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Carbon mitigation with woody biomass and CCS: an economic assessment

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Coordinatore del Dottorato	Tutore del Dottorando
Prof. Carlo Barbante	**Prof. Carlo Carraro**

Carbon mitigation with woody biomass and CCS: an economic assessment

Alice Favero

July 20, 2013

Dedication

To Emanuele and our children.
To my parents and my sisters.

Be patient, be brave, be optimistic.

Acknowledgements

This project is the result of a long journey sometimes in good company, sometimes alone. It started in Venice, passed through Milan and stopped in the woods of Connecticut where sometimes I got lost but almost of the time I felt at home. I have tried to be a good climber, focusing on each step especially when the final destination seemed too far, even unreachable. I must confess that I could not have done this work on my own. My team supported me in each step. It is a great team, so this achievement is for them.

This achievement is first of all and above all for Emanuele. He was the best mentor I have ever found by accident. I want to thank him for his infinite support, his honesty and his unconditional love.

Maria is the integral part of this thesis. She was with me when I started this adventure, on my lap when I was writing, on the couch when I was thinking how to solve problems or deal with new questions. I remember what she was doing at each chapter of this thesis, my big girl.

”Baby Charlie” has made this thesis even more exciting. His/her presence was the only company during the nights when I was finalizing everything.

I hope this achievement will show my children that if they are brave, optimistic and patient, they will collect fruit from the hard work.

I acknowledge the thoughtful input and consistent encouragement provided by my supervisor Professor Carlo Carraro.

Without Professor Robert Mendelsohn I would probably still be looking for an interesting topic. Many thanks to him for his unwavering support, his humor, and his ability to encourage me. He is the most enthusiastic and patient person I have met in my life.

I also acknowledge Professor Brent Sohngen for giving me the opportunity to use his timber model. Sometimes I felt like as I were in the woods of Connecticut but his and Adam Diagneault’s support was a great help in learning this new tool.

My family members helped me a lot in more ways that I can say during this journey.

My mother Rosanna and my father Sandro provided me with a childhood of exploration and love and they have been always wise and supporting parents. To them, I give love and gratitude. Without their generosity of time and patience during the hard times, I could not have met this challenge.

My sisters Martina and Francesca are the lightness and humor that have helped me to see beyond stress and difficulties. They know me better than anyone else despite different points of view and with an ocean between us.

Margherita and Erio Massetti offered, at all times, their understanding and acceptance and I am appreciative of their generosity of time and unwavering attention to Maria.

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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.

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 et al. 2003; Lackner 2003; Matthews and Caldeira 2007; Stolaroff et al. 2008; Eisenberger et al. 2009; Chen and Tavoni, 2013). 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; 2008; Azar et al. 2006; 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 (bio-energy) and it lowers the stock of CO_2 in the atmosphere (CCS). For these peculiar characteristics, BECCS plays a critical role in many scenarios of mitigation policies generated by integrated assessment models (IAMs) (Clarke et al. 2009; Edenhofer et al. 2010; van Vuuren et al. 2011; Rose et al. 2012).

Despite being attractive and promising, a large use of BECCS raises some important questions about biomass supply and the CCS technology. First, IAMs do not have enough detail about global forests and arable land to make careful forecasts of biomass supply across time and across the planet. It is unclear if a large scale production of bio-energy supply would affect other competing uses of land (e.g. timber for industrial sector, food production and ecosystem), what would be the demand for water for irrigation purposes, and the emission balance (Berndes 2002; Rhodes and Keith 2008; van Vuuren et al. 2010; Gough and Upham 2011). Second, 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).

This Thesis analyzes some of the key questions associated with the use of BECCS particularly focusing on woody biomass used in integrated gasification combined cycle (IGCC) power plants with CCS. Chapter 2 describes the role of the BECCS technology on the optimal power mix and the mitigation portfolio. Then Chapter 3 investigates whether and how the trade of woody biomass will affect the importance of the BECCS technology. Chapter 4 studies the effects of bio-energy demand on the timber market and land use. Finally, Chapter 5 shows how a woody biomass program included in a mitigation policy could be an efficient substitute to a formal carbon sequestration program (eg. REDD).

The primary tool used in this work is the integrated assessment model WITCH (Bosetti et al. 2006; 2007; 2009) described in the Appendix A. In Chapter 2 and Chapter 3 I use the regional biomass supply curves obtained from the Global Biosphere Optimisation Model (GLOBIOM) developed by IIASA (Havlk et al. 2011). The supply curves consist of second generation woody biomass coming from short rotation tree plantations and forest logging residues for each region. The GLOBIOM model also provides the maximum biomass endowment for each region at any time period. In Chapter 3, together with Emanuele Massetti, I develop a new version of WITCH that includes the international trade of biomass (new equations are described in Appendix A). Finally, in Chapters 4 and 5 instead of using the biomass supply curves from GLOBIOM, together with Professor Robert Mendelsohn, I link WITCH to the forestry model GTM (Sohngen et al. 1999; Sohngen and Sedjo 2000; Sohngen and Mendelsohn 2003; Daigneault et al. 2012). We first develop a new version of the GTM model introducing the aggregate demand for biomass for energy[1] and then we link this new version to WITCH (see Appendix D for a description of the forestry model and Appendix E for the soft-link).

In all Chapters I use the same baseline scenario and three mitigation scenarios which are de-

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[1] The previous version of the GTM model includes only the demand for bio-energy for the USA (Daigneault et al. 2012)

scribed in Appendix C and Appendix G. The baseline scenario is a Business As Usual (BAU) scenario with no greenhouse gas mitigation policies over the century while three carbon tax schedules are used to simulate alternative mitigation strategies from modest to severe. The mitigation scenarios lead to radiative forcing levels of 4.8, 3.8 and 3.2 W/m^2.[2] Finally, I assume no sequestration policies (other than carbon capture and storage) are available in this analysis.

Chapter 2 analyzes the role of BECCS under mitigation policy scenarios from two perspectives. First, it studies the implications of including the BECCS technology in the mitigation portfolio on both the optimal power mix and investments in the power sector. Then, it focuses on how the use of BECCS will affect emissions and, as a consequence, the public budget using the three representative tax scenarios.

The importance of BECCS under climate mitigation scenarios has already been recognized and discussed in the literature. Numerous studies have shown that the use of BECCS makes it technically possible and less expensive to limit radiative forcing to very low levels. First, the use of BECCS allows reaching stabilization target that would have been infeasible without it (Krey and Riahi, 2009; van Vuuren et al. 2010; Edenhofer et al. 2010; Rose et al. 2012). Second, BECCS makes it cost effective to delay the adoption of more costly mitigation measures until the second half of the century (Krey and Riahi 2009; van Vuuren et al. 2010; Thomson et al. 2011). Finally, BECCS greatly reduces policy cost (Azar et al. 2006; Krey and Riahi, 2009). The literature presents a wide range in estimates of BECCS consumption under mitigation scenarios: between 50 and 160 EJ/yr in 2050 and 70-250 EJ/yr in 2100 (Luckow et al. 2010; Dooley and Calvin 2011; Reilly and Paltsev 2007; Gillingham et al., 2008; Calvin et al. 2009). However, none of those studies has analyzed either the BECCS consumption at regional level or its effect on the technological mix as well as the implications on the investment flows. Finally, the issue of negative emissions from BECCS has never been linked to the effect on the revenue from the carbon tax.

This Chapter aims at answering the following research questions: (i) what are the implications of introducing the BECCS technology on the optimal energy mix? (ii) how does this new technology drive the investments in the power sector? and (iii) how large is the effect of having BECCS in the mitigation portfolio on both the emissions abatement and the revenue from the carbon tax?

Chapter 3 analyses the role of the international trade of woody biomass and its implications on the climate change mitigation policy. In particular, it focuses 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 woody biomass is unevenly distributed among

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[2] These levels are reached in the scenarios with the biomass supply curves from the GLOBIOM model and under the assumptions that the BECCS technology is available at global scale and woody biomass is not traded internationally.

world regions. For instance, Latin America and Sub-Saharan Africa have a very large production potential while some regions have very low potential (Berndes et al. 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 et al. (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 et al. 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 either on optimal abatement or on the cost of achieving a given mitigation target.

In this Chapter I 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, on the optimal power mix and on GHG emissions, using the three representative tax scenarios. I 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.

Chapter 4 provides a global, dynamic and detailed description of the woody biomass supply under climate mitigation scenarios.

The existing literature on woody biomass has revealed that woody biomass competes with traditional forest products and that the increased demand for forest outputs will increase the price of forestland and therefore the amount of forests (Ince et al., 2011; 2012; Daigneault et al., 2012; Moiseyev et al., 2011; Lauri, et al., 2012). Although these regional and national studies are adequate for showing the qualitative impacts of a woody biomass program, they do not reveal the global response. Only a few studies have evaluated the global implications of woody biomass on the forest sector (Raunikar et al. 2010; Buongiorno et al., 2011). A limitation of these studies as well as the regional studies is that they examine arbitrary quantities of woody biomass for energy. The quantities are not tied to carbon prices nor are they able to capture the price feedbacks from the energy sector to the land sector and back. This depends on the magnitude of the biomass program since biomass will get more expensive as it competes against timber products and other uses of land. It also depends on the price of carbon which will determine the aggregate amount of mitigation desired over time. In practice, these factors change over time requiring a dynamic analysis which is partially missing in the literature. Finally, only two studies provide a global analysis of the role played by biomass on a mitigation portfolio in a dynamic framework (Gillingham et al. 2008; Popp et al. 2011) but they lack a detailed description of the forestry sector.

This Chapter addresses these shortcomings in the literature by combining WITCH to a detailed, global and dynamic forestry model, GTM (Sohngen et al 1999; Sohngen and Sedjio 2000; Sohngen and Mendelsohn 2003; Daigneault et al 2012). In particular, for each policy scenario WITCH calculates the global quantity demanded of woody biomass over time. The quantity demanded for woody biomass from WITCH is then added to the demand for industrial wood products in GTM. The timber model then solves for the international price of wood. The price is then entered back into WITCH which generates a new quantity demanded. The two models iterate back and forth until demand equals supply. The combined model is then used to explore the desired size of the woody biomass market, the impact on industrial timber, the price of timber, the size of forestland, and the impact on other land uses under different degrees of policy's stringency.

Chapter 5 uses the same scenarios developed in Chapter 4 to show that forest bio-energy production is a clever way to implement forest sequestration. Although this aspect has already been discussed in the literature (Malmsheimer et al. 2011; Havlk et al. 2011; Daigneault et al. 2012; Sedjo and Tian 2012) they do not neither quantify this effect at the global level nor provide policy insights for this result.

This Chapter shows that the woody biomass program will establish a market that secures carbon sequestration benefits and does not require complex land use regulations (forests that are owned by many) which are very problematic on a global scale (Mendelsohn et al. 2012). In addition, the market will address some of the problems associated with a formal sequestration program such as additionality and leakage (Murray et al 2004; Murray et al 2007, Richards and Andersson 2001).

Finally, the Appendix presents a detailed description of the WITCH and the GTM model, the assumptions and policy scenarios used in each chapter and the soft-link of WITCH and GTM.

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2. WOOD BIO-ENERGY AND CARBON CAPTURE AND STORAGE UNDER CLIMATE MITIGATION POLICY

2.1 Introduction

As policy makers consider stringent targets for greenhouse gas emissions, integrated assessment models are increasingly relying on biomass energy as a critical energy source. Numerous studies have shown that it is technically possible to limit radiative forcing to very low levels (eg. 2.6 W/m^2 which is consistent with limiting global mean surface temperature increase not more than 2°C target) if bio-energy with CCS (BECCS) is employed at large-scale (Clarke et al. 2009; Krey and Riahi 2009; Edenhofer et al. 2010; van Vuuren et al. 2011; Rose et al. 2012). BECCS is attractive because it delivers two desired outputs at the same time: it generates carbon free electricity (bio-energy) and it lowers the stock of CO_2 in the atmosphere (CCS). First carbon dioxide fixed in biomass through photosynthesis is captured when biomass is burned and it is then sequestered in underground deposits via CCS (Obersteiner et al. 2001; Rhodes and Keith 2005; 2008; Azar et al. 2006; 2010; Chum et al. 2011).

The literature presents three types of benefits from the use of BECCS in the IAMs. 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. 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 the adoption of more costly mitigation measures until the second half of the century (Krey and Riahi 2009; van Vuuren et al. 2010; Thomson et al. 2011). Krey and Riahi (2009) find that emissions can peak in 2030 while 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.

In this work[1] I analyze the role of BECCS under mitigation policy scenarios from two perspectives. First, I study the implications of including the BECCS technology in the mitigation portfolio on both the optimal power mix and investments in the power sector. Then, I analyze how the use of BECCS will affect emissions and, as a consequence, the public budget using three representative tax scenarios.

The key role of BECCS in the optimal power mix under mitigation scenarios have already been presented in the literature with global BECCS consumption ranging from 50 and 160 EJ/yr in 2050 and 70-250 EJ/yr in 2100 (Luckow et al. 2010; Dooley and Calvin 2011; Reilly and Paltsev 2007; Gillingham et al., 2008; Calvin et al. 2009). The difference in the estimates is explained first by different assumptions about biomass feedstocks (woody biomass, crops bio-energy, agricultural and forestry residues). For instance, some studies use only biomass from forest while others combine both bio-energy crops and woody biomass supply (see for example Gillingham et al. 2008). Moreover, some studies assume limited biomass potential while others do not limit the amount of land available to meet the increasing demand for biomass. For instance, the MERGE model uses all the biomass potential (195 EJ/yr) in all the policies scenarios by 2100 (Magne et al. 2010, p.98). Finally, the demand for BECCS is highly influenced by the stringency of the policy.

However, none of these studies has analyzed either the BECCS consumption at regional level or its effect on the technological mix as well as the implication on the investment flows. Finally, the issue of negative emissions from BECCS has never been linked to the effect on the revenue from the carbon tax.

This work aims at answering the following research questions: (i) what are the implications of introducing the BECCS technology on the optimal energy mix? (ii) how does this new technology drive the investments in the power sector? and (iii) what is the magnitude of the effect of having biomass in the mitigation portfolio on both the emissions abatement and the revenue from the carbon tax?

In order to answer to these questions I use the integrated assessment model WITCH (Bosetti et al. 2006; 2007; 2009), the regional biomass supply curves obtained from the Global Biosphere Optimization Model (GLOBIOM) developed by IIASA (Havlk et al. 2011) and the cost of storing CO_2 underground that is region-specific (Bosetti et al 2006). The WITCH model is described in the Appendix A while the assumptions on biomass supply and CCS are in Appendix B. I simulate three representative carbon tax scenarios with and without the use of BECCS (see Appendix C) in order to analyze the implications of the BECCS technology on the power sector and emissions

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[1] This Chapter is based on the article "Investments and Public Finance in a Green, Low Carbon Economy" *Energy Economics* 34 (2012) S15-S28 (with Carlo Carraro and Emanuele Massetti).

abatement for the same cost of CO_2.

This Chapter is organized as follows. Section 2 presents the effects of BECCS on the optimal power generation mix and investments in the power sector. Section 3 discusses the effect BECCS on emissions and revenue from the carbon tax. Conclusions follow with a summary of the findings.

2.2 The impacts of BECCS on optimal power mix and investments in the power sector

2.2.1 Power mix

In this Section I analyse the impact of including BECCS in the mitigation portfolio on the optimal power mix.

I assume that using woody biomass for energy is carbon neutral since the carbon released during combustion was offset by the carbon captured during the growth of the trees. Moreover, biomass combined with the CCS technology will captured 90% of the amount of carbon released during the combustion process. According to these assumptions, higher carbon taxes make BECCS technology more and more attractive. In early years the carbon prices are not large enough to sufficiently incentivize the demand for BECCS. The economy starts to consume BECCS in 2020 in the t3 scenario, in 2025 in the t2 scenario and in 2040 in the t1 scenario.

As the carbon tax increases the demand for BECCS will increase both in absolute terms (Figure 1a) and as a percentage of the total electricity generation (Figure 1b). The levels of biomass production range from 16 EJ/year to 64 EJ/year in 2050 and rise to 64-81 EJ/year in 2100 depending on the scenario. Both the t2 and the t3 scenarios reach a peak of 92 EJ/yr and 107 EJ/yr respectively and after that the demand for BECCS collapses because biomass becomes too expensive.

These estimations are included in the range presented in the literature. In the GCAM model, biomass production ranges from 120-160 EJ/yr in 2050 rising to 200-250 EJ/yr by 2100 in the 400 ppm stabilization scenario (Luckow et al. 2010). While in Dooley and Calvin (2011) biomass with CCS provides about 25% of electricity by 2095 in the 400 ppm scenario. The IMAGE model predicts that 130-270 EJ can be produced at a cost below 2 USD/GJ and more at higher prices (Hoogwijk et al. 2009). In the EPPA model global biomass energy production will be equal to 50-150 EJ/year by 2050 and 220-250 EJ/year by 2100 under stabilization policies (Reilly and Paltsev 2007). The MiniCAM estimated bio-energy production of 200 EJ/yr (450ppm CO_2 stabilization target); 190 EJ/yr (550 ppm CO_2 stabilization target) and 70 EJ/yr (650 ppm CO_2 stabilization target) in 2100 (Gillingham et al., 2008). Finally, Calvin et al. (2009) found that models use approximately to 180-200 EJ/yr in 2095 in the 2.6 W/m^2 scenario.

