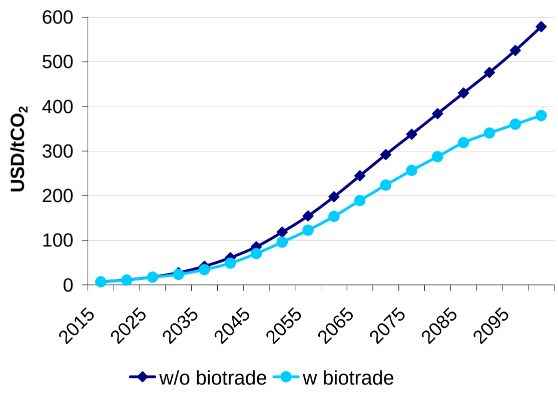



Figure 10: Carbon price with and without woody biomass trade.

permits. In some cases trade of biomass will induce an increase of emission trading, in some a contraction. Exporters of biomass will increase demand of permits (reduce sale of permits) while biomass importers will reduce demand of permits (increase supply of permits). Despite being an attractive area for further research, we do not explore here how trade changes regional demand and supply of emission permits and thus regional costs. Since the price of emission permits does not change under alternative distribution rules, we use a representative equal-per-capita distribution of permits to study how trade changes the carbon price and global mitigation costs.

Figure 10 shows the effect of biomass trade on the carbon price. In 2030 the carbon price is reduced by 15%. In 2100 there is a 34% reduction: a ton of $CO_2$ costs 579 USD/t$CO_2$ when biomass is not traded while it costs 380 USD/t$CO_2$ with trade.

Biomass trade also changes the optimal mitigation mix, as seen for the tax scenarios. In particular, it increases the amount of emissions removed from the atmosphere and increases GHG emissions by the same amount.

Finally, the introduction of biomass trade increases the overall efficiency of climate policy decreasing stabilization costs. We measure policy costs as the difference between discounted GDP in the mitigation scenario and in the Reference scenario between 2010-2050 and between 2010-2100. We use a discount rate equal to 5%. Trade of biomass reduces the global cost of reaching the 3.8 W/m$^2$ target by 15% (from 10 USD Trillion to 8 USD Trillion) over the period 2010-2050 and by 14% (from 26 USD Trillion to 22 USD Trillion) over the period 2010-2100 with respect to the same scenario without trade. This is a sizable reduction of mitigation costs that is comparable to the value of other major mitigation technologies.

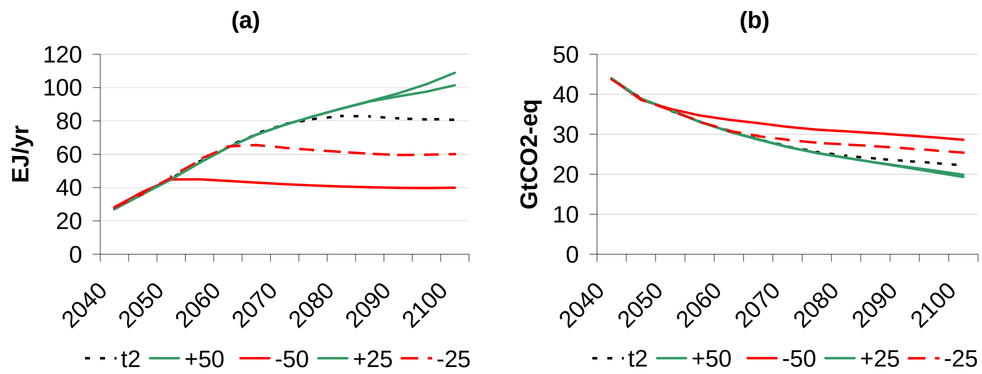



Figure 11: International price of biomass (a) and biomass international market volume (b) under different assumption on biomass potential.

# 6 Sensitivity analysis

In this Section we test the robustness of our findings under different assumptions on the (i) the maximum amount of biomass potential ($\overline{Q}_{wbio}$) and on (ii) the transportation cost of biomass. The sensitivity analysis is done on the t2 carbon tax scenario.