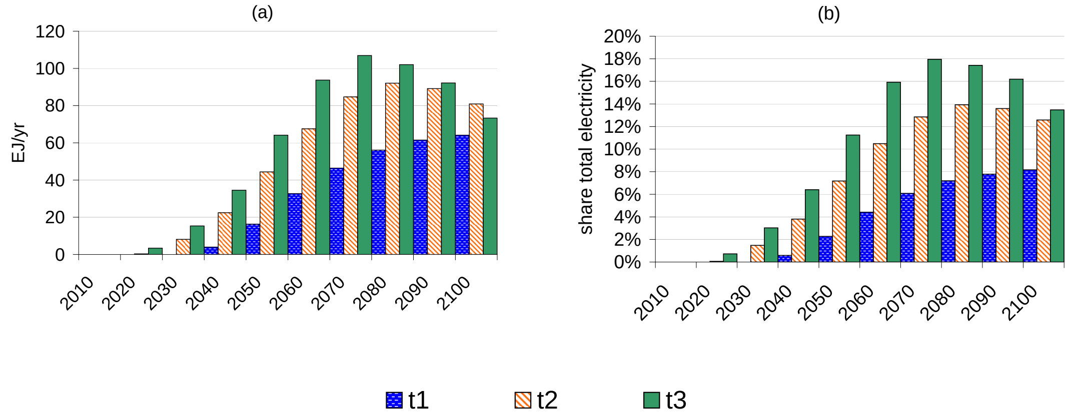

Fig. 2.1: BECCS production in EJ/yr (a) and share of total electricity (b) under the three carbon tax scenarios.

At the regional level, regions with the high amount of biomass available and low CCS costs are the countries that consume more BECCS electricity. For instance, LACA covers 27-32% of the global BECCS consumption in 2050 and 30-35% in 2100 while MENA does not consume BECCS as it has no domestic supply of biomass according to GLOBIOM (See Appendix B). The maximum biomass potential from GLOBIOM is indeed a key determinant of these results. In fact, as the carbon tax increases, many regions use all their regional biomass endowment. In particular, in t1 only WEURO, EEURO, SASIA and INDIA consume all the amount of woody biomass available by 2100. While in both the t2 and t3 all regions - with the exception of CAJAZ, LACA and SSA - use all their endowment by the end of the century (Figure 2).

The introduction of the BECCS technology in the mitigation portfolio has also a substantial impact on the technological mix. The impact is mainly due to the competition of coal, biomass and gas for the same CCS sites. As the carbon tax increases it becomes more efficient to use the CCS site for biomass instead of coal and gas. This is due the fact that biomass with CCS provide negative emissions into the system while both coal and gas still produce net positive emissions.

In t1, 46% of CCS deployments are coupled with bio-energy, 4% with natural gas fired systems, and 50% with coal by 2100. In t2, the share of biomass reaches 64% as well as the share of natural gas by 12% while coal declines to 24%. Finally, in the t3 71% of CCS deployments are coupled with bio-energy systems, 11% with natural gas fired systems, and only 17% with coal (Figure 3). Similar results have been found in Luckow et al. (2010) where by 2100 46% of CCS deployments are coupled with bio-energy systems, 26% with natural gas fired systems, and 24% with coal in the scenario 400 ppm.

There is a significant expansion of BECCS at the expense of coal with CCS. This is confirmed comparing the same carbon tax scenarios with and without the use of BECCS. In fact, when BECCS is not available the share of coal is 94% in t1 and 79% in both the t2 and t3 in 2100. Also the share of gas is higher when BECCS is not included in the power mix but the difference is less significant. However, recent developments in natural gas extraction techniques have the potential to reduced natural gas prices substantially and suggest that natural gas might compete more with biomass than indicated by these scenarios.

2.2.2 Investments

In order to study the impact of the BECCS technology on investments in the power sector I first compare the Business as Usual scenario (BaU) to the tax scenarios and then I compare the tax scenarios with and without BECCS.

Examining the investments in the power sector, the climate policy first induces energy savings and then a decarbonization of energy supply. One of the cheapest ways to reduce carbon emissions is indeed to increase energy efficiency. In addition, negative-zero- or low-carbon - generation technologies have investment costs per unit of installed capacity higher than the traditional coal or gas fired power plants that they are meant to replace[2]. Therefore, installed capacity needs to rise to meet the same demand for electricity. Had the electricity demand for the BaU scenario to be supplied by low-carbon technologies, the total amount of investments in the power sector would certainly increase. There are thus two forces at play: more technologically advanced power plants will increase investment costs per unit of installed capacity, but at the same time installed capacity will decline as electricity demand declines (with respect to the BaU scenario). The optimal balance of these two forces varies regionally, intertemporally and depends on the stringency of climate policy (the severity of the carbon tax). The higher is energy intensity in the BaU scenario, the higher is the potential to reduce energy consumption before moving on to more expensive options. Typically, energy intensity is higher in developing countries and it is decreasing over time. Therefore, climate policy induces higher investments in the power sector (1) in non-OECD economies, (2) in later years and/or (3) when the carbon price is high.

Figure 4 illustrates these findings. At the global level, investments in t1 are equal to the BaU scenario until 2040. The t2 induces a pattern similar to the BaU scenario until 2025; then investments are higher. The t3 scenario is the most demanding: more investments are needed from 2020. In energy-efficient OECD economies, investments are higher than in the BaU scenario,

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[2] See Edenhofer et al. (2011) for an overview of costs of renewable electricity generation.

with the exception of the t1 scenario until 2045. In the highest carbon tax scenarios investments reach a plateau in 2050 because power plants have a long lifetime: once the optimal capacity is installed, investments are needed only for marginal adjustments and to replace obsolete plants. In non-OECD economies, carbon taxes promote large energy efficiency improvements and greatly reduce investment needs in power supply for the first decades. This is why they are lower than the BaU scenario for the first 15 years (until 2025). In the lowest carbon tax, most of the emission reductions until 2050 come from energy efficiency gains. Hence, investments in the power sector are similar to the BaU scenario. The t2 and t3 induce both energy efficiency and decarbonization. The net effect is a large increase of investments with respect to the BaU scenario for the t3 scenario after 2025. Most of the incremental investments at the global level induced by the carbon taxes in all scenarios in 2050 are in non-OECD countries.

Figure 5 presents the distribution of investments in the power sector across technologies[3]. In the Business as Usual (BaU) scenario, coal power plants receive the largest amount of investments: 39% of cumulative investments during the period 2010-2100. Wind power[4] and nuclear increase their share of total investments from 7% in 2050 to 12% in 2100 (wind) and from 23% in 2050 to 32% in 2100 (nuclear). Hydropower attracts instead a declining share of investments: from 15% (2050) to 12% (2100). Natural gas attracts a stable 8% of total investments in the power sector. Without the carbon tax there are no incentives to invest in IGCC power plants with CCS since there are no costs on emissions.

With carbon taxes, the investments mix changes significantly as they are diverted from coal power generation to IGCC power plants with CCS with either coal or biomass, nuclear and wind. Cumulative investments in wind power increase between 32% and 68% during 2010-2100 with respect to the BaU scenario (lowest value of the interval in t1 and highest in t3). Cumulative investments in nuclear power increase between 29% and 63% during 2010-2100. Finally, gas with CCS enters the investment mix later than IGCC with CCS with both coal and biomass, because in these scenarios natural gas is more expensive than coal and contains a more fraction of carbon than biomass. The real game changer in investments in the power mix are the investments in IGCC power plants. The use of the BECCS technology drives high investments across time and scenarios. In the most modest scenario (t1), cumulative investments in IGCC with CCS amount to 27% of

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[3] Hydroelectric power capacity is assumed to be already fully exploited and follows an exogenous dynamic.

[4] In WITCH, solar photovoltaic is not competitive with the other power generation technologies and therefore does not contribute to primary energy supply in any scenario. It is important to appreciate that a high penetration of renewables will require investments in new power grids. If new grids will be more expensive than the traditional ones, investments in the power sector will be higher than in my scenarios, which focus only on power generation.

total investments in the power sector for 2010-2100 of which 43% devoted to coal power plant and 57% to biomass power plants. The share increases to 31% and 32% of total investments in t2 and t3 respectively of which 71-77% devoted to biomass and 23-29% to coal. In absolute terms, the average investments in BECCS power plants per year will be between 109 to 205 USD Billions depending on the scenario. These values are comparable to the average investments in nuclear power plants in mitigation scenarios and pulverized coal power plants in the BaU (253 USD Billions/year).

2.3 Effects of BECCS on emissions and the revenue from the carbon tax

The availability of bio-energy combined with CCS enlarges the mitigation choice set in each region shifting the aggregate regional marginal abatement cost curve to the right and therefore increasing the efficiency of mitigation policy under carbon tax scenarios. The overall cost of the policy remains unchanged while optimal abatement increases. Therefore, the question is not if but rather by how much BECCS reduces GHG emissions at global level. In order to answer to this question I compare the same carbon tax scenarios with and without the use of BECCS.

Figure 6 compares cumulative GHG emissions over the period 2010-2100 under the three tax scenarios, with and without BECCS. Dark bars represent the emissions abatements relative to the BaU scenario for the three taxes without BECCS. Light bars represent instead the amount of emissions removed (”negative emissions”) from the atmosphere due to the use of the BECCS technology. Finally, black lines represent the additional emissions’ abatement that occurs when the BECCS technology is available. Results confirm the key role played by BECCS in climate mitigation scenarios found in the literature (see among others Edenhofer et al 2010, van Vuuren et al 2007, 2010, 2011; Krey and Riahi 2009; Rose et al 2012). BECCS reduces cumulative emissions by 262 Gt CO_2-eq in the t1 scenario, by 428 Gt CO_2-eq in the t2 scenario and by 519 Gt CO_2-q in the t3 scenario. Moreover more than 89% of the reduction in GHGs emissions is due to the removal of emissions from the atmosphere while the remaining share is due to other emissions abatement actions such as the shift from fossil fuel technologies to bio-energy.

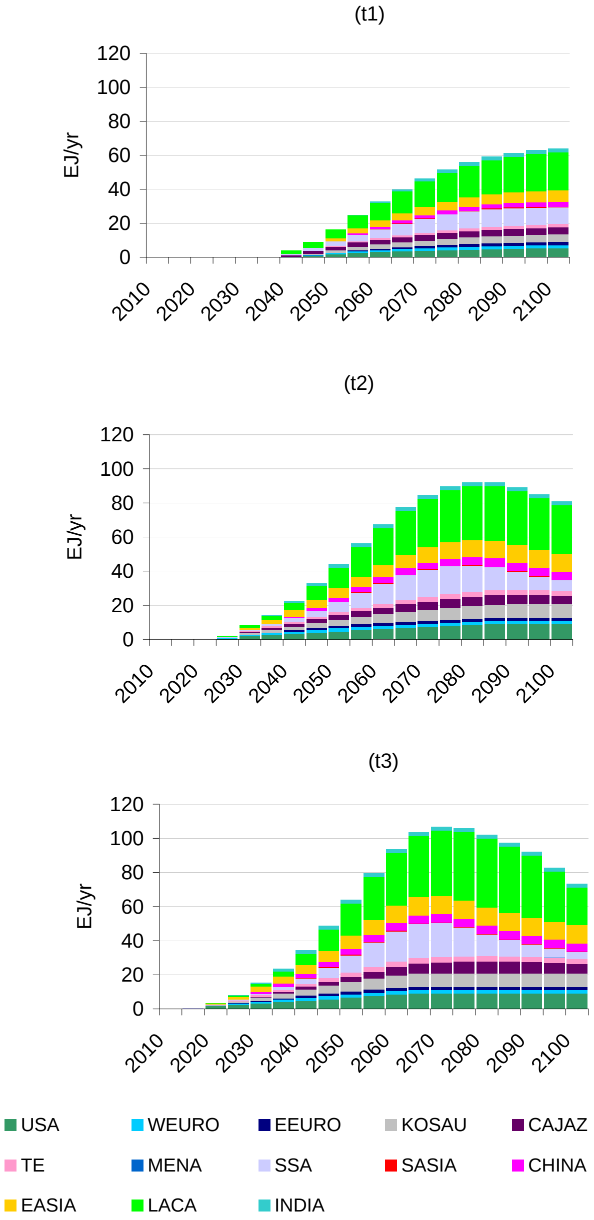

Fig. 2.2: BECCS consumption by regions under different carbon tax scenarios

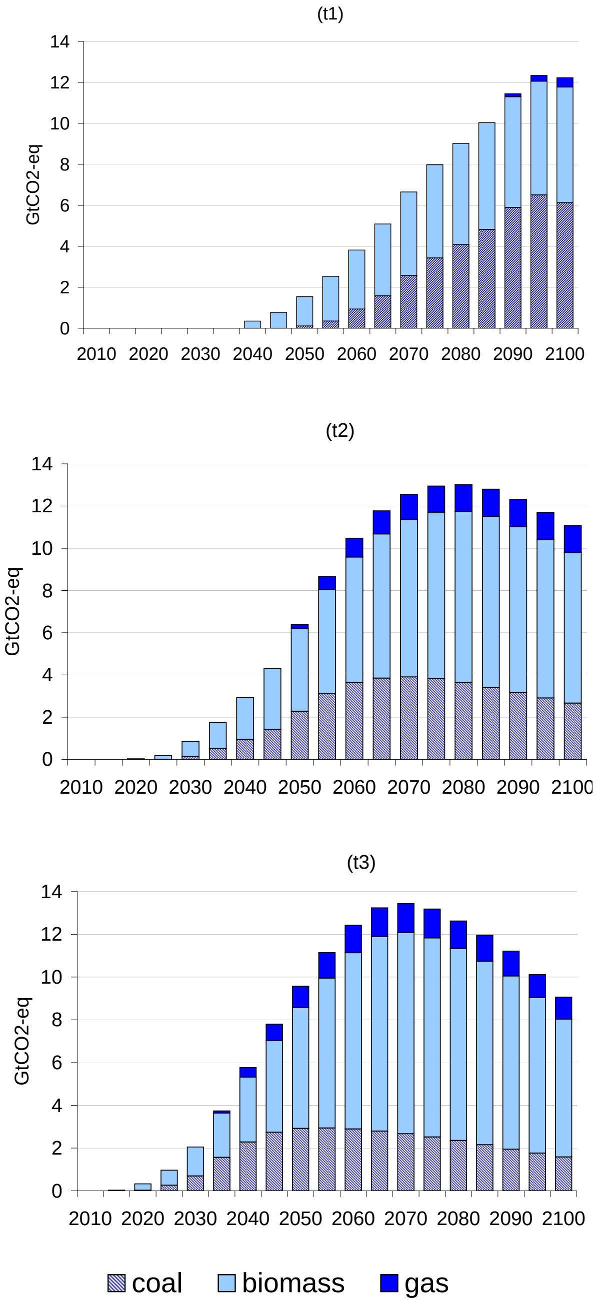

Fig. 2.3: CCS deployments coupled with biomass, natural gas and coal fired systems under different carbon tax scenarios

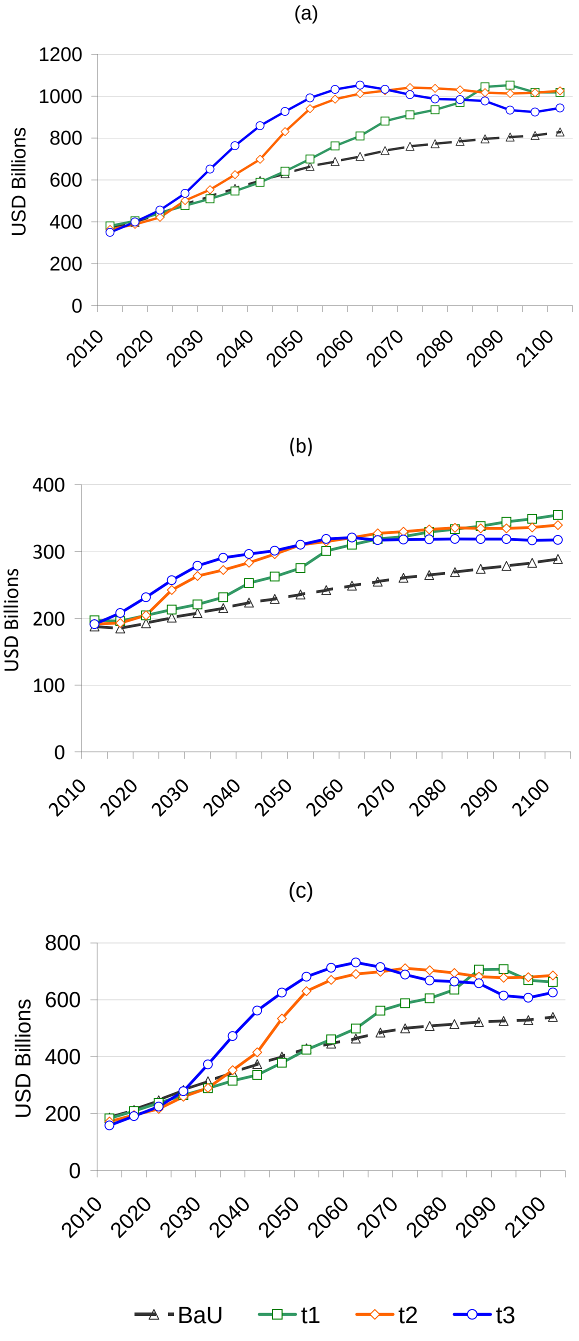

Fig. 2.4: Investments in the power sector in (a) the World, (b) OECD and (c) Non OECD under the BaU scenario and the three carbon tax scenarios with BECCS.