We change the maximum amount of biomass potential ($\overline{Q}_{wbio}$) using symmetric intervals (-50%, -25%, +25%, + 50%) around the central value. The cost function is not changed.

The left panel of Figure 11 shows that when the maximum possible production of biomass increases (decreases) also global use of biomass increases (decreases). However, the model is more sensitive to reductions than to increase of biomass potential. The right panel of Figure 11 shows how GHG emissions change. A 50% reduction of global biomass maximum potential translates into about 10 extra Gt $CO_2$ emissions in 2100. This is a substantial increase (+50% of global emission) that suggests great caution. Although GLOBIOM is quite conservative in estimating the maximum biomass potential compared to other models, our estimates of mitigation potential under the three tax scenarios might be excessive. Analogously, the cost saving potential of trade found in the cap-and-trade scenario might also be overestimated.

We also test how biomass transportation costs affect the price. We simulate two scenarios, in the first scenario transportation cost are cut by 50% (tcx0.5) while in the second they are doubled (tcx2) with respect to the central value. Transportation costs play a key role at the beginning of the century, when they are high compared to the price of biomass. Doubling transportation costs discourage trade (trade begins in 2035 instead of 2030) and reduce the price that BECCS power generation firms are willing to pay for biomass (by 30% in 2050, by less than 5% after 2070).

Reducing the cost of transport by half anticipated the beginning of biomass trade (from 2030 to 2025) and increases the price that BECCS power firms are willing to pay (by 10% in 2050 and by about 1% in 2100).

# 7 Conclusions

This paper evaluates the potential of the trade of woody biomass under climate mitigation scenarios. In particular, we focus on the physical trade of woody biomass used in IGCC power plants combined with CCS (so called BECCS). We examine the characteristics of a potential global market for woody biomass, the impact of trade on biomass demand and on the power mix and the impact of trade on total emissions using three representative carbon tax scenarios. We then test the impact of trade on mitigation costs by assuming that the long-term radiative forcing target obtained by the central value of the carbon tax is attained using a cap-and-trade policy scheme.

Results show that in all scenarios there is big incentive in trading biomass. At least 50% of biomass consumed globally is from the international market. With trade, global biomass consumption increases from 66-90 EJ/yr to 101-147 EJ/yr in 2100, depending on the tax scenario. The effect of biomass trade on climate polices is significant. We show that, under different carbon taxes, biomass trade substantially increases the efficiency of climate policy. Cumulative abatement of GHG emissions over the entire century increases by 120-323 Gt $CO_2$ depending on the tax scenario. Radiative forcing declines by 0.1-0.3 $W/m^2$. This means that achieving a given long-term climate mitigation target with trade of biomass is cheaper. A cap-and-trade policy scheme to achieve the 3.8 $W/m^2$ radiative forcing target in 2100 costs 14% less, in terms of global discounted output, when trade is available.

We find that the global market of biomass is large both in volume and in value. This generates large financial flows to/from exporting/importing regions. Sub-Saharan Africa and Latin America, the two largest exporters in our scenarios, receive financial inflows equal to 1-13% and 1.2-14% of their GDP in 2100, respectively. Selling biomass would become a major economic activity of Sub-Saharan Africa. In the highest carbon tax scenario, the transfer to Sub-Saharan Africa would be around 3.5 USD Trillion per year in 2100.

Some of the studies in the literature assume that regions can trade biomass but have never assessed the importance of this option in achieving the mitigation goals nor they have assessed the magnitude of the financial flows triggered by biomass trade.

We show that trading biomass substantially increases the efficiency of climate policy because biomass is unevenly distributed across world regions and it is therefore highly desirable. Limits to trade of biomass would lower welfare in all regions. Therefore, policy makers should reduce trade barriers and should build a sound regulation for a new major commodity market.

There are some limitations in our analysis that need to be discussed.