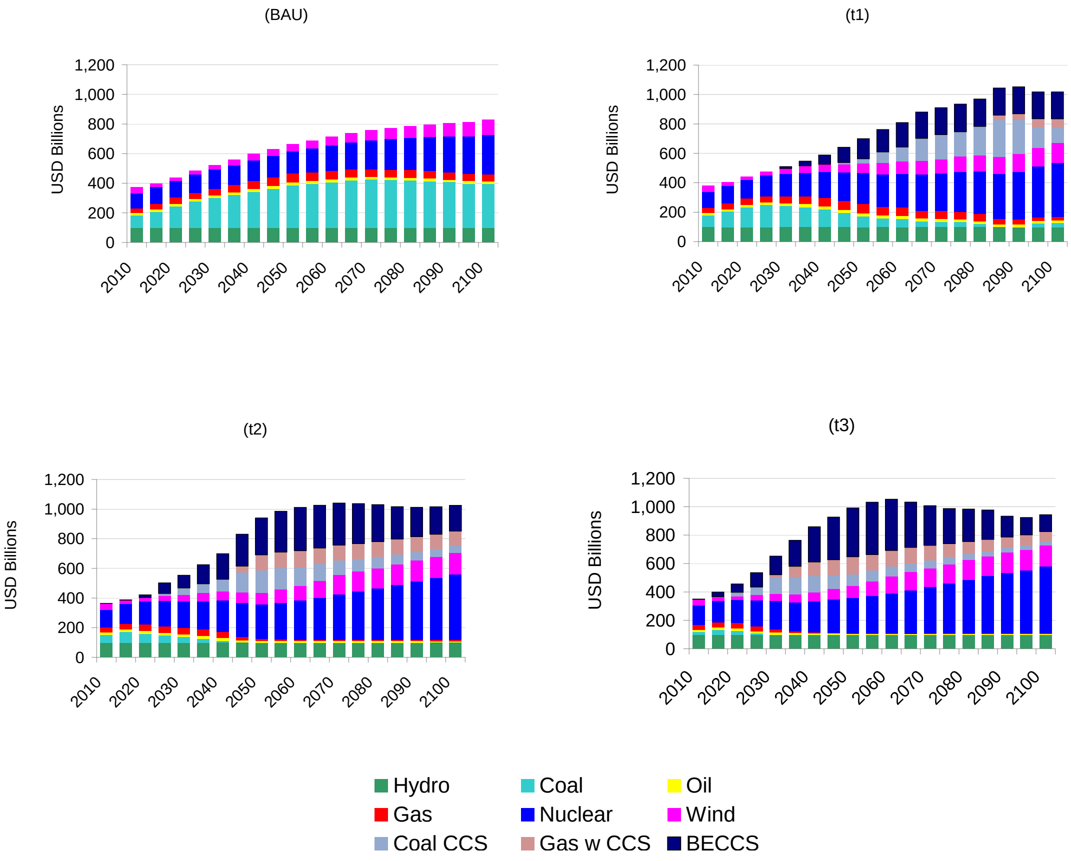

Fig. 2.5: Investments in the power sector across technologies under the BaU scenario (a) and the three carbon taxes scenarios with BECCS

As a result, the amount of CO_2-eq captured through the CCS increases when BECCS is an available mitigation option. In t1 420 Gt CO_2-eq are stored in deep geologic reservoirs around the world in 2010-2100. The amount increases to 669 Gt CO_2-eq in t2 and reaches 743 Gt CO_2-eq in t3. Those figures are 15%, 31% and 37% higher than the scenarios without BECCS.

These estimates are within the bounds of estimates published in technical reports and presented in the literature. The IPCC Special Report on CCS (Metz et al. 2005) estimates that the technical potential in geological formations will be equal to 2000 Gt CO_2-eq by 2100. In Edenhofer et al. (2010) the amount of carbon that is captured with CCS ranges from 275 GtC (in POLES) to 520 GtC (in TIMER) in the 400ppm scenario by 2100. Luckow et al. (2010) found 1530 Gt CO_2-eq will be stored in deep geologic reservoirs around the world by the end of the century under a stabilization scenario of 400 ppm. Finally, in Dooley and Calvin (2011) the amount of CO_2-eq stored with CCS in equal to 1600 Gt CO_2-eq by 2100.

The use of BECCS has also a long-term effect on GHGs concentration that will be reduced

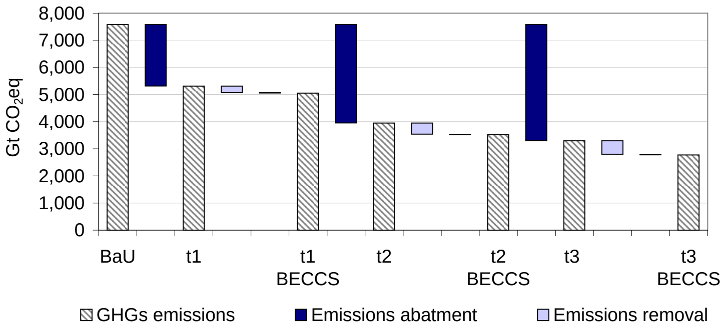

Fig. 2.6: 2010-2100 cumulative abatement with and without BECCS under three carbon tax scenarios

by 24 ppm CO_2-eq (from 705 to 682 ppm) in t1, by 38 ppm CO_2-eq (from 601 to 563) in t2, and 45 ppm CO_2-eq (from 551 to 506) in t3 inducing a decrease in temperature of 0.1-0.2 C by 2100 depending on the scenario.

Finally, emissions from the power sector deserve a special note. The electric power sector changes from being the largest source of emissions in the world (BaU) to being a low source of emissions (under modest policy scenarios) to being a source of negative emissions (when BECCS is available). In particular, in t2 the global electricity sector is 100% decarbonized by 2055 and is responsible for 5 $GtCO_2$ of net negative emissions per year for the period 2010-2100. In t3 it is 100% decarbonized by 2040 and the electricity sectors role in delivering negative emissions to the global economy grows more than 6 $GtCO_2$ per year for the period 2010-2100 (Figure 7). Similar results have been found in Dooley and Calvin (2011) with a 93% of the electricity sector decarbonized by 2050 and is responsible for 11Gt CO_2-eq per year by 2100 in the 400ppm stabilization scenario.

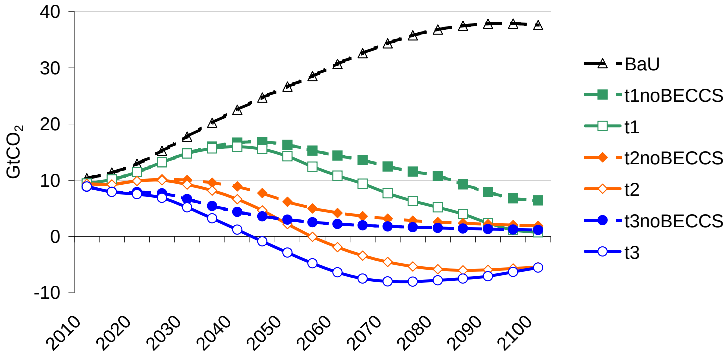

Fig. 2.7: Emissions from the electric sector under the BaU and the policy scenarios 2010-2100

The revenue from the carbon tax will be another element affected by the use of BECCS. The amount of the revenue depends on the level of the tax and on the tax base (GHGs emissions). Using the BECCS technology the economy removes emissions from the atmosphere and thus reduces the tax base. In order to quantify this effect, I compare the revenue from the carbon tax with and without the use of BECCS across scenarios.

In the scenario without BECCS all carbon taxes generate substantial fiscal revenues at the global level. The amount of the revenues varies from a minimum of 87 USD Billion in 2015 in the t1 scenario to 30 USD Trillion in 2100 in the t3 scenario (Figure 8). In terms of GDP, global tax revenues vary from a fraction of percentage point to 9% in 2100 in the t3 scenario.

When I introduce the BECCS technology there is a reduction in the net revenue of carbon tax in all scenarios because the tax base is reduced by the amount of emissions that have been removed from the atmosphere. For instance, in 2100 revenue is reduced by 14% in the lowest carbon tax scenario, by 29% in the 3.8W/m2 scenario reaching a reduction of 47% in the highest carbon tax scenario by 2100 [5](Figure 8). The gap between the revenue with and without BECCS is lower in the lowest carbon tax scenario as the tax is not high enough to drive a high consumption of BECCS.

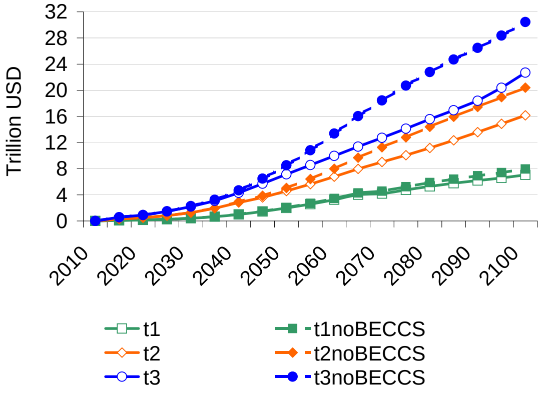

Fig. 2.8: Global revenue from carbon taxes without and with BECCS.

Like the emissions, tax revenues from the power sector also deserve a special note. When biomass is used in IGCC power plants with CCS 90% of the carbon previously stored in the trees will be sequestered and stored underground via CCS. This means that power plants that use biomass, not only will exempt from the carbon tax taxes, but will also receive a subsidy.

Figure 9 substantiates this statement by illustrating the difference between the flow of taxes

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[5] Since the carbon tax is uniform in all regions these figures are equal to the differences of emissions in the corresponding scenarios in 2100.

out of the power sector and the flow of subsidies into the power sector in OECD and non-OECD economies with and without the use of BECCS. In OECD in both t2 and t3 the power sector becomes a net recipient of subsidies when BECCS is allowed (Figure 9a). In the t3 scenario the power sector does not provide carbon tax revenues after 2045, in the t2, after 2060. In 2100 subsidies are 100 USD Billion higher than the revenue in the t2 scenario and 2,400 USD Billion higher in the t3. The picture changes for the non-OECD: only in t3 the power sector becomes a net recipient of subsidies after 2055 (Figure 9b). This is due to the presence of MENA and TE which are high carbon intensity economies and have low (TE) or zero (MENA) biomass potential. Therefore, they do not take any advatages from the use of the BECCS technology on their emissions' abatement.

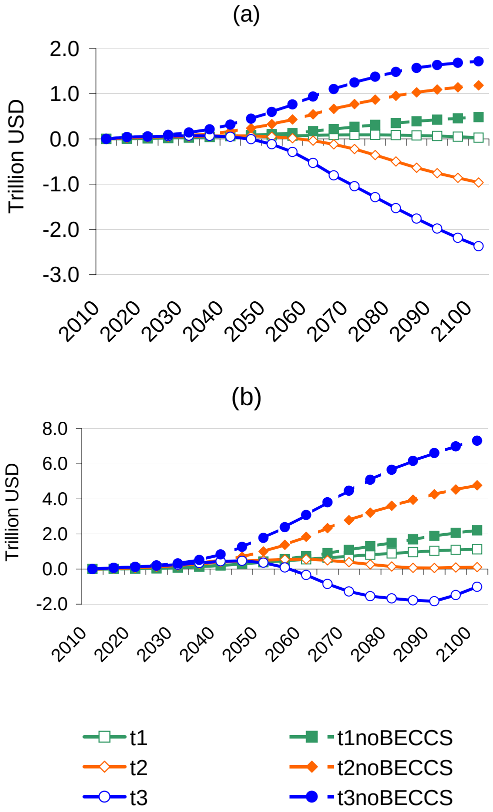

Fig. 2.9: Difference between the flow of taxes out of the power sector and the flow of subsidies into the power sector in OECD (a) and no-OECD economies (b).

2.4 Discussion

This Chapter evaluates the potential of the BECCS technology under climate mitigation scenarios. In particular, I focus on woody biomass used in IGCC power plants combined with CCS. I examine first the impact of BECCS on the power mix and on investments in the power sector and then the effects of BECCS on total emissions using three representative carbon tax scenarios.

First, results show that the demand for bio-energy with CCS will increase across time and scenarios. In early years the carbon prices are not large enough to sufficiently incentivize the demand for BECCS. The economy starts to consume BECCS in 2020 in the t3 scenario, in 2025 in the t2 scenario and in 2040 in the t1 scenario. As the carbon tax increases the demand for BECCS will increase both in absolute terms and as a percentage of the total electricity generation. The level of biomass production ranges from 16 EJ/yr to 73 EJ/yr in 2050 and peak in 2080 at 92 EJ/yr in the t2 scenario and in 2070 at 107 EJ/yr in the t3 scenario as it becomes too expensive. These estimations are included in the range presented in the literature of 50-160 EJ/yr in 2050 and 70-250 EJ/yr in 2100 (Reilly and Paltsev 2007; Gillingham et al. 2008; Calvin et al. 2009; Luckow et al. 2010; Popp et al. 2011).

The introduction of the BECCS technology in the mitigation portfolio has a significant impact in the electricity mix. The impact is due to the competition of coal, biomass and gas for the same CCS sites. As the carbon tax increases it becomes more efficient to use the CCS site for biomass instead of coal and gas. In t1, by 2100 46% of CCS deployments are coupled with bio-energy systems, 4% with natural gas fired systems, and 50% with coal. In t2, the share of biomass increases to 64% as well as the share of natural gas by 12% while the coal declines to 24%. Finally, in the t3 71% of CCS deployments are coupled with bio-energy systems, 11% with natural gas fired systems, and only 17% with coal.

The increasing demand for BECCS electricity requires new investments in IGCC power plants equipped with CCS. In particular, the cumulative investments in biomass IGCC power plants with CCS amount to 15-25% of total investments in the power sector for 2010-2100 with average investment per year of around 109-205 USD Billions depending on the scenario.

Second, results show that, under different carbon taxes, BECCS substantially increases the efficiency of climate policy providing new abatement opportunities. The BECCS technology provides additional cumulative abatement of 262 GtCO_2-eq (t1), 428 GtCO_2-eq (t2) and 519 GtCO_2-eq (t3) for 2010-2100. Moreover more than 89% of the reduction in GHGs emissions is due to the removal of emissions from the atmosphere while the remaining share is due to the shift from fossil fuel technologies to bio-energy. As a result, GHGs concentration will be reduced by 24 ppm CO_2-eq (from 705 to 682 ppm) in t1, by 38 ppm CO_2-eq (from 601 to 563) in t2, and 45 ppm CO_2-eq (from 551 to 506) in t3 inducing a decrease in temperature of 0.1-0.2 C by 2100 depending on the scenario.

The introduction of negative emissions in the system has substantial effects also on the public budget reducing the revenue from the carbon tax since the amount of the revenue depends on the level of the tax and on the tax base (GHGs emissions). In order to quantify this effect, I compare the revenue from the carbon tax with and without the use of BECCS across scenarios. When the BECCS technology is available there is a reduction in the net revenue of carbon tax in all scenarios of by 14-47% by 2100. Examining the tax revenues from the power sector, in OECD in both t2 and t3 the power sector becomes a net recipient of subsidies when BECCS is allowed. In the t3 scenario the power sector does not provide carbon tax revenues after 2045, in the t2, after 2060. In 2100 subsidies are 100 USD Billion higher than the revenue in the t2 scenario and 2,400 USD Billion higher in the t3. The picture changes for the non-OECD: only in t3 the power sector becomes a net recipient of subsidies after 2055. However, it is important to note that the subsidies will not necessarily become rents for the power sector. The biomass resource owner might well get most of the subsidy.

Finally, there are some limitations in my analysis that need to be identified. In particular, the results are sensitive to the regional maximum potential of biomass from the GLOBIOM model. For instance, many regions use all their biomass endowments when the price of carbon increases. In particular, results show that in t1 WEURO, EEURO, SASIA and INDIA consume all the amount of woody biomass available by 2100. In both the t2 and t3 all regions - with the exception of CAJAZ, LACA and SSA - use all their endowment by the end of the century.

Thefore, the disparity between demand and supply of biomass under mitigation scenarios makes the international trade of biomass an important research question in the analysis of the BECCS technology.

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3. TRADE OF WOODY BIOMASS FOR ELECTRICITY GENERATION UNDER CLIMATE MITIGATION POLICY

3.1 Introduction

The "Climate bathtub" model provides the easiest description of the fundamental laws that regulate global climate. The bathtub represents the Earth's atmosphere. The water in the tub corresponds to the amount of Greenhouse Gases (GHG) in the atmosphere, which eventually determines global mean temperature and global climate. Anthropogenic and natural emissions increase the level of GHG concentration (the flow into the tub). Natural and artificial sinks remove GHG from the atmosphere (the flow out of the tub). Since the industrial revolution the inflow of GHG has been greater than the outflow. As a consequence, the concentration of GHG has constantly increased and global mean temperature is now about 0.8 °C higher than in the pre-industrial times. The "Climate bathtub" provides simple and clear policy insights to avoid excessive global warming: the level of GHG in the atmosphere can be controlled by limiting the inflow of GHG emissions or by increasing the outflow.[1] A reduction of GHG emissions typically requires cutting emissions from fuel combustion and from industrial process or reducing deforestation and other land use emissions. In order to increase the absorption of GHG it is possible to enhance land carbon sinks (IPCC 2000; Sands and Leimbach 2003; Sohngen and Mendelsohn 2003) or to use ad-hoc absorption techniques. It is clear that the optimal — i.e. the least cost — policy mix is the one that acts on both the inflow and the outflow in order to equate the marginal cost of reducing the level of GHG in the atmosphere. The research community and policy makers have traditionally paid more attention to measures that address the inflow rather than the outflow of GHG from the atmosphere. However, the focus is quickly shifting towards absorption techniques because the level of GHG in the atmosphere is increasing so fast that even shutting the inflow of GHG to zero could not be sufficient to keep global warming below the desired level.