First, according to GLOBIOM we assume a regional maximum amount of biomass in order to guarantee the carbon neutrality of bio-energy. Our estimates are sensitive to the total maximum potential of biomass. Therefore this study should be replicated using other forestry models. In addition, without a complete integration of WITCH and GLOBIOM we are not able to capture potentially significant feedback of energy and forestland sectors.

Second, we assume that woody biomass can only be used in BECCS power plants and that biomass from crops cannot be used in BECCS power generation.

Finally, we do not assume any governmental support to promote domestic production of bio-energy such as subsidies and we have not set any domestic targets on renewables. In addition, we assume neither barriers nor social and political limitations in trading biomass and acceptability of the BECCS technology. However, energy security and geopolitical issues exist and must be carefully considered.

## A Appendix - Model equations

In this Appendix we reproduce the main equations of the WITCH model not presented in the main text. For a full description of the model and calibration details please refer to Bosetti et al. (2006, 2007, 2009). The website www.witchmodel.org contains useful information on the model.

### A.1 Final good sector

Output is produced by combining a capital-labor intermediate input with energy services ($ES$) in a constant elasticity of substitution (CES) production function:

$$Y_{fg}(n,t) = \psi(n,t)\left[\alpha_{fg}(n)\left(K_g(n,t)^{\zeta}L(n,t)^{1-\zeta}\right)^{\rho_{fg}} + (1-\alpha(n))ES(n,t)^{\rho_{fg}}\right]^{1/\rho_{fg}}. \tag{A.1}$$

Total factor productivity $\psi$ evolves exogenously with time. The labor force is set equal to population ($L$), which evolves exogenously. Capital ($K_g$) evolves as follows:

$$K_g(n,t+1) = K(n,t)(1-\delta_g) + I(n,t), \tag{A.2}$$

where $\delta$ is the sector-specific depreciation rate of capital. The price of $K_g$ is normalized to one.

Energy services are a CES aggregate of energy ($EN$) and of a stock of knowledge ($K_{rd}$):

$$ES(n,t) = \left[\alpha_{rd}(n)K_{rd}(n,t)^{\rho_{es}} + \alpha_{en}(n)EN(n,t)^{\rho_{es}}\right]^{1/\rho_{es}}. \tag{A.3}$$

"New ideas" $Z_{rd}$ contribute to the formation of the knowledge stock and are obtained by combining investments $I_{rd}$ with the stock of knowledge already developed in country $n$ and international knowledge spillovers from other countries (Bosetti et al. 2009):

$$Z_{rd}(n,t) = \psi(n,t)\,K_{rd}^{a}(n,t)\,I_{rd}^{b}(n,t)\left\{\left[\frac{K_{rd}(n,t)}{\sum_n K_{rd}(n,t)}\right]\left[\sum_{m\neq n} K_{rd}(m,t) - K_{rd}(n,t)\right]\right\}^{c}, \tag{A.4}$$

where $\psi$ is a productivity parameter, $0 < a < 1$, $0 < b < 1$, $0 < c < 1$ and $a+b+c < 1$. In any given period $t$ the marginal cost of 'new ideas' $Z$ increases as $I_{rd}$ increases and reduces the marginal product of R&D to simulate short-term frictions in the R&D market.[24] New ideas are used to build the stock of knowledge capital $K_{rd}$:

[24] Countries that are far from the technology frontier can potentially benefit from a large stock of knowledge: $\left[\sum_{m\neq n} K_{rd}^{a}(m,t) - K_{rd}^{a}(n,t)\right]$. However they also have limits in their "absorption capacity": $\left[K_{rd}^{a}(n,t)\,/\sum_n K_{rd}^{a}(n,t)\right]$.

$$K_{rd}\left(n,t+1\right)=K_{rd}\left(n,t\right)\left(1-\delta_{rd}\right)+Z_{rd}\left(n,t\right). \tag{A.5}$$

Energy is a combination of electric ($EL$) and non-electric energy ($NEL$):

$$EN(n,t)=\left[\alpha_{el}EL(n,t)^{\rho_{EN}}+\alpha_{nel}NEL(n,t)^{\rho_{en}}\right]^{1/\rho_{en}}. \tag{A.6}$$

Each input is further decomposed into several sub-components that are aggregated using CES and linear production functions:

$$EL(n,t)=EL_2(n,t)+\alpha_{hydro}EL_{hydro}(n,t)\ , \tag{A.7}$$

$$EL_2(n,t)=\left[\alpha_{ff}(n)FF(n,t)^{\rho_{el}}+\alpha_{nuclear}(n)EL_{nuclear}(n,t)^{\rho_{el}}+\alpha_{wind}(n)EL_{wind}(n,t)^{\rho el}\right]^{1/\rho_{ff}}\ , \tag{A.8}$$

$$FF(n,t)=\left[\alpha_{coal}(n)EL_c(n,t)^{\rho_{ff}}+\alpha_{oil}(n)El_{oil}(n,t)^{\rho_{ff}}+\alpha_{gas}(n)EL_{gas}(n,t)^{\rho_{ff}}\right]^{1/rho_{ff}}\ , \tag{A.9}$$

$$EL_c(n,t)=\left[EL_{coal}(n,t)+EL_{coalccs}(n,t)+EL_{beccs}(n,t)\right]\ . \tag{A.10}$$

Non-electric energy is obtained by linearly adding coal and traditional biomass and an oil-gas-bio-fuels (OGB) aggregate. The use of coal in non-electric energy production is quite small and limited to a few world regions, and is thus assumed to decrease exogenously over time in the same fashion as traditional biomass. The price of traditional biomass is assumed to be zero because it is traded in the informal market. The NEL aggregate is thus:

$$NEL(t,n)=F_{nel,coal}+F_{nel,tradbio}+OGB(t,n); \tag{A.11}$$

$$OGB(t,n)=\left[\tau_{oil}F_{nel,oil}(t,n)^{\rho_{ogb}}+\tau_{gas}F_{nel,gas}(t,n)^{\rho_{ogb}}+\tau_{biofuel}F_{nel,biofuel}^{\rho_{ogb}}\right]^{1/\rho_{ogb}}. \tag{A.12}$$

## A.2 Oil Sector

Crude oil is used both in the electric and in the non-electric sector in WITCH. The total oil demand $F_{oil}\left(t,n\right)$ is given by the sum of oil used in the electric sector $F_{el,oil}\left(t,n\right)$ and non-electric $F_{fg,oil}\left(t,n\right)$:

$$F_{oil}(t,n) = F_{el,oil}(t,n) + F_{fg,oil}(t,n). \quad \text{(A.13)}$$

Firms in the oil sector extract oil using eight different technologies, depending on the oil type (from light crude oil to extra heavy tar sands) indexed with $v \in V\{1,...,8\}$. Total production of oil is:

$$Q_{oil}(t,n) = \sum_{v} Q_{oil}(t,n,v). \quad \text{(A.14)}$$

Oil production in a given year cannot exceed the extraction capacity $OIL_{cap}(t,n)$ cumulatively built in the country. Extraction capacity depreciates at the rate $\delta$:

$$Q_{oil}(t,n,v) \leq OIL_{cap}(t,n,v); \quad \text{(A.15)}$$

$$OIL_{cap}(t+1,n,v) = OIL_{cap}(t,n,v)(1-\delta) + I_{oilcap}(t,n,v)/\phi(t,n,v); \quad \text{(A.16)}$$

where $\phi(t,n,v)$ is the investment cost in extraction capacity for oil of type $v$. Further details on the oil cost function are provided in Massetti and Sferra (2010).