A growing literature shows that bio-energy with carbon capture and sequestration (BECCS) is

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[1] A third method to control global and local temperature is solar radiation management, which leaves the stock of greenhouse gases (GHG) in the atmosphere unchanged but mitigate radiative forcing by absorbing less solar radiation (The Royal Society, 2009).

an attractive emission reduction option because it generates electricity and absorbs carbon dioxide (CO_2) emissions at the same time (Clarke et al. 2009; Edenhofer et al. 2010; van Vuuren et al. 2011; Rose et al. 2012).[2] The mechanism is relatively simple: CO_2 fixed in biomass through photosynthesis is captured in power plants during the combustion process and it is then sequestered in underground deposits (Obersteiner et al. 2001; Rhodes and Keith 2005; 2008; Azar et al. 2006; 2010; Chum et al. 2011). The result is the generation of electricity with net "negative" emissions.[3]

The literature developed using Integrated Assessment Models (IAM) highlights three important benefits of BECCS. First, the use of BECCS allows reaching stabilization targets that would otherwise be unattainable. 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 is unfeasible also in the IMAGE model 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. Rose et al. (2012) find that BECCS is necessary to attain any level of radiative forcing below 3 W/m^2. Second, BECCS allows to buy time. Emissions can peak later and costly mitigation measures can be delayed until the second half of the century (Krey and Riahi 2009; van Vuuren et al. 2010; Thomson et al. 2011). Finally, BECCS greatly reduces the cost of mitigation policy. In Azar et al. (2006) BECCS reduces the cost of keeping the concentration of GHG at 350 ppm CO_2 in 2100 by 80% and by 42% the cost of the 450 ppm CO_2 target. Krey and Riahi (2009) find analogous results.

In this paper[4] I study 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 et al. 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 et al. (2004), Hansson and Berndes (2009) and Laurijssen and Faaij (2009) assess the relative advantages of the physical trade of biomass, the

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[2] The other method that is under exam is Direct engineered capture of CO_2. The method relies on technologies whose primary goal is to absorb CO_2 from the atmosphere (Keith 2000; Kraxner et al. 2003; Lackner 2003; Matthews and Caldeira 2007; Buesseler et al. 2008; Stolaroff et al. 2008; Eisenberger et al. 2009; Chen and Tavoni, 2013).

[3] The amount of net negative emissions depends on whether and in what proportion biomass is used with other fuels, on the amount of emissions associated to biomass production, including emissions from fertilizer use, and on the efficiency of CCS.

[4] This Chapter is based on the article "Trade of woody biomass for electricity generation under climate mitigation policy" revised and resubmitted to Resources and Energy Economics with Emanuele Massetti.

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 et al. 2010) and REMIND (Popp et al. 2011) include trade of biomass among regions. However, none of these studies has assessed the effect of introducing trade of biomass on the energy mix, on the optimal abatement under a carbon tax or on the cost of achieving a given mitigation target.

With this study I 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, on the optimal power mix and on GHG emissions, using three representative tax scenarios. I 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. I use a new version of the integrated assessment model WITCH (Bosetti et al. 2006; 2007; 2009) that includes international trade of biomass. Regional biomass supply curves are from the Global Biosphere Optimization Model (GLOBIOM) developed by IIASA (option 3 in Havlk et al. 2011). I consider woody biomass coming from short rotation tree plantations on marginal land and forest logging residues. The GLOBIOM model also provides the maximum biomass endowment for each region at any time period.

This paper is organized as follows. Section 2 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 and on emissions abatement. Section 3 discusses the effect of biomass trade on mitigation policy costs under a cap-and-trade policy scenario. Section 4 shows results of sensitivity analysis. Conclusions follow with a summary of my findings.

3.2 Results: carbon tax scenarios

I assume that all world regions credibly commit to reduce all GHG emissions from 2015. In the carbon tax policy framework[5] all countries agree on a uniform global tax $T(t)$. Taxes are equal to 2, 7 and 14 USD/tCO_2 in 2015 and reach 158, 576 and 1,161 USD/tCO_2 in 2100. In order to assess the impact of trade of biomass I run the tax scenarios with and without trade (a detailed description on carbon taxes scenarios is presented in Appendix C).

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[5] For convenience I refer to the tax on all GHG emissions as the “carbon tax” even if this tax is on all GHG emissions.

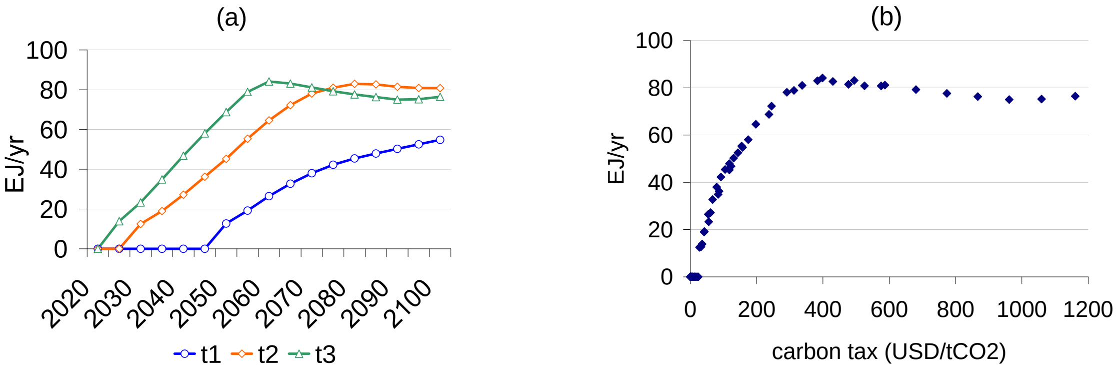

Fig. 3.1: Biomass international market volume

3.2.1 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 volume and of value traded.

Figure 1a shows that regions start trading biomass between 2025 and 2050, depending on the tax level. The market starts in 2025 when the carbon tax is equal to 36 USD/tCO_2 in the scenario t3, in 2030 when the carbon tax is equal to 28 USD/tCO_2 in the scenario t2 and in 2050 when the carbon tax is equal to 32 USD/tCO_2 in the scenario t1. In 2050 regions trade 13-69 EJ/yr of biomass depending on the tax scenario. The market peaks at about 83 EJ/yr, constrained by the exogenous limit on global biomass production and by a growing demand for domestic use in exporting regions. By pooling all observations from the three tax scenarios I find that the relationship between the carbon price and the market volume is concave until 400 USD/tCO_2, then the market volume slightly declines and it reaches a plateau in correspondence of the highest tax levels (Figure 1b). 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 I use regional aggregates instead of single countries. There is very little information on the possible size of biomass trade in the literature. Only van Vuuren et al. (2007) provide estimates of the international market of biomass. They show that world regions trade approximately 50 EJ/yr in 2050 in the most stringent stabilization target (450 ppm CO_2-eq, thus somehow comparable with my t3 scenario).

When the market starts the international price of biomass (net of transportation cost) can be

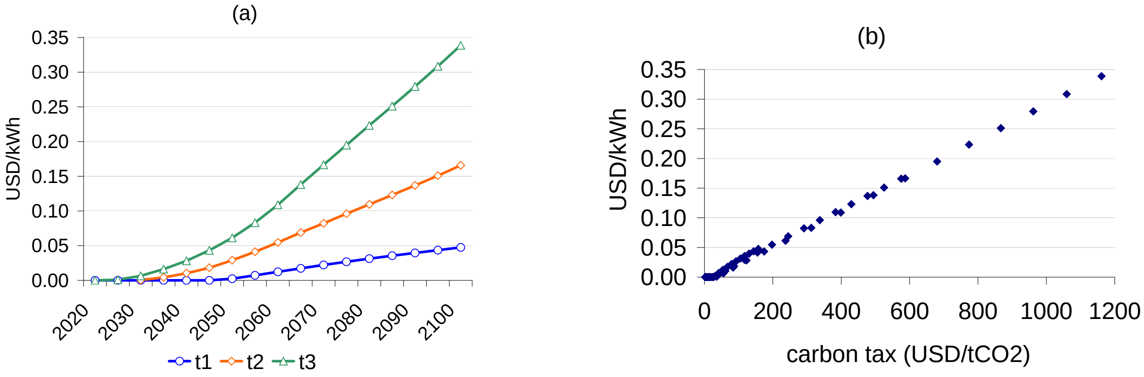

Fig. 3.2: International price of biomass.

as low as 0.11 USD/GJ, thus revealing a substantial excess of production capacity in countries with large production potential. In 2050 the price is equal to 0.56-17 USD/GJ, depending on the tax scenario. In 2100 it reaches 13-94 USD/GJ with an average annual growth rate equal to 4-6% depending on the scenario (Figure 2a). From equation (A.2.6) I determined that the price of biomass must increase proportionally to the carbon tax ($\partial p_{F_{wbio}}/\partial T = e\omega + \gamma\,\xi D$). By pooling all observations from the three tax scenarios I confirm that this holds in my scenarios (Figure 2b). A 100 USD tax increase approximately corresponds to a 8 USD/GJ increase in the price of biomass, which is roughly equal to $e\omega + \gamma\,\xi D$ (Figure 2b). The price of 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 A.2.6) and firms in the forestry sector gain pure rents.[6]

Financial transactions connected to biomass trade increase over time due to the growing market and to the growing price. In the t2 and t3 tax scenarios the volume of the market peaks but the price continues to grow. 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 I 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 international 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 the price declines because producers use less expensive resources.

At regional level, trade dynamics are explained by the endowment of biomass, biomass produc-

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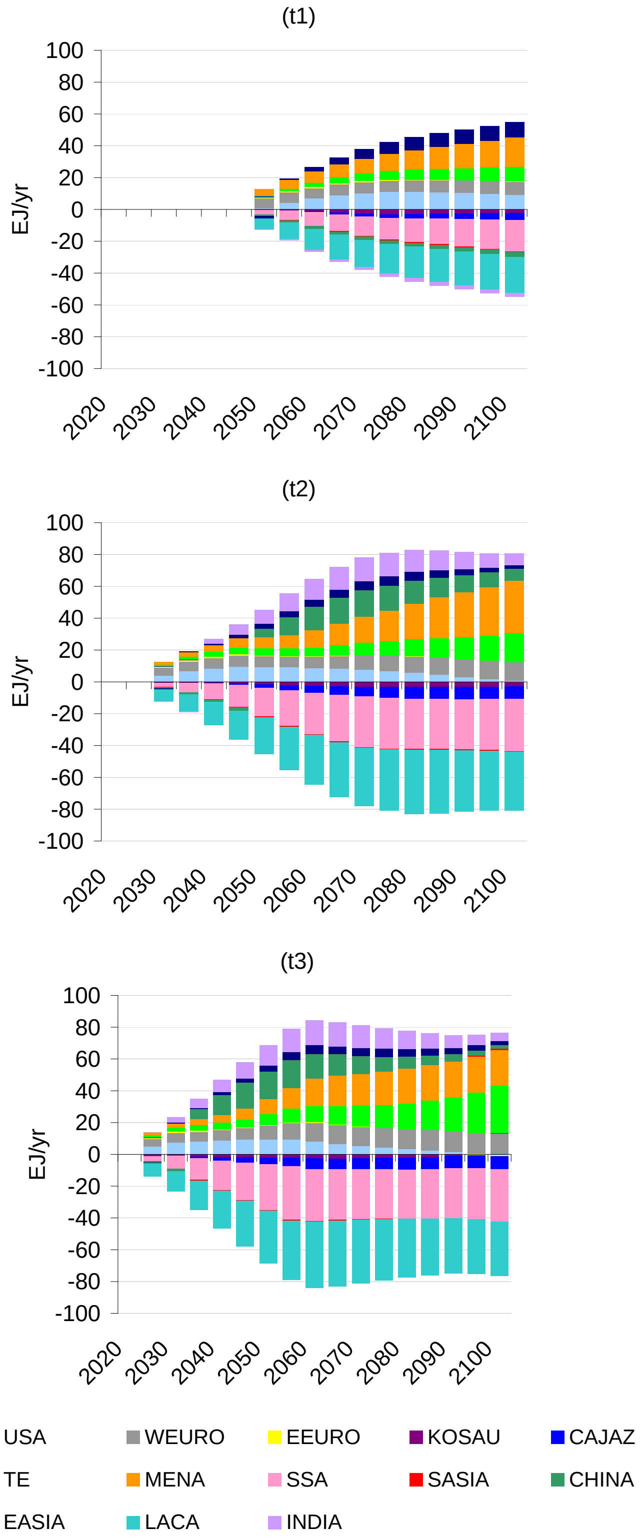
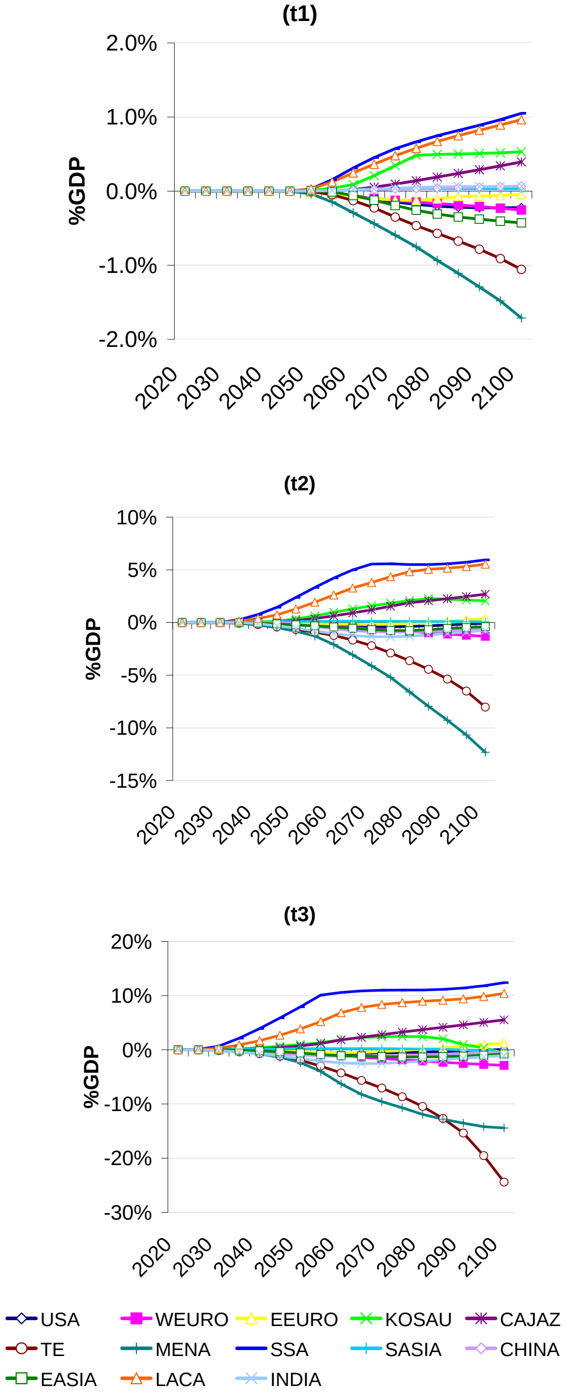
[6] Firms in the forestry sector are competitive. The cap on total production acts as a cartel mechanism that restricts global output.

tion 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). I find that biomass trade generates large financial inflows in Sub-Saharan Africa and Latin America, where most of global production is concentrated, and large outflows in MENA, the largest importer (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 becomes a major economic activity. At the opposite, biomass becomes a major import commodity for the Middle East and North Africa, which record outflows equal to about 30% of regional GDP per year (4 USD Trillion) in 2100 (in the highest carbon tax scenario). While it is easy to understand why it is optimal for MENA to spend such a large fraction of GDP to import biomass in my scenarios, it is not obvious that accepting high carbon taxes would be an optimal strategy for MENA countries in the real world.



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

Fig. 3.3: Net import of biomass (EJ / year) under different carbon tax scenarios.



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

Fig. 3.4: Revenue and expenditure from the international market of biomass as a % of GDP under different carbon tax scenarios.

3.2.2 The impact of trade on biomass demand and on the power mix

The introduction of trade unleashes a large global demand for biomass. Biomass producers respond with an expansion of supply 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. This level of biomass production falls within the range found in the literature for similar policy targets (Reilly and Paltsev 2007; Gillingham et al. 2008; Calvin et al. 2009; Hoogwijk et al. 2009; Luckow et al. 2010; Magne et al. 2010).

Trade significantly alters the regional distribution of supply and demand for biomass, shifting biomass use where its marginal product is higher and biomass production where the marginal cost is lower, as illustrated in Figure 5. Regions with a relatively low cost and/or a large endowment of biomass see a surge of demand from other regions. In those regions the international price of biomass is higher than the domestic price in autarky thus leading to an expansion of production and to a contraction of domestic demand. For instance, in 2050, trade changes the optimal supply of biomass from 5-18 EJ/yr to 11-40 EJ/yr in Latin America and from 3-10 EJ/yr to 5-32 EJ/yr in Sub-Saharan Africa, depending on the tax scenario. At the same time, 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. The simultaneous expansion of supply and contraction of demand boosts exports. I find opposite results in regions with relatively high cost and/or small endowment of biomass.

The impact of biomass trade on the optimal mix of power generation technologies varies depending on whether a country is an importer or an exporter of biomass. In importing countries the availability of cheaper biomass increases the use of BECCS power generation while the opposite happens in exporting countries. The aggregate impact on global power generation is illustrated in Figure 6. BECCS power generation gains shares of the power mix at the cost of coal power plants with CCS, gas with CCS and nuclear. In 2050 the share of electricity from biomass power plants with CCS increases from 4-16% to 6-29% while the share of electricity from coal power plants with CCS decreases from 8-10% to almost zero with trade. In 2100 BECCS power generation displaces coal power generation with CCS in the t2 and t3 scenarios with trade. Biomass with CCS generates a quarter of total power supply in all scenarios. Also the share of electricity produced by gas power plants with CCS declines, but to a lesser extent.[7] Demand for nuclear power decreases in regions that import woody biomass and it increases in exporting regions. For instance, in both TE and WEURO demand for nuclear power declines by 11% in 2050 in the t3 scenario. In LACA the de-

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[7] 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. I might therefore underestimate the role of natural gas in my mitigation scenarios.

mand for nuclear power increases instead by 7%. Nuclear and BECCS are close substitutes because they are able to provide base-load power with zero or negative CO_2 emissions. Interestingly, by reducing the carbon intensity of power generation trade also reduces the cost of electricity and thus stimulates higher power generation demand.

3.2.3 The impact of trade on emissions

With biomass trade regions that have low biomass production potential and/or high production costs expand the use of BECCS, regional marginal abatement cost curves move to the right and mitigation policy becomes more efficient. This leads to a substantial increment of GHG emission abatement while the marginal abatement cost is unaffected. 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 while the remaining share is due to the shift from fossil fuel power technologies to BECCS.

At global level, trade reduces the carbon intensity of output by 4%, 30% and 38% in the three tax scenarios, respectively. Also global energy intensity of output decreases at the end of the century, because trade increases the efficiency of the power mix, as discussed above. 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. As a result GHGs concentrations decline by 10 ppm CO_2-eq (from 680 ppm to 670 ppm) in the t1 tax scenario 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 7a). Global mean temperature in 2100 is 0.05-0.15°C lower in scenarios with biomass trade (Figure 7b).

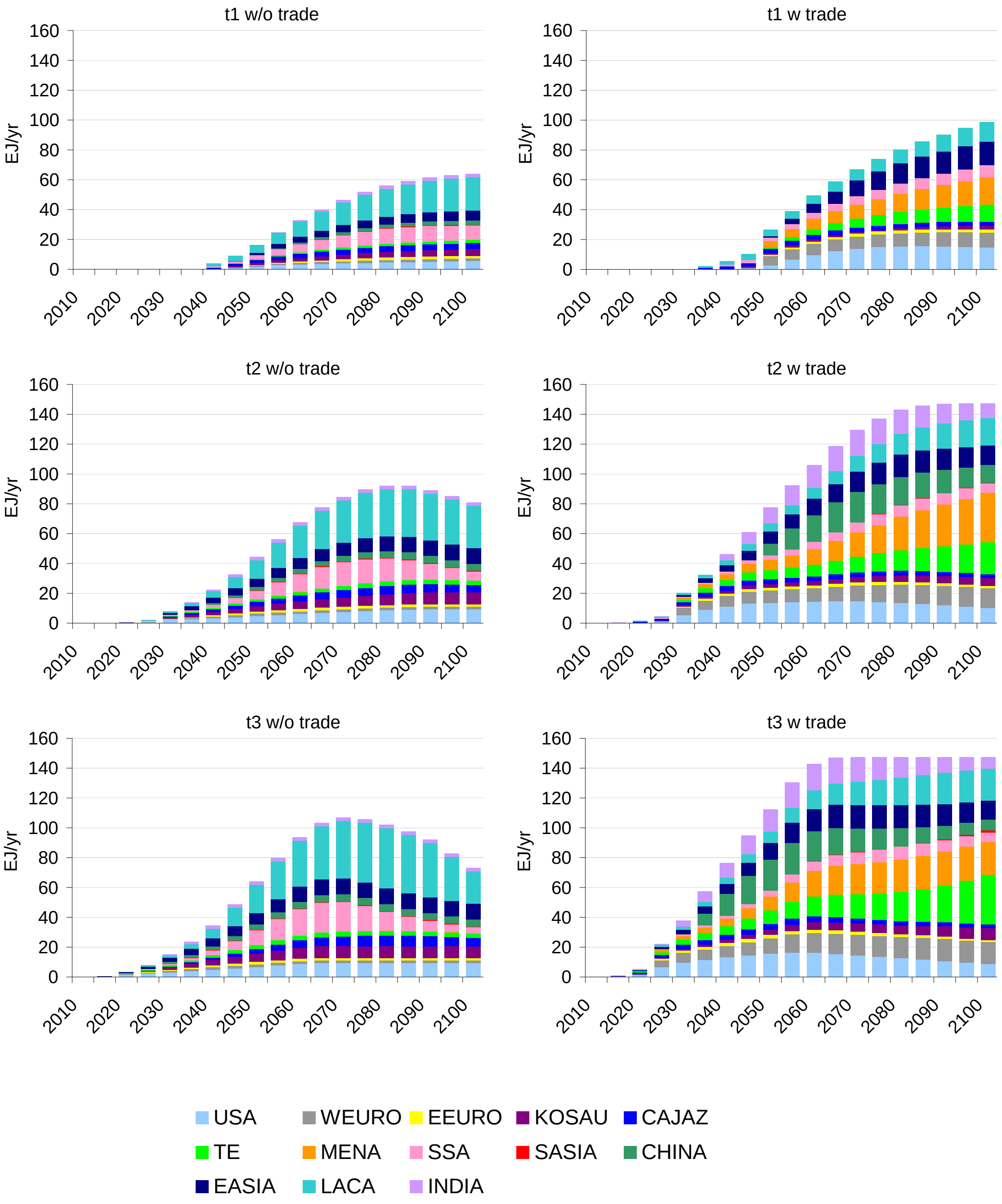

Fig. 3.5: Regional consumption of woody biomass under three carbon tax scenarios with and without biomass trade.

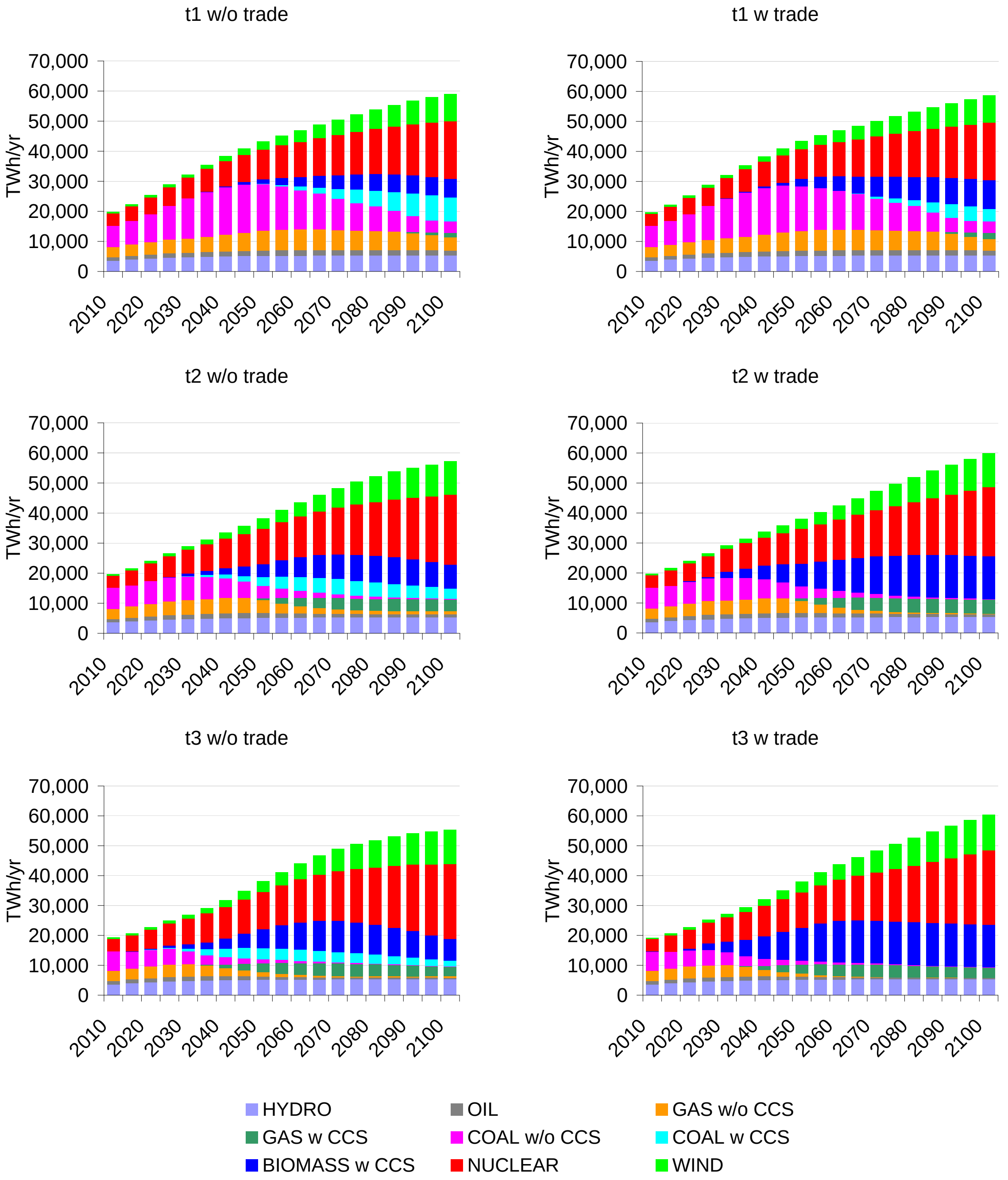

Fig. 3.6: Electricity generation by technology under three carbon tax scenarios with and without biomass trade.

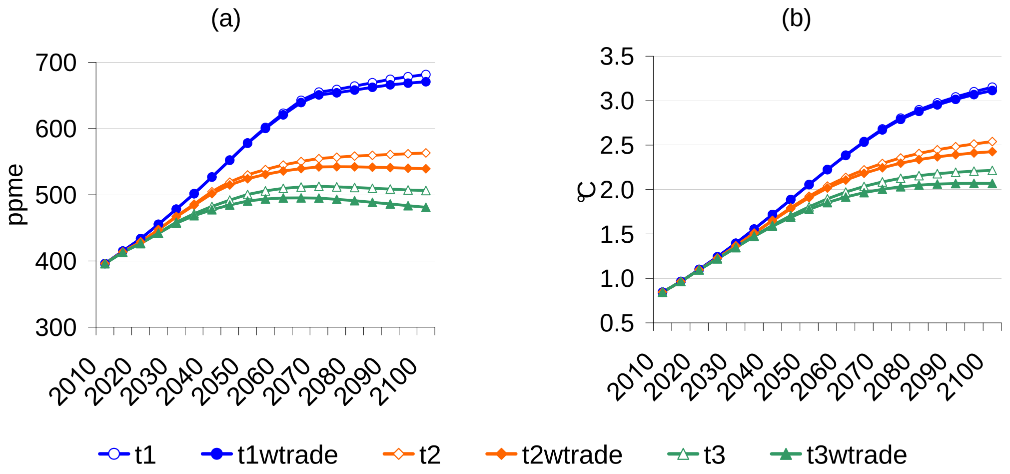

Fig. 3.7: (a) GHGs concentration and (b) increase in temperature with respect to pre-industrial levels under three carbon taxes with and without biomass trade.

3.3 The economic value of biomass trade

In the previous Sections I used representative carbon tax scenarios to illustrate the impact of biomass trade on BECCS demand and supply, on the power generation mix and on GHG emissions. One limit of using carbon taxes as a policy tool is that changes in the technology frontier affect the optimal amount of abatement but do not change marginal abatement costs (fixed by the tax) and leave basically unaffected policy costs.[8] In order to overcome this limit in this Section I model climate policy using a cap-and-trade scheme. Under cap-and-trade shifts in the technology frontier do not affect the overall amount of emission reductions but change the price of emission permits and the cost of achieving a given stabilization target. I can thus measure the economic value of introducing biomass trade, defined as the difference between mitigation policy costs without and with trade.

I assume that all regions agree to achieve a global level of radiative forcing equal to 3.8 W/m^2 from 2015, as in the t2 scenario. Each region receives an allocation of emission permits and is entitled to buy or sell permits from other regions at the international market clearing price.[9] Since the price of emission permits does not change under alternative distribution rules (Coase, 1960), I use a representative equal-per-capita distribution of permits to study how trade changes the carbon price and global mitigation costs.[10]

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[8] Cumulative GDP 2010-2100 decreases by 0.01-0.22% when biomass trade is allowed.

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

[10] Different allocation rules would change the regional economic impacts of biomass trade as well as the net position

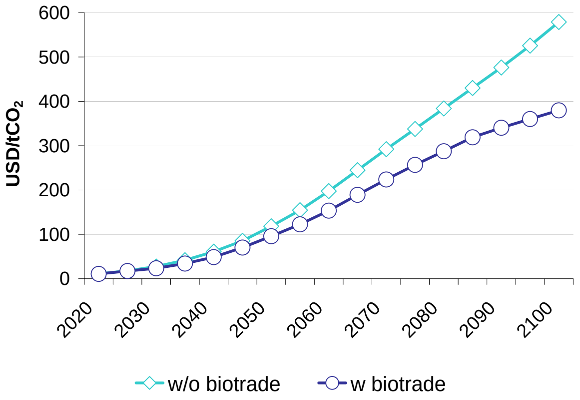

Fig. 3.8: Carbon price with and without woody biomass trade.

Figure 9 shows the effect of biomass trade on the carbon price. Biomass trade reduces the price of emission permits by 15% in 2030 and by 34% in 2100. Emitting one ton of CO_2 costs 579 USD/tCO_2 in 2100 without trade of biomass while it costs 380 USD/tCO_2 with trade. This is a substantial reduction of marginal abatement costs, with benefits spreading across regions thanks to emission trading.

Trade of biomass increases the overall efficiency of climate policy and thus reduces stabilization costs, defined as the difference between discounted GDP (5% annual rate) in the mitigation scenario and discounted GDP in the Reference scenario. It reduces the global cost of reaching the 3.8 W/m^2 target from 10 USD Trillion to 8 USD Trillion over the period 2010-2050 and from 26 USD Trillion to 22 USD Trillion over the period 2010-2100 relative to the same scenario without trade. This implies that the economic value of introducing biomass trade is equivalent to 2 USD Trillion over 2010-2050 and to 4 USD Trillion over 2010-2100, in discounted terms. In other words, in my scenario limiting the international trade of biomass increases stabilization costs by 14% over the course of the twenty-first century. This increase is comparable to the GDP losses recorded in scenarios with either technological constraints or delayed participation in climate mitigation actions.[11]

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of regions on the international carbon market. In some cases trade of biomass induces an increase of emission trading, in some a contraction. Exporters of biomass increase demand for permits (reduce sale of permits) while biomass importers reduce demand for permits (increase supply of permits). Despite being an attractive area for further research, I do not explore here how trade changes regional demand and supply of emission permits and thus regional costs.

[11] According to Azar et al. (2006) the cost of achieving a 450 ppm $C0_2$-eq target increases by 40% respectively. Luderer et al. (2011) find that restrictions in biomass availability result in a 25% increase of mitigation costs in ReMIND-R. Delaying an international climate agreement or a delayed participation of some key countries has similar consequences (Clarke et al. 2009; van Vliet et al. 2009).

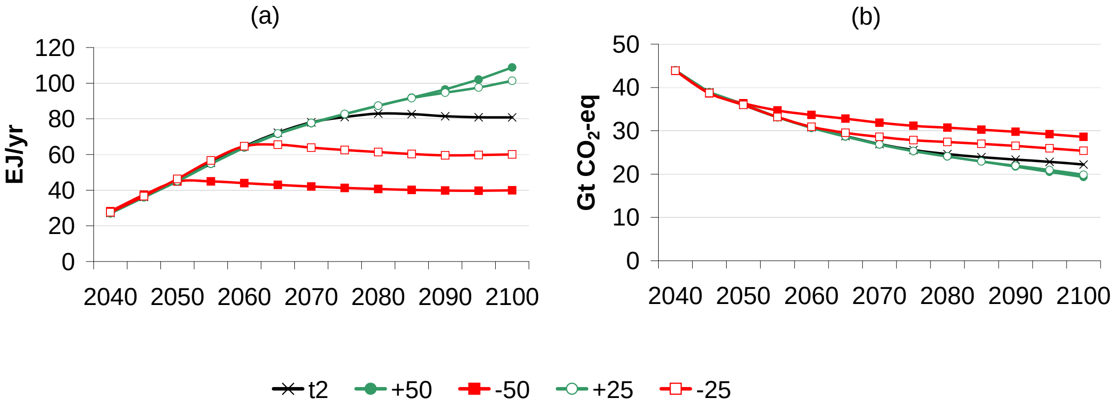

Fig. 3.9: International volume of biomass trade (a) and GHGs emissions (b) under different assumptions on biomass potential.