An upper bound to cumulative oil production constraints extraction below feasible level:

$$\sum_{s=0}^{t} Q_{oil}(s,n,v) \leq OIL_{res}(n,v) \quad \forall t. \quad \text{(A.17)}$$

Emissions from oil extraction are responsibility of the producing region and are differet for each fuel type, with unconventional oil resources having the highest emission coefficient $\chi_v$:

$$MOIL(t,n) = \sum_{v} \chi_v Q_{oil}(t,n). \quad \text{(A.18)}$$

## References


Azar, C., Lindgren, K., Larson E., Mllersten K., 2006. Carbon Capture and Storage from Fossil Fuels and Biomass Costs and Potential Role in Stabilizing the Atmosphere. Climatic Change 74 (1): 47-79.

Azar, C., Lindgren, K., Obersteiner, M., Riahi, K., van Vuuren, D., den Elzen, K. , Mllersten, K., Larson, E.D., 2010. The Feasibility of Low $CO_2$ Concentration Targets and the Role of Bioenergy with Carbon Capture and Storage (BECCS). Climatic Change 100 (1): 195-202.

Barro R., Sala-i-Martin, X., 2003. Economic Growth (2nd edn). MIT Press: Cambridge, MA.

Berndes, G., 2002. Bioenergy and Waterthe Implications of Large-scale Bioenergy Production for Water Use and Supply. Global Environmental Change 12 (4): 253271.

Berndes, G., Hoogwijk, M., van den Broek, R., 2003. The Contribution of Biomass in the Future Global Energy Supply: a Review of 17 Studies. Biomass and Bioenergy 25 (1): 1-28.

Bosetti, V., Carraro, C., Galeotti, M., Massetti, E., Tavoni, M., 2006. A World Induced Technical Change Hybrid Model. The Energy Journal, Special Issue. Hybrid Modeling of Energy-Environment Policies: Reconciling Bottom-up and Top-down, 13-38.

Bosetti, V., De Cian, E., Sgobbi, A., Tavoni, M., 2009. The 2008 Witch Model: New Model Features and Baseline. FEEM Working Paper 2009.085.

Bosetti, V., Massetti, E., Tavoni, M., 2007. The WITCH Model: Structure, Baseline, Solutions. FEEM Working Paper 2007.010.

Buesseler, K.O., Doney, S.C., Karl, D.M., Boyd, P.W., Caldeira, K., Chai, F., Kenneth H. Coale, de Baar, H.J.W., Falkowski, P.G., Johnson, K.S., Lampitt, R.S., Michaels, A.F., Naqvi, S.W.A., Smetacek, V., Takeda, S., Watson A.J., 2008. Ocean Iron Fertilization–Moving Forward in a Sea of Uncertainty. Science 319 (5860) (January 11): 162-162.

Calvin, K., Edmonds, J., Bond-Lamberty, B., Clarke, L., Kim, S.H., Kyle, P., Smith, S.J., Thomson, A., Wise, M., 2009. 2.6: Limiting Climate Change to 450 ppm $CO_2$ equivalent in the 21st Century. Energy Economics 31, Supplement 2 (0): S107-S120.

Chum, Helena, Andre Faaij, Jos Moreira, Gran Berndes, Parveen Dhamija, Hongmin Dong, Benot Gabrielle, et al. 2011. Bioenergy. In IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation [O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlmer, C. Von Stechow (eds)],. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

Clarke, L., Edmonds, J., Krey, V., Richels, R., Rose, S., Tavoni, M., 2009. International Climate Policy Architectures: Overview of the EMF 22 International Scenarios. Energy Economics

31, Supplement 2: S64-S81.

Edenhofer, O., Knopf, B., Barker, T., Baumstark, L., Bellevrat, E., Chateau, B., Criqui, P., Isaac, M., Kitous, A., Kypreos, S., Leimbach, M., Lessmann, K., Magn, B., Scrieciu, S., Turton, H., van Vuuren, D., 2010. The Economics of Low Stabilization: Model Comparison of Mitigation Strategies and Costs. The Energy Journal 31: 11-48.

Eisenberger, P., Cohen, R., Chichilnisky, G., Eisenberger, N., Chance, R., Jones, C., 2009. Global Warming and Carbon-Negative Technology: Prospects for a Lower-Cost Route to a Lower-Risk Atmosphere. Energy & Environment 20 (6): 973-984.