3.4 Sensitivity analysis

In this Section I test the robustness of my findings under different assumptions on (i) the regional maximum amount of biomass potential ($\overline{Q}_{wbio}$) and on (ii) the international transportation cost of biomass (TC). I run sensitivity analysis scenarios using the t2 carbon tax.

There is large uncertainty on the maximum supply potential of woody biomass both at regional and at global level (see Berneds et al. 2003). The uncertainty arises because both the energy content of biomass feedstocks and the total amount of land available for woody biomass are still matter of debate. For example, I assume that the energy woody biomass contains 7.5 GJ of energy per cubic meter following assumptions used in GLOBIOM. However, in the literature the energy content of biomass ranges from 2.1 GJ to 22 GJ per cubic meter (Kyle 2011; Pirraglia et al. 2012; Guerrero-Lemus and Martinez-Duart, 2013). The amount of land available for woody biomass depends on the assumptions made on soil, on water requirements and on the distribution of productive land across different uses. In this work I derive regional biomass cost and potential from GLOBIOM assuming that woody biomass is grown only on marginal land (option 3 described in Havlik et al. 2011). This is a restrictive assumption but I might still overestimate the real production possibilities. At the same time I might underestimate the productivity or the extension of marginal land. In order to test how sensitive the core set of my results is to these assumptions, I symmetrically shift upward and downward the upper bound on production potential ($\overline{Q}_{wbio}$) by 25% and 50%, uniformly across all regions. In doing so I keep the shape of the cost function constant. This means that additional production happens on less productive land. I also still assume that global agricultural and forestry production is unchanged.

Figure 9a shows that when the maximum possible production of biomass increases (decreases) also global trade of biomass increases (decreases). However, the model is more sensitive to a contraction of biomass potential rather than to an increase. In particular, a reduction of 50% reduces the volume of biomass traded by the same amount in 2100. A 50% increase of biomass potential will instead induce a 35% increase of biomass trade. In Figure 9b I compare the increase in GHG emissions from 2010 to 2100 under different assumptions on biomass potential. The figure shows that increasing (decreasing) the amount of biomass available at the global level increases (decreases) emissions abatement relative to the t2 scenario. However, the impact is small: cumulative emissions for 2010-2100 are 1% lower when there is 50% more biomass available while a 50% reduction of biomass potential leads to a 7% increase in cumulative emissions.

Finally, I test how biomass international transportation costs affect the price of woody biomass. I simulate two scenarios in which transportation costs are first cut by 50% (tcx0.5) and then doubled (tcx2) with respect to the central value (t2). I find that transportation costs play a key role at the beginning of the century, when they are high compared to the price of biomass. Reducing the cost of transport by half anticipates the start of biomass trade (from 2030 to 2025) and increases the price that BECCS power firms are willing to pay to purchase biomass (by 10% in 2050 and by about 1% in 2100). Doubling transportation costs delays the beginning of trade from 2030 to 2035 and reduces the price of biomass by 30% in 2050 and by about 5% after 2070.

3.5 Discussion

This work studies trade of woody biomass in climate mitigation scenarios. In particular, I focus on biomass used in IGCC power plants combined with CCS (so called BECCS). I examine the characteristics of a potential global market for woody biomass, the impact of trade on biomass demand, on the power mix and on GHG emissions using three representative carbon tax scenarios. I then test the impact of trade on climate policy costs by assuming that the long-term radiative forcing target obtained by the medium value of the carbon tax is attained using a cap-and-trade policy scheme. Some studies in the literature assume that regions can trade biomass but have never assessed the implications of trade on the efficiency of climate policy, on technology choices and on the cost of achieving a fixed mitigation target. To my knowledge this is the first study that provides an economic assessment of the cost of limiting trade of woody biomass.

Results show that the incentive to trading biomass is large in both high and low carbon tax scenarios. In all tax scenarios that I examine at least 50% of biomass consumed globally is from the international market. I find that biomass trade substantially increases the efficiency of climate policy because biomass demand and supply are unevenly distributed across world regions. With trade, global biomass consumption increases from 66-90 EJ/yr to 101-147 EJ/yr in 2100, depending on the tax scenario.

Financial flows between importing and exporting regions are large and woody biomass becomes a major global commodity. Sub-Saharan Africa and Latin America, the two largest exporters in my scenarios, receive financial inflows equal to 1-13% and 1.2-14% of their GDP in 2100. The Middle East and Northern Africa (MENA) region is the largest importer, with about 20% of GDP in 2050 used to buy biomass in the highest tax scenario. This is a possibly unrealistic but perfectly rational and cost effective choice for MENA in a scenario in which carbon taxes are very high. It is rather hard to imagine that MENA would accept such a costly climate policy. However it is not within the scope of this work to discuss the political plausibility of my tax scenarios. I use representative abstract policy tools to study the impact of the trade option. The scenarios should not be interpreted as forecasts.

Limiting trade of woody biomass increases cumulative abatement of GHG emissions over the 21st century by 120-323 Gt CO_2, depending on the tax scenario. This translates into 0.1-0.3 W/m^2 of additional radiative forcing. Moreover, I show that limiting biomass trade is expensive. In the cap-and-trade policy scheme, the 3.8 W/m^2 radiative forcing target in 2100 costs 14% less, in terms of global discounted output, when trade is available.

The main limit of my analysis is the lack of a fully consistent integration of GLOBIOM and WITCH. This reduces the scope of my analysis because I cannot allow greater flexibility across different land uses and I are not able to guarantee full consistency of biomass demand, LULUCF baseline emissions and LULUCF abatement. However, as discussed in the text, the inconsistencies might be limited because the models, although not integrated, share similar assumptions (WITCH and GLOBIOM) or run in cluster (GLOBIOM and G4M). Furthermore, these inconsistencies should be assessed bearing in mind the large uncertainty that still surrounds global biomass production potential, production costs and energy content of biomass. Further research is needed but the limits of this study are not expected to substantially alter my main results.

An important message from my study is that unbalances in demand and supply of biomass under climate mitigation policy are likely to be large and will thus create strong incentives to trade. Any restriction to market mechanisms that limits the efficient distribution of biomass is likely to be costly and should be allowed only if equally large economic, social or ecological costs from trade not considered in this study do exist.

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4. EVALUATING THE ROLE OF LAND IN MITIGATION STRATEGIES INVOLVING WOODY BIOMASS

4.1 Introduction

As policy makers consider stringent targets for greenhouse gas emissions, integrated assessment models (IAMs) are increasingly relying on biomass energy as a critical energy source. Numerous studies have shown that bio-energy combined with the carbon dioxide capture and storage technology (BECCS) is of considerable importance for achieving low radiative forcing levels (eg. 2.6 Wm^2 is consistent with limiting global mean surface temperature increase to 2C) (Azar et al., 2006; van Vuuren et al., 2007; Edenhofer et al., 2010; van Vuuren et al. 2010; Rose et al. 2012). In addition, many studies have shown that the unavailability of BECCS severely impacts the cost of stringent mitigation policies (Azar et al. 2006; 2010; Krey and Riahi 2009). Finally, bio-energy combined with CCS offers the flexibility to delay some mitigation actions into the future to accommodate likely delays in implementing a binding global climate agreement (Krey and Riahi 2009; van Vuuren et al. 2010; van Vuuren and Riahi, 2011).

However, it is not clear how much biomass to expect across time and across the planet. The IAMs simply do not have enough detail about global forests and arable land to make careful estimates of biomass supply over time.[1] As result, they cannot accurately predict how biomass demand affects forestland or farmland. Integrating the dynamic demand for bio-energy from the IAMs with the complex dynamic structure of forests and forest supply is a daunting intertemporal task.

The existing literature on woody biomass has revealed that woody biomass competes with traditional forest products and that the increased demand for forest outputs will increase the price of forestland and therefore the amount of forests. For example, there is a set of US models (Ince et al. 2011; 2012; Daigneault et al. 2012) and a set of EU models (Moiseyev et al. 2011; Lauri, et al. 2012) all of which confirm these results. It is also clear that this increase in forestland will cause overall carbon sequestration rates to increase (Malmsheimer et al. 2011; Havlk et al. 2011;

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[1] Some IAMs include either a land-use module (eg. GCAM see Edmonds et al. 2013) or biomass supply functions (eg. MERGE see Magne et al. 2011).

Daigneault et al. 2012; Sedjo and Tian 2012). Note that crop bio-energy would have the opposite effect on carbon sequestration because it would increase the relative value of cropland (Fargione et al. 2008; Melillo et al. 2009; Searchinger et al. 2009; Wise et al. 2009). Although regional and national studies are adequate for showing the qualitative impacts of a woody biomass program, they do not reveal the global response.

Only a few studies have evaluated the global implications of woody biomass on the forest sector (Raunikar et al. 2010; Buongiorno et al., 2011). A limitation of these studies as well as the regional studies is that they examine arbitrary quantities of woody biomass for energy.[2] The quantities are not tied to carbon prices nor are they able to capture the price feedbacks from the energy sector to the land sector and back. Past studies have examined the effects of requiring a specific amount of biomass but they do not evaluate whether these amounts are efficient. In order to determine how bio-energy should fit into an efficient carbon mitigation strategy, one must model whether bio-energy is more or less expensive than other mitigation alternatives. This depends on the magnitude of the biomass program since biomass will get more expensive as it competes against timber products and other uses of land. It also depends on the price of carbon which will determine the aggregate amount of mitigation desired over time. In practice, these factors change over time requiring a dynamic analysis which is partially missing in the literature.

Only two studies have followed a dynamic path in analysing the role played by biomass on a mitigation portfolio (Gillingham et al. 2008; Popp et al. 2011). Both studies use land use models and assume that bio-energy demand can be met by both agricultural crops and woody biomass. In this way they provide a broader description of the dynamic interactions between the land sector and the energy sector. However, their analyses lack a detailed description of the forestry sector which limits how accurately they capture woody biomass in their models.

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[2] Raunikar et al. (2010) used the biomass energy projections developed for IPCC for the story lines A2 and B1 story lines.

Buongiorno et al. (2011) used the biomass energy projections developed for IPCC for the story line A1B and RPA forest assessment.

Ince et al. (2011) used the biomass energy demand from the US Department of Energy, Annual Energy Outlook 2010.

Moiseyev et al. (2011) used the biomass energy projections developed for IPCC for the story lines A1 and B2 story lines.

Ince et al. (2012) used the biomass energy projections developed for IPCC for the story lines A1B, A2 and B2 story lines.

Daigneault et al. (2012) used the projections of biomass demand are developed from the baseline projection of regional bioenergy consumption fro 2010-2035 in the 2010 Energy Information Administration Annual Energy Outlook.

This work [3] addresses these shortcomings in the literature by combining a detailed global, dynamic model of forests (GTM) (Sohngen et al. 1999; Sohngen and Sedjo 2000; Sohngen and Mendelsohn 2003; Daigneault et al. 2012) with a sophisticated integrated assessment model of climate and energy (WITCH) (Bosetti et al. 2006; 2007; 2009). Both models as well as their soft link are described in Appendix A, D and E. The combined model is then used to evaluate alternative mitigation strategies from modest to severe.

WITCH calculates the global quantity demanded of woody biomass over time for each policy scenario. The quantity demanded for woody biomass from WITCH is then added to the demand for industrial wood products in GTM. The timber model then solves for the international price of wood. The price is then entered back into WITCH which generates a new quantity demanded. The two models iterate back and forth until demand equals supply. For each mitigation strategy, WITCH assures that the outcome takes into account a dynamic carbon price trajectory and the competition between woody biomass and other mitigation options. The forest model takes into account the competition between industrial wood products and woody biomass, the intensity of forest management, the competition for land between forestry and agriculture, and the price of forest products.

This work is organized as follows. In Section 2 I analyze the results of the two models under alternative mitigation scenarios. I explore the desired size of the woody biomass market, the impact on industrial timber, the price of timber, the size of forestland and other land use. Finally Section 3 summarizes the results and discusses the policy implications.

4.2 Results

4.2.1 Woody biomass market

I assume that using woody biomass for energy is carbon neutral. That is, I assume that the carbon released during combustion was offset by the carbon captured during the growth of the trees (this is not exactly correct because the storage occurs over a long time before the release). In addition, I assume that biomass power plants receive credits for the extra forest sequestration. [4] Given these assumptions, higher carbon taxes make woody biomass more attractive relative to fossil fuel. With the BAU scenario, carbon prices are effectively zero which leads to minimal use of woody

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[3] This Chapter is based on the FEEM working paper "Evaluating the Global Role of Woody Biomass as a Mitigation Strategy" with Robert Mendelsohn.

[4] This means that at the time of burning biomass power plants receive a subsidy equal to the carbon tax for each extra ton of carbon stored in forest with slash and soil.

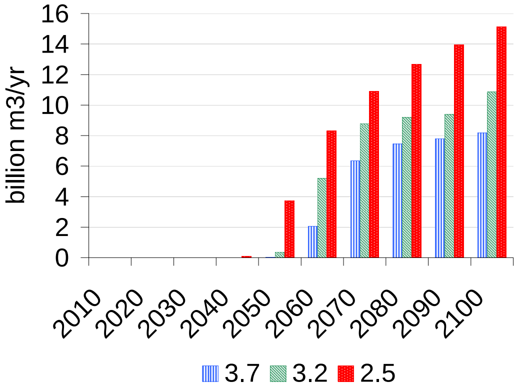

Fig. 4.1: Woody biomass for energy consumed at the global level 2010-2100 under different mitigation policy scenarios

biomass for energy (only wood residues at mills would be used). In order for companies to switch wood into fuel, the carbon price must be about 130 USD/tCO_2. In the most stringent scenario, woody biomass is used as fuel in 2045, in the most moderate scenario in 2055, and in the most moderate policy in 2060. Note, however, that the model is forward looking so that the timber model anticipates the demand for woody biomass far before it is actually burned.

As the price of carbon increases, the demand for woody biomass increases. In 2100, it will reach 15.2 billion m^3/yr (144 EJ/yr), 10.9 billion m^3/yr (94 EJ/yr), and 8.2 billion m^3/yr (77 EJ/yr) in the three scenarios respectively (Figure 2). In all scenarios, the biomass consumed is burned in IGCC power plants equipped with CCS which provides 13-26% of global electricity by 2100 depending on the scenario.

4.2.2 Forest sector and timber price

As mitigation policies become more stringent, there is a huge shift in the demand for wood. This leads to a rapid increase in the international price of wood depending on the scenario. By 2100, wood quadruples in price to almost 780 USD/m^3 for the most moderate scenario and it is almost nine times bigger in the most stringent scenario reaching 1650 USD/m^3 (Figure 3).

These changes in price encourage a large expansion of total timber production in the second half of the century. In the BAU scenario with no additional woody biomass, total global production reaches 3.3 billion m^3/yr by 2100. However, in the most stringent scenario, total global timber production almost quintuples by 2100 to 15.4 billion m^3/yr. Even in the most moderate scenario, total wood production is more than double reaching 8.8 billion m^3/yr by 2100.

Despite the huge increase in wood supply, the traditional industrial wood sector (sawtimber

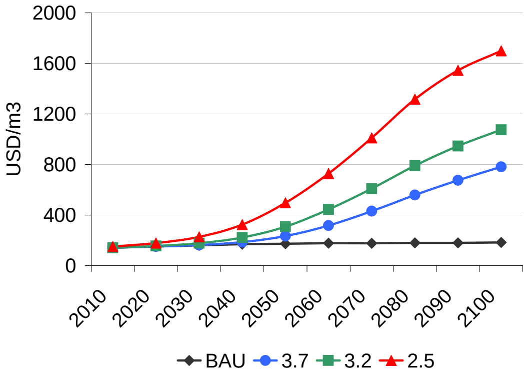

Fig. 4.2: International price of wood under the BAU scenario and climate policy scenarios

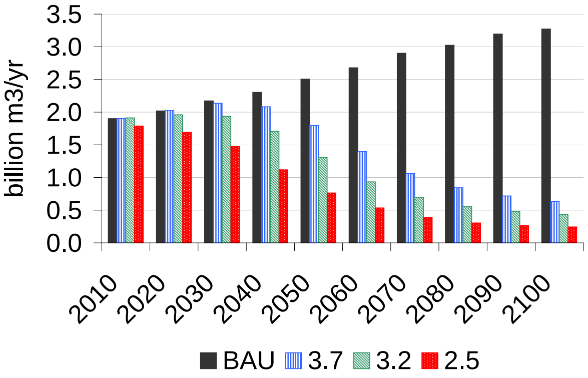

Fig. 4.3: World industrial timber production under the BAU scenario and climate policy scenarios

and paper) shrinks. In the BAU scenario, rising demand causes the industrial wood sector to grow slowly over time reaching 3.3 billion m^3/yr by 2100. However, by 2100, industrial wood demand falls to 0.2 billion m^3/yr in the most stringent scenario. Even with the least stringent policy, industrial wood quantities fall to 0.6 billion m^3/yr (Figure 4).

Although using woody biomass helps address needs of the energy sector, it would have huge impacts on the saw timber and pulp and paper sectors. Almost all of this effect is due to the high price of wood (there is also a small income effect from the reduction of global consumption per capita[5]). The most stringent mitigation policy causes the demand for woody biomass to become more price inelastic than the demand for industrial wood causing a large substitution from sawtimber and paper to energy.

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[5] The introduction of the carbon tax will reduce the world consumption per capita (Z in Equation D.0.1 Appendix D) by 0.6-2.1% in 2050 and by 2.6-9.7% in 2100 with respect to the baseline scenario.

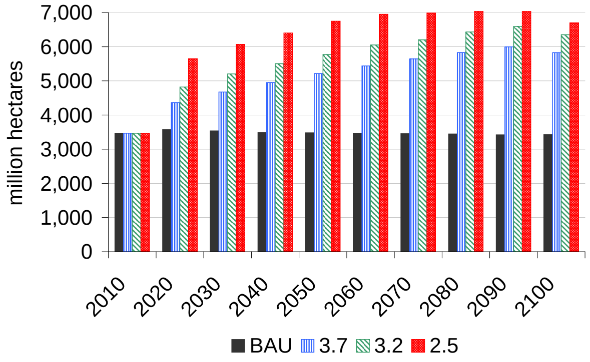

Fig. 4.4: Forest area under the BAU scenario and the three carbon taxes

4.2.3 Forestland and land use change

In order to support the large increase in wood supply, forestland expands dramatically. In the BAU scenario, the global forestland that is harvested remains somewhat constant over the century at 350 million ha. As mitigation increases, this forestland increases both over time and across scenarios (Figure 5). Because the model is forward looking, forestland expands before biomass is actually burned in great quantities. Already by 2060, forestland has expanded by 57-98% depending on the scenario. By 2100, forestland area has expanded by 2,400 million ha in the most moderate scenario and by 3,200 million ha in the most severe scenario with respect to the BAU. Note that this area is equivalent to a third of the current global agriculture land and pasture land together. [6] Thus, the impact on global land use can be very large.

Because of the inelasticity of inaccessible forests supply in the forestry model, the expansion is mainly into farmland and only partially into inaccessible forests. [7] A by product of the woody biomass program is therefore a decrease in food production and higher prices for food. In addition, there would be a reduction in the demand for animal products and the level of human demand of calories.

As the forest area expands, it will capture and store more carbon with respect to the BAU scenario. In the BAU scenario, global forests accumulate a small amount of carbon in the first half of the century and then roughly hold that carbon constant for the rest of the century. By 2100 the BAU forests stores an additional 66 Gt CO_2 or about 0.8 Gt CO_2 per year. With the mitigation scenarios, there is a distinct increase in the global total stock of carbon stored in forests

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[6] In 2011 global permanent meadows and pastures land was about 3,400 million ha and arable land and agriculture area was about 5,000 million ha (faostat.fao.org).

[7] Inaccessible forests are reduced by 1-2% relative to the baseline scenario.

that increases by 685 Gt CO_2, 908 Gt CO_2 and 1279 Gt CO_2 by 2100 (or about 9.4-16.8 Gt CO_2 /yr stored) as the scenarios progress in stringency.

The extra sequestration from the biomass program reveals the advantage of using woody biomass rather than crop bio-energy. While the former will increase the stock of carbon stored in the forest, the latter will have the opposite effect because it would increase the relative value of cropland causing forestland to shrink (Fargione et al. 2008; Melillo et al. 2009; Searchinger et al. 2009; Wise et al. 2009).

4.3 Discussion

A wide suite of IAMs are relying on bio-energy with CCS (BECCS) to meet stringent limits. However, the IAMs do not have enough detail about global forests and arable land to make careful estimates of biomass supply over time and across regions. As a result, they are not adequate to estimate the effect of biomass demand on industrial timber demand, the international price of wood and forest land use in a dynamic framework. Integrating the complex dynamic demand for bio-energy from the IAMs with the complex dynamic structure of forests and forest supply is a daunting intertemporal task.

The aim of this paper is to provide a global, dynamic and detailed description of woody biomass supply under various climate mitigation scenarios. We explore the desired size of the woody biomass market, the size of forestland, and the size of farmland. These land use changes in turn may impact both the wood available for timber and paper and the land available to grow food.

By linking the economic model WITCH (Bosetti et al. 2006; 2007; 2009) and the forestry model GTM (Sohngen et al. 1999; Sohngen and Sedjo 2000; Sohngen and Mendelsohn 2003; Daigneault, et al. 2012) we quantify these effects. We examine a BAU scenario and three mitigation strategies that would lead to radiative forcing of 3.7, 3.2 and 2.5 W/m^2 in 2100.

As carbon prices rise, woody biomass becomes ever more attractive relative to fossil fuel. By the middle of the century, woody biomass becomes competitive and demand rises each decade. This increases the total demand for wood significantly in the second half of the century. More stringent policies (going from a 3.7 W/m^2 target to a 2.5 W/m^2 target) increase the demand for bio-energy from 77 to 144 EJ/yr by 2100. This big increase in demand for wood leads forestland to expand dramatically. Woody biomass demand is predicted forestland by 2,400-3,200 million ha relative to the BAU by 2100. Most of this new forestland will come from current farmland as inaccessible forests are unlikely to be productive enough. This in turn may place ever greater pressure on forestland put aside for conservation, especially in tropical countries with weak government enforcement. There may consequently be a conflict of interest between conservation and woody biomass for energy.

It is also interesting to compare the results with other studies of bio-energy. Previous studies predict that bio-energy would be almost twice our results ranging from 150 to 350 EJ/yr by 2100 (Azar et al. 2006; 2010; van Vuuren et al. 2007; 2013; Popp et al. 2011; Calvin et al. 2009; Gillingham et al. 2008; Luckow et al. 2010). The higher demand is the result of different assumptions about the type of biomass feedstock (all of them consider both crop and wood bio-energy), the use of agricultural and forestry residues and the biomass energy output (which ranges from 100 GJ/ha/yr to 400 GJ/ha/yr). However, we suspect that earlier studies arrived at a much higher demand because they also underestimated the cost of converting farmland to forestland. If increasing the size of the forest requires a substantial loss of farmland, biomass will be relatively expensive and therefore less attractive.

Despite the huge increase in forests and wood supply, the traditional industrial wood sector (sawtimber and paper) shrinks from 3.3 billion m^3/yr in the BAU to 0.2-0.6 billion m^3/yr in the mitigation scenario by 2100. Although BECCS helps address the needs of the energy sector, it would have huge impacts on the saw timber and pulp and paper sectors. Consumers will be going paperless because they have no other choice and construction will need to find new materials to substitute for timber. BECCS would also have huge impacts on agriculture as up to one third of farmland may be converted to growing woody biomass. Unless farmers can respond with large increases in productivity per hectare, aggregate food supplies will fall sharply.

As the forest area expands, there will be an increase in the global stock of carbon stored in the forest of 685-1,279 $GtCO_2$ by 2100. The extra sequestration from the biomass program reveals the advantage of using woody biomass rather than crop bio-energy. While wood bio-energy increases the stock of carbon stored in the forest, the crop bio-energy has the opposite effect because it would increase the relative value of cropland causing forestland to shrink (Fargione et al. 2008; Melillo et al. 2009; Searchinger et al. 2009; Wise et al. 2009).

There remain some important topics to study in this field. First, the current analysis does not include forest residues (branches and leaves normally left at the forest site) in biomass supply. Because woody biomass is predicted to increase, more woody debris will be left in the woods. An important research question will be whether it is better to leave this debris in the woods or harvest it for bio-energy. Second, the analysis does not address the impact of climate change on forestland which could well influence the future supply of wood and biomass. Third, the analysis does not address likely changes in traditional biofuel (charcoal and wood logs) use. The implications of the woody biomass program on this sector might be similar to what will happen in the traditional wood industrial sector[8]. For instance, if the price of wood raises enough, some traditional fuelwood would get siphoned off. Finally, the analysis does not examine the response by the farming sector to having less available farmland. Will this stimulate further increases in farm productivity thus limiting impacts on farm outputs? All of these issues should be addressed in future research.

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[8] In 2011 1.89 billion m^3 of wood was used for traditional biofuel whereas industrial roundwood was 1.58 billion m^3.

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5. A WOODY BIOMASS OR A CARBON SEQUESTRATION PROGRAM? THE USE OF MARKETS VERSUS REGULATION

5.1 Introduction

One important thrust of climate policy is to increase the storage of carbon in forests. By increasing planting, intensifying forest management, and lengthening rotations, one can store significant amounts of carbon in the worlds forests (Sohngen and Sedjo 2000; Sohngen and Mendelsohn 2003; Richards and Stokes 2004; Sathaye et al 2006). Such forest carbon sequestration programs are efficient and belong in a globally efficient mitigation program (Sohngen and Mendelsohn 2003) with its size depending on the stringency of the mitigation targets or the price of carbon. For example, climate negotiators have been working for years at trying to create a set of global regulations (REDD) that would reduce carbon emissions from tropical forest deforestation.

Despite the importance of incorporating land use regulations into a global carbon program, it has been difficult to create effective global mechanisms to encourage forest carbon sequestration (Marland et al. 2001; Sedjo and Marland 2003; Antonari and Sathaye 2007; MacCauley and Sedjo 2011; Mendelsohn et al. 2012). Land use traditionally creates local externalities and so tends to be regulated at the local or state level. Land itself is heterogeneous which makes national or global regulations cumbersome and inefficient. Countries are fiercely protective of their sovereignty and so are highly resistant to surrendering land use decisions to foreign bodies. All of this explains why land use remains largely a local prerogative.

Efforts to engage in forest sequestration have generally proven ineffective. For example, the Clean Development Mechanism (CDM) tried to finance some small sequestration projects. Several tree planting projects were proposed. But such programs have difficulty ensuring that the planted trees are not prematurely harvested. It is expensive to monitor remote sites over long periods of time. The projects could not ensure that the planted forest represented an actual increase in the global forest, as extensive government planting programs simply substitute for private market planting that would have otherwise taken place. Tropical forest efforts are particularly at risk because of poorly enforced property rights. Technically, these forests belong to the government and yet private individuals live and depend on these forests for their livelihood. Regulations and payments to governments in and of themselves do not provide any incentive for local forest dwellers to change their behaviour (and protect the forest).

Despite the technical feasibility and the efficiency of carbon sequestration, these regulatory problems limit the effectiveness of creating a set of global regulations to sequester carbon in forests. In this work [1], I explore an alternative idea. Instead of directly paying for people to store carbon in forests, create a woody biomass program for energy. The program would effectively raise the price of timber and create a market incentive to plant more trees and grow more forests. Local people would voluntarily convert land to forests because it would be profitable. In this work, I demonstrate that a woody biomass program would create an incentive to store a vast amount of carbon in forests (the amount depending on the stringency of the mitigation program). Further, by employing carbon capture and storage (CCS) devices at the energy plant, one could effectively pump carbon out of the atmosphere. That is, the biomass program would actually reduce atmospheric carbon (not just prevent new emissions).

Although using woody biomass for energy (with CCS) (BECCS) is expensive, it is part of the answer to reaching stringent targets. Recent mitigation studies aimed at holding atmospheric carbon to levels low enough to hold warming at 2C (Azar et al., 2006; van Vuuren et al., 2007; Edenhofer et al., 2010; van Vuuren et al. 2010; Rose et al. 2012; Kriegler et al 2012) all incorporate using woody biomass for energy. The Kriegler et al study is perhaps the most compelling because it is a model comparison analysis asking how to reach a target of 2C. All six of the Integrated Assessment models participating in the study rely on BECCS to reach the target. In addition, many studies show that if BECCS is not available, the cost of stringent mitigation policies will increase dramatically (Azar et al. 2006; 2010; Krey and Riahi 2009). Finally, BECCS offers the flexibility to delay some mitigation actions into the future accommodating delays in implementing a global climate agreement (Krey and Riahi 2009; van Vuuren et al. 2010; van Vuuren and Riahi, 2011).

Of course, one concern is whether the world can supply all of this woody biomass. I examine this critical question by starting with the demand for woody biomass over time generated by WITCH, an Integrated Assessment Model (Bosetti et al 2006; 2007; 2009) and one of the models in the Kriegler et al study. I then employ the Global Timber Model (GTM) (Sohngen et al. 1999; 2003) to determine how to supply this future demand. The forest model considers buying land from agriculture, planting these lands, and increasing management intensity at each suitable location across the world. It makes decisions decades in advance to provide this supply. Ultimately, the

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[1] This Chapter is based on the FEEM working paper "Evaluating the Global Role of Woody Biomass as a Mitigation Strategy" with Robert Mendelsohn.

model calculates what prices wood would have to reach over time to make this profitable. This in turn reveals how expensive the woody biomass will be. The price is then entered back into WITCH, which then recalculates how much woody biomass it demands. The two models iterate to solve for the price where supply equals demand at every moment in time.

This Chapter is organized as follows. In Section 2 I analyze the effect of the mitigation policy of forest carbon sequestration under alternative mitigation scenarios. Section 3 summarizes the results and discusses the policy implications.

5.2 Result

I assume that using woody biomass for energy is carbon neutral. That is, I assume that the carbon released during combustion was offset by the carbon captured during the growth of the trees (this is not exactly correct because the storage occurs over a long time before the release. [2]). In addition, I assume that biomass power plants receive credits for the extra forest sequestration. [3] Given these assumptions, higher carbon taxes make woody biomass more attractive relative to fossil fuel. Also moving from a mild to a stringent long term mitigation target, the higher price path encourages more cumulative use of woody biomass. Going from the 3.7 to the 2.5 W/m2 target increases the demand for woody biomass from 8.2 to 15.2 billion m3/yr (from 77 to 144 EJ/yr) in 2100.

In order to support the large increase in wood supply, forestland expands dramatically. In the BAU scenario, the global forestland that is harvested remains somewhat constant over the century at 3,500 million ha. As mitigation increases, forestland increases both over time and across scenarios. Because the forestry model is forward looking, forestland expands before biomass is actually burned in great quantities. Already by 2060, forestland has expanded by 1,950-3,480 million ha depending on the scenario. By 2100, forestland area has expanded by 70% in the most moderate scenario and by 95% in the most severe scenario with respect to the BAU scenario. As the forest area expands, it will capture and store more carbon with respect to the BAU scenario.

Figure 1 compares the carbon stored in forests each year in the BAU scenario and in each mitigation scenario. In the BAU scenario, global forests accumulate a small amount of carbon in the first half of the century and then roughly hold that carbon constant for the rest of the century. By 2100 the BAU forests stores an additional 66 Gt CO2 or about 0.8 Gt CO2 per year.

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[2] Carbon in biomass harvested for bioenergy is assumed to be immediately released to the atmosphere. However, forest regrowth will capture and store atmospheric CO2 over time. There is therefore a time dependency to the carbon impact of forest harvest for bioenergy.

[3] This means that, at the time of burning biomass, power plants receive a subsidy equal to the carbon tax for each extra ton of carbon stored in forest with slash and soil.

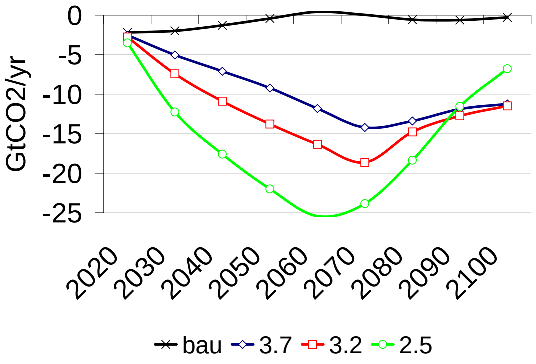

Fig. 5.1: CO2 stored in forests each year in the BAU scenario and in each mitigation scenario

With the mitigation scenarios, there is a distinct increase in the global stock of carbon stored in forests that grows by 685 Gt CO2, 908 Gt CO2 and 1279 Gt CO2 by 2100 (or about 9.4-16.8 Gt CO2/yr stored) as the scenarios progress in stringency.

Figure 2 tracks where in the forest the additional carbon relative to the BAU is accumulating. I assume that the total ecosystem carbon is given by the aboveground forest, slash, and soil carbon. I also track the variation of both carbon stored in timber products (yellow bar) and emissions from fuel used to harvest and transport wood to be processed (orange bar) relative to BAU from the initial period 2010.

At first, the accumulation is mostly above ground biomass as trees are grown in preparation for the biomass program. There is also some below ground accumulation of soil carbon as farmland is converted back into forests. In the second half of the century, the forests will be harvested for energy and the aboveground carbon will be burned but then captured by CCS. [4] However, there is a large growth in woody debris left in the woods. Finally, because overall wood products are falling with the mitigation strategies, the amount of carbon stored in market products (which is small) is declining.