Gillingham, K., Smith, S., Sands, R., 2008. Impact of Bioenergy Crops in a Carbon Dioxide Constrained World: An Application of the MiniCAM Energy-agriculture and Land Use Model. Mitigation and Adaptation Strategies for Global Change 13 (7): 675-701.

Gough C., Upham, P., 2011. Biomass energy with carbon capture and storage (BECCS or Bio-CCS). Greenhouse Gas Sci Technol. 1:324-334 (2011).

Hansson, J., Berndes, G., 2009. Future Bioenergy Trade in the EU: Modelling Trading Options from a Cost-effectiveness Perspective. Journal of Cleaner Production 17, Supplement 1 (November): S27-S36.

Havlik, P., Schneider, U.A., Schmid, E., Bttcher, H., Fritz, S., Skalsk, R., Alok, K., DeCara, S., Kindermann, G., Kraxner, F., Leduc, S., McCallum, I., Mosnier, A., Sauer, T., Obersteiner, M., 2011. Global Land-use Implications of First and Second Generation Biofuel Targets. Energy Policy 39 (10) (October): 5690-5702.

Heinim, J., Junginger, M., 2009. Production and Trading of Biomass for Energy An Overview of the Global Status. Biomass and Bioenergy 33 (9): 1310-1320.

Hoogwijk, M., Faaij, A., de Vries, B., Turkenburg, W., 2009. Exploration of regional and global cost-supply curves of biomass energy from short-rotation crops at abandoned croplands and rest land under four IPCC SRES land-use scenarios. Biomass and Bioenergy, 33, pp. 26-43.

Hoogwijk, M., Faaij, A., van den Broek, R., Berndes, G., Gielen, D., Turkenburg, W., 2003. Exploration of the Ranges of the Global Potential of Biomass for Energy. Biomass and Bioenergy 25 (2) (August): 119-133.

IPCC. 2000. Land Use, Land-use Change, and Forestry. A Special Report of the IPCC. Cambridge University Press. Cambridge: Intergovernmental Panel on Climate Change.

Keith, D.W. 2000. Geoengineering the Climate: History and Prospect. Annual Review of Energy and the Environment 25 (1): 245-284.

Kraxner, F., Nilsson, S., Obersteiner, M., 2003. Negative Emissions from BioEnergy Use, Carbon Capture and Sequestration (BECS) the Case of Biomass Production by Sustainable Forest

Management from Semi-natural Temperate Forests. Biomass and Bioenergy 24 (45) (April): 285-296.

Krey, V., Riahi, K., 2009. Implications of Delayed Participation and Technology Failure for the Feasibility, Costs, and Likelihood of Staying Below Temperature targetsGreenhouse Gas Mitigation Scenarios for the 21st Century. Energy Economics 31, Supplement 2 (0): S94-S106.

Lackner, K.S. 2003. A Guide to $CO_2$ Sequestration. Science 300 (5626) (June 13): 1677-1678.

Laurijssen, J., Faaij, A.,. 2009. Trading Biomass or GHG Emission Credits? Climatic Change 94 (3): 287-317.

Luckow, P., Wise, M.A., Dooley, J.J., Kim S.H., 2010. Large-scale Utilization of Biomass Energy and Carbon Dioxide Capture and Storage in the Transport and Electricity Sectors Under Stringent $CO_2$ Concentration Limit Scenarios. International Journal of Greenhouse Gas Control 4 (5): 865-877.

Magne, B., Kypreos, S., Turton, H., 2010. Technology Options for Low Stabilization Pathways with MERGE. The Energy Journal Volume 31 (Special Issue): 83-108.

Massetti E., Sferra, F., 2010. A Numerical Analysis of Optimal Extraction and Trade of Oil under Climate Policy. Working Papers 2010.113, Fondazione Eni Enrico Mattei.

Matthews H.D., Caldeira K.. 2007. Transient Climatecarbon Simulations of Planetary Geoengineering. Proceedings of the National Academy of Sciences 104 (24) (June 12): 9949-9954.

Metz, B., Davidson, O., de Coninck, H., Loos, M., Meyer, L., 2005. Carbon Dioxide Capture and Storage. Cambridge, United Kingdom: IPCC.

Nordhaus, W.D., Yang, Z., 1996. A regional dynamic general-equilibrium model of alternative climate-change strategies. American Economic Review, 86 (4), 741-765.

Obersteiner, M., Azar, C., Kauppi, P., Mllersten, K., Moreira, J., Nilsson, S., Read, P., Riahi, K., Schlamadinger, B., Yamagata, Y., Yan, J., van Ypersele J.P., 2001. Managing Climate Risk. Science 294 (5543) (October 26): 786-787.

Popp, A., Dietrich, J.P., Lotze-Campen, H., Klein, D., Bauer, N., Krause, M., Beringer, T., Gerten, D., Edenhofer, O., 2011. The Economic Potential of Bioenergy for Climate Change Mitigation with Special Attention Given to Implications for the Land System. Environmental Research Letters 6 (3) (July 1): 034017.

Reilly, J., Paltsev, S., 2007. Biomass Energy and Competition for Land. MIT Joint Program on the Science and Policy of Global Change.

Rhodes, J.S., Keith, D.W., 2005. Engineering Economic Analysis of Biomass IGCC with Carbon Capture and Storage. Biomass and Bioenergy 29 (6): 440-450.

Rhodes, J.S., Keith, D.W., 2008. Biomass with Capture: Negative Emissions Within Social and Environmental Constraints: An Editorial Comment. Climatic Change 87 (3): 321-328.

Rokityanskiy, D., Bentez, P.C., Kraxner, F., McCallum, I., Obersteiner, M., Rametsteiner E., Yamagata, Y., 2007. Geographically Explicit Global Modeling of Land-use Change, Carbon Sequestration, and Biomass Supply. Technological Forecasting and Social Change 74 (7): 1057-1082.

Rose, S.K., Ahammad, H., Eickhout, B., Fisher, B., Kurosawa, A., Rao, S., Riahi, K., van Vuuren, D.P., 2012. Land-based Mitigation in Climate Stabilization. Energy Economics 34 (1): 365-380.

Sands, R.D., Leimbach, M., 2003. Modeling Agriculture and Land Use in an Integrated Assessment Framework. Climatic Change 56: 185-210.

Schlamadinger B., Faaij A, Daugherty, E., 2004. Should We Trade Biomass, Electricity, Renewable Certificates or $CO_2$ Credits? IEA.

Smeets, E.M.W., Faaij, A.P.C., Lewandowski, I.M., Turkenburg, W.M., 2007. A Bottom-up Assessment and Review of Global Bio-energy Potentials to 2050. Progress in Energy and Combustion Science 33 (1) (February): 56-106.

Sohngen, B., Mendelsohn, R., 2003. An Optimal Control Model of Forest Carbon Sequestration. American Journal of Agricultural Economics 85 (2) (May 1): 448-457.

Stolaroff, J.K., Keith, D.W, Lowry G.V., 2008. Carbon Dioxide Capture from Atmospheric Air Using Sodium Hydroxide Spray. Environmental Science & Technology 2008 42 (8), 2728-2735.

The Royal Society. 2009. Geoengineering the Climate Science, Governance and Uncertainty.

Thomson, A., Calvin, K., Smith, S.J., Kyle, P.G., Volke, A., Patel, P., Delgado-Arias, S., Lamberty, B.B., Wise, M.A., Clarke, L.E., Edmonds, J.A., 2011. RCP4.5: a Pathway for Stabilization of Radiative Forcing by 2100. Climatic Change 109 (1): 77-94.

UNFCCC. 2010. Copenhagen Accord 2010. unfccc.int/resource/docs/2009/cop15/eng/l07.pdf.

Van Vuuren, D., den Elzen, M., Lucas, P., Eickhout, B., Strengers, B., van Ruijven, B., Wonink, S., van Houdt, R., 2007. Stabilizing Greenhouse Gas Concentrations at Low Levels: An Assessment of Reduction Strategies and Costs. Climatic Change 81 (2): 119-159.

Van Vuuren, D., Stehfest, E., den Elzen, M., Kram, T. van Vliet, J., Deetman, S., Isaac, M., Goldewijk, K.K., Hof, A., Mendoza Beltran, A., Oostenrijk, R., van Ruijven, B., 2011. RCP2.6: Exploring the Possibility to Keep Global Mean Temperature Increase Below 2C. Climatic Change 109 (1): 95-116.

Van Vuuren, D., Stehfest, E., den Elzen, M., van Vliet, J., Isaac, M., 2010. Exploring IMAGE Model Scenarios That Keep Greenhouse Gas Radiative Forcing Below 3 W/m2 in 2100. Energy Economics 32 (5): 1105-1120.

**NOTE DI LAVORO DELLA FONDAZIONE ENI ENRICO MATTEI**

**Fondazione Eni Enrico Mattei Working Paper Series**

**Our Note di Lavoro are available on the Internet at the following addresses:**
http://www.feem.it/getpage.aspx?id=73&sez=Publications&padre=20&tab=1
http://papers.ssrn.com/sol3/JELJOUR_Results.cfm?form_name=journalbrowse&journal_id=266659
http://ideas.repec.org/s/fem/femwpa.html
http://www.econis.eu/LNG=EN/FAM?PPN=505954494
http://ageconsearch.umn.edu/handle/35978
http://www.bepress.com/feem/

**NOTE DI LAVORO PUBLISHED IN 2013**

| | | |
|---|---|---|
| CCSD | 1.2013 | Mikel Bedayo, Ana Mauleon and Vincent Vannetelbosch: Bargaining and Delay in Trading Networks |
| CCSD | 2.2013 | Emiliya Lazarova and Dinko Dimitrov: Paths to Stability in Two-sided Matching with Uncertainty |
| CCSD | 3.2013 | Luca Di Corato and Natalia Montinari: Flexible Waste Management under Uncertainty |
| CCSD | 4.2013 | Sergio Currarini, Elena Fumagalli and Fabrizio Panebianco: Games on Networks: Direct Complements and Indirect Substitutes |
| ES | 5.2013 | Mirco Tonin and Michael Vlassopoulos: Social Incentives Matter: Evidence from an Online Real Effort Experiment |
| CCSD | 6.2013 | Mare Sarr and Tim Swanson: Corruption and the Curse: The Dictator's Choice |
| CCSD | 7.2013 | Michael Hoel and Aart de Zeeuw: Technology Agreements with Heterogeneous Countries |
| CCSD | 8.2013 | Robert Pietzcker, Thomas Longden, Wenying Chen, Sha Fu, Elmar Kriegler, Page Kyle and Gunnar Luderer: Long-term Transport Energy Demand and Climate Policy: Alternative Visions on Transport Decarbonization in Energy Economy Models |
| CCSD | 9.2013 | Walid Oueslati: Short and Long-term Effects of Environmental Tax Reform |
| CCSD | 10.2013 | Lorenza Campagnolo, Carlo Carraro, Marinella Davide, Fabio Eboli, Elisa Lanzi and Ramiro Parrado: Can Climate Policy Enhance Sustainability? |
| CCSD | 11.2013 | William A. Brock, Anastasios Xepapadeas and Athanasios N. Yannacopoulos: Robust Control of a Spatially Distributed Commercial Fishery |
| ERM | 12.2013 | Simone Tagliapietra: Towards a New Eastern Mediterranean Energy Corridor? Natural Gas Developments Between Market Opportunities and Geopolitical Risks |
| CCSD | 13.2013 | Alice Favero and Emanuele Massetti: Trade of Woody Biomass for Electricity Generation under Climate Mitigation Policy |