Finally, my analysis compares the size of the biomass program to all the mitigation being undertaken in WITCH (Figure 3). Not only is the biomass program a carbon neutral source of energy, but it also reduces the CO2 in the atmosphere. As the carbon tax rises, the demand for biomass rises, and more CO2 is sequestered by both the forest (Extra forest sequestration in Figure 3) and the CCS technology (CCS biomass in Figure 3). Altogether, biomass accounts for 20-27% of total GHG cumulative abatement for 2020-2100. The extra stock of carbon in the forest accounts

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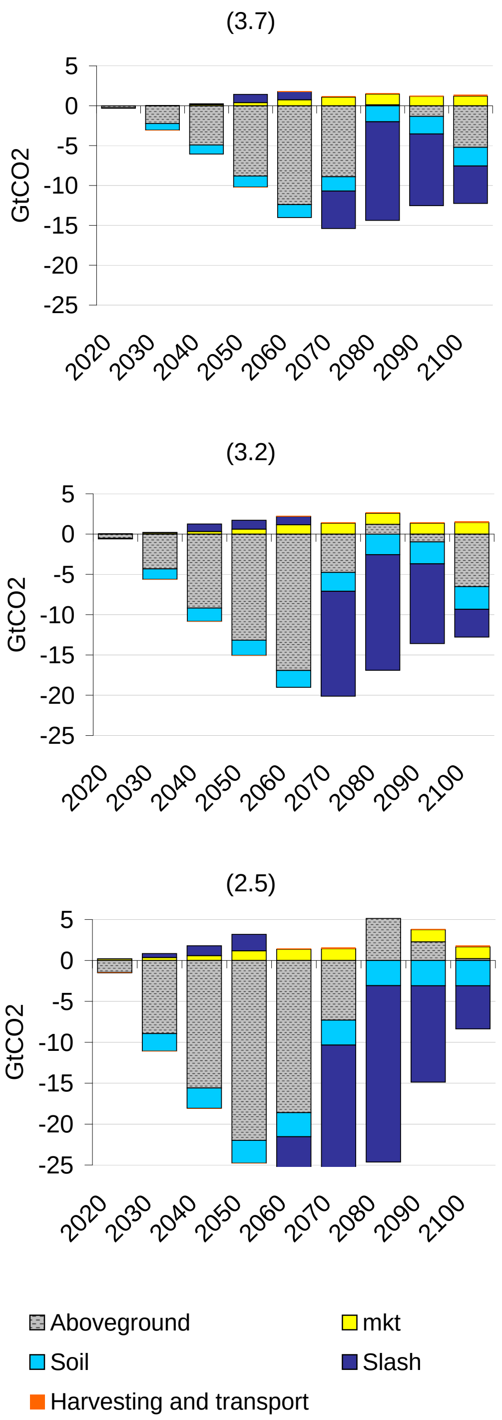
[4] In this study bio-energy is always combined with the CCS technology. Therefore, 90% of the amount of carbon released is sequestered back through CCS.



Notes: a negative value implies that the forest is acting as a sink for forest carbon and absorbing carbon. A positive value implies that the forest is acting as a source of emissions.

Fig. 5.2: Change in emissions from forest with respect to the BAU scenario under different mitigation scenarios.

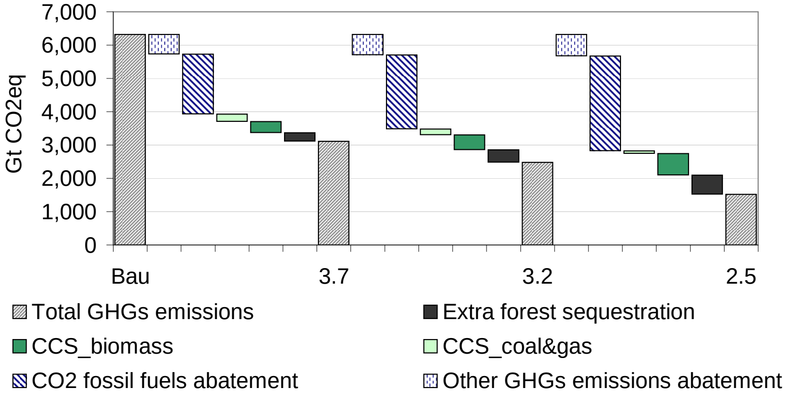


Fig. 5.3: Cumulative GHGs emissions 2020-2100 under the BAU and the three mitigation scenarios

for 256-574 Gt CO2 while the extra stock in the ground (from CCS) accounts for 341-647 Gt CO2.

These results show that a formal forest sequestration program is not a necessary precondition in order to obtain the forest sequestration gains. The market itself will store this extra stock because of the incentives of the woody biomass program alone. The woody biomass program is consequently a clever mechanism to secure carbon sequestration benefits.

5.3 Discussion

Forest sequestration can contribute to major reductions in atmospheric CO2 through capturing and storing atmospheric CO2 in live biomass, dead organic matter, and soil pools (Sohngen and Sedjo 2000; Sohngen and Mendelsohn 2003; Richards and Stokes 2004; Sathaye et al 2006). Therefore, a great deal of climate negotiating effort is currently being spent to create regulations to store more carbon in the worlds forests. For instance, the Bali Action Plan in 2007 recognizes the importance of reducing emissions from deforestation and degradation (REDD) to reach a global climate change deal.

Despite the importance of incorporating forest carbon sequestration into a global mitigation program, it has been difficult to create effective global mechanisms to encourage forest sequestration at the global level (Marland et al. 2001; Sedjo and Marland 2003; Antonari and Sathaye 2007; MacCauley and Sedjo 2011; Mendelsohn et al. 2012). Those difficulties arise because land is heterogeneous and so tends to be regulated as a local public good. Customs and laws treated land use as a local issue, whereas storing more carbon in the forest is a global objective without any global enforcement mechanisms. In addition, there are several problems associated with a formal sequestration program such as additionality, permanence and leakage (Chomitz 2002; Sedjo and Sohngen 2012; Murray et al 2004; 2007, Richards and Andersson 2001).

This paper explores an alternative mechanism to store more carbon in forests by creating a market for burning woody biomass for energy. We combine a detailed global, dynamic model of forests (GTM) (Sohngen et al. 1999; Sohngen and Sedjo 2000; Sohngen and Mendelsohn 2003; Daigneault et al. 2012) with a sophisticated integrated assessment model of climate and energy (WITCH) (Bosetti et al. 2006; 2007; 2009) to demonstrate that a woody biomass is a clever way to implement forest sequestration.

First, it effectively raises the price of timber and creates market incentives to plant more trees and grow more forests. Therefore, people would voluntarily convert land to forests and store more carbon in forest because it would be profitable. Further, coupled with CCS, the program effectively pumps carbon dioxide out of the atmosphere. That is, the biomass program would actually reduce atmospheric carbon (not just prevent new emissions).

Our analysis shows that an extensive woody biomass program is technically feasible. However, burning woody biomass for fuel is expensive and would only be done if the price of carbon is sufficiently high. For example, the runs suggest it would only be employed in the second half of this century and the extent of its use would depend on the stringency of mitigation targets. The study suggests that woody biomass would eventually become so valuable that it would reduce land for agriculture as the biomass program would cause global forests to increase by 70-90% by 2100. This in turn would substantially increase the carbon stored in global forests by 685 to 1,280 Gt CO2 by 2100. At first, the accumulation is mostly above ground biomass as trees are grown in preparation for the energy program. In the second half of the century, the forests will be harvested for energy and the aboveground carbon will be burned but then captured by CCS. However, there will be a large growth in woody debris left in the woods.

Finally, our analysis compares the size of the biomass program to all the mitigation being undertaken in WITCH. Altogether, biomass accounts for 20-27% of total GHG cumulative abatement for 2020-2100. The extra stock of carbon in the forest accounts for 256-574 Gt CO2 while the extra stock in the ground (from CCS) accounts for 341-647 Gt CO2.

The elegance of the woody biomass program is that it harnesses markets to encourage local land owners to plant and manage trees without any explicit sequestration policy or regulation like the REDD. Further, the use of woody biomass is a critical element in global programs with stringent mitigation targets (such as holding warming to 2C).

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6. CONCLUSIONS AND POLICY RECOMMENDATIONS

The aim of this Thesis is to expand understanding of the scope of potential contributions from woody biomass combined with carbon capture and storage (BECCS) in mitigating anthropogenic GHG emissions. Chapter 2 provides a general overview of the BECCS technology and the basic mechanisms by which it may contribute toward GHG emissions abatement. Chapter 3 provides assessments of the international trade of woody biomass. Chapter 4 discusses the effect of the increased demand for woody biomass on land-use. Finally, Chapter 5 shows the effect of bio-energy demand onfor forest carbon sequestration. This concluding Chapter attempts to integrate these results into a broader set of conclusions regarding potential contributions from bio-energy systems and to develop a coherent set of policy recommendations.

In this Thesis use the integrated assessment model (IAM) WITCH (described in Appendix A) to evaluate the potential role of the BECCS technology under climate mitigation scenarios with different levels of stringency. In Chapters 2 and 3 I use regional biomass supply cost functions derived from the Global Biosphere Optimization Model (GLOBIOM) (option 3 in Havlik et al. 2011). Cost functions are derived in GLOBIOM assuming that woody biomass production cannot substitute agricultural or forestry activities. Woody biomass is obtained from either forest logging residues or from short rotation tree plantations on marginal land, which is productive land that is not necessary to support agricultural and forestry production (see Appendix B.2).

Bio-energy with carbon capture and sequestration (CCS) for power generation plays a critical role in stringent mitigation policy scenarios generated by integrated assessment models (IAMs) (Clarke et al. 2009; Edenhofer et al. 2010; van Vuuren et al. 2011; Rose et al. 2012). 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; 2008; Azar et al. 2006; 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 (bio-energy) and it lowers the stock of CO_2 in the atmosphere (CCS).

My results show that, first, the demand for wood bio-energy with CCS will increase across time and scenarios. In early years the carbon prices are not large enough to sufficiently incentivize the demand for BECCS. The economy starts to consume BECCS between 2020 and 2040 depending on the policy scenario. As the carbon tax increases the demand for BECCS will increase both in absolute terms and as a percentage of the total electricity generation. Bio-energy production ranges from 16 EJ/yr to 73 EJ/yr in 2050 and 66-90 EJ/yr in 2100. The introduction of the BECCS technology in the mitigation portfolio has a significant impact on the electricity mix and the investments in the power sector. In particular, as the carbon tax increases it becomes more efficient to use the CCS site for biomass instead of coal and gas and the increasing demand for BECCS electricity requires new investments in biomass integrated gasification combined cycle (IGCC) power plants equipped with CCS (Section 2.2.2). The use of BECCS substantially increases the efficiency of climate policy providing additional cumulative abatement of 262 -519 $GtCO_2$-eq for 2010-2100. Finally, the introduction of negative emissions in the system has substantial effects on the public budget reducing the revenue from the carbon tax since the amount of the revenue depends on the level of the tax and on the tax base (GHGs emissions) (Section 2.3). Results presented in Chapter 2 are extremely sensitive to the regional maximum potential of biomass from the GLOBIOM model. For instance, many regions use all their biomass endowments when the price of carbon increases. The disparity between demand and supply of woody biomass under mitigation scenarios makes the international trade of biomass an important research question in the analysis of the BECCS technology.

Therefore, in Chapter 3 I examine the characteristics of a potential global market for woody biomass, the impact of trade on biomass demand, on the power mix and on GHG emissions using the carbon tax scenarios used in Chapter 2. I then test the impact of trade on climate policy costs by assuming that the long-term radiative forcing target obtained by the medium value of the carbon tax is attained using a cap-and-trade policy scheme. Results show that the incentive to trading biomass is large in both high and low carbon tax scenarios. In all tax scenarios at least 50% of biomass consumed globally is from the international market. Financial flows between importing and exporting regions are large and woody biomass becomes a major global commodity (Section 3.2.1). I found that biomass trade substantially increases the efficiency of climate policy because biomass demand and supply are unevenly distributed across world regions. Limiting trade of woody biomass increases cumulative abatement of GHG emissions over the 21st century by 120-323 Gt CO_2, depending on the tax scenario (Section 3.2.3). Moreover, I show that limiting biomass trade is expensive. In the cap-and-trade policy scheme, the 3.8 W/m^2 radiative forcing target in 2100 costs 14% less, in terms of global discounted output, when trade is available (Section 3.3).

The main limit of Chapters 2-3 is the lack of a fully consistent integration of GLOBIOM and WITCH as the biomass supply cost functions and maximum biomass production potential are not the result of a fully coherent linkage between WITCH and GLOBIOM. Therefore I cannot exclude inconsistencies between economic activity in WITCH and agricultural and forestry demand in GLOBIOM. However, the constraint to the expansion of woody biomass at the cost of agriculture and forestry reduces possible inconsistencies. I also cannot exclude inconsistencies between biomass cost functions, LULUCF baseline emissions and LULUCF abatement cost functions. However, the inconsistencies should be limited because the same cluster of models was used in order to provide these estimates. In addition, inconsistencies are minimized by restricting biomass plantations on residual land as described in Appendix B.2.

Not only the WITCH model but also a wide suite of other IAMs are relying on BECCS to meet stringent limits. However, the IAMs do not have enough detail about global forests and arable land to make careful estimates of biomass supply over time and across regions. As a result, they are not adequate to estimate the effect of biomass demand on industrial timber demand, the international price of wood, forest land use and forest sequestration in a dynamic framework. Integrating the complex dynamic demand for bio-energy from the IAMs with the complex dynamic structure of forests and forest supply is a daunting intertemporal task. Chapters 4 and 5 aim at addressing this issue.

This study combines the IAM WITCH with the spatially detailed global dynamic forestry model GTM in order to study the effects of bio-energy demand on land use. The combined model determines the desired size of the woody biomass market, and the resulting amount of forestland, and farmland under alternative mitigation strategies. Results reveals that, moving from a mild to a stringent policy would increase the demand of woody biomass from 8.2 to 15.2 billion m3/yr increasing forestland by 70% to 95% and shrinking farmland by almost a third in the most stringent scenario (Section 4.2.3). The demand for industrial wood products would fall 80% to 90% and farm output would also be negatively affected (Section 4.2.2).

In Chapter 5 I explore an alternative mechanism to store more carbon in forests by creating a market for burning woody biomass for energy. Coupled with CCS, the woody biomass program effectively pumps carbon dioxide out of the atmosphere. However, by raising the value of wood, it also encourages vast amounts of land to be converted to forest and to store more carbon. The elegance of the biomass program is that it harnesses markets to encourage local land owners to plant and manage trees, rather than cumbersome global land use regulations. Results illustrate that the increased demand for woody biomass under the climate mitigation scenario would lead to large scale afforestation that indirectly removes carbon from the atmosphere with an increase in the global stock of carbon stored in the forest of 685-1,279 GtCO2 by 2100 (Section 5.2). Further, the use of woody biomass is a critical element in global programs with stringent mitigation targets (such as holding warming to 2C).

The main limit of Chapters 4 and 5 is that the analysis does not include forest residues (branches and leaves normally left at the forest site) in biomass supply. An important research question will be whether it is better to leave this debris in the woods or harvest it for bio-energy. In addition, I do not include the impact of climate change on land which might influence the future supply of wood and biomass. Both topics are important issues to be addressed in future research.

Finally, the policy recommendations presented in this Thesis can be summarized as follow:

(a) BECCS is a critical technology in achieving stringent mitigation target (Chapter 2).

(b) Unbalances in demand and supply of woody biomass under climate mitigation policy are likely to be large and will thus create strong incentives to trade. Any restriction to market mechanisms that limits the efficient distribution of biomass is likely to be costly and should be allowed only if equally large economic, social or ecological costs from trade not considered in this thesis do exist (Chapter 3).

(c) Although using woody biomass helps address needs of the energy sector, it would have huge impacts on the saw timber and pulp and paper sectors (Chapter 4).

(d) The increasing demand for wood for bio-energy will require additional land for forest, by 2100 the amount of land devoted to forest could be equal to a third of the current global land devoted to agriculture and pasture. Thus, the impact on global land use can be very large. A by product of the woody biomass program is therefore a decrease in food production and higher prices for food. However, there will be some pressure to utilize forests that otherwise would have been left unmanaged (Chapter 4).

(e) As the forest area expands, there will be an increase in the global stock of carbon stored in the forest. The extra sequestration from the biomass program reveals the advantage of using woody biomass rather than crop bio-energy. While the former will increase the stock of carbon stored in the forest, the latter will have the opposite effect because it would increase the relative value of cropland causing forestland to shrink (Chapter 5).

(f) From a political point of view, a mitigation program that includes the use of woody biomass will be more acceptable than a mitigation program combined with a forest sequestration policy such as the REDD (Chapter 5).

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APPENDIX

A. THE WITCH 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[1] (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 Thesis the non-cooperative solution is used to build both the Reference and the policy scenarios. Since I work in a cost-effectiveness framework, I do not include the feedback of climate change on the economy, which is instead active 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.[2]

The major pitfall of WITCH is the low detail in non-electric energy technologies. WITCH lacks a detailed set of end-use energy technologies and does not distinguish between transport and residential energy uses. Therefore, the demand for biomass from the transportation sector is not included in this analysis.[3] However, this issue is not likely to be of concern in this study since woody biomass is generally not used in the transport sector.

WITCH is calibrated to reproduce the observed value of GDP and other energy variables in

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[1] WITCH has a damage function that translates global mean temperature in productivity impacts to the final good sector. Although, in this thesis I do not include the damage function and I focus on climate policy costs net of environmental benefits.

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

[3] The model was recently expanded to include a transport sector representing the use and profile of light domestic vehicles (LDVs) but this latest version was not used in this study (see Bosetti and Longden, 2012).

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 ψ grows exogenously — 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).

In this Appendix I briefly sketch the general structure of the model and I illustrate the main equations. 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 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 ($wbio$). I do not use backstop energy technologies that are part of the standard version of the model.[4]

A.1.1 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 ψ to generate output GY_{fg}:

$$GY_{fg} = G\left[K_g,\ K_{rd},\ EL,\ F,\ L,\ \psi\right], \tag{A.1.1}$$

where I omit time and region indexes when no ambiguity arises.

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

$$Y_{fg}(n,t) = \psi(n,t)\left[\alpha_{fg}(n)\left(K_g(n,t)^{\zeta}L(n,t)^{1-\zeta}\right)^{\rho_{fg}} + \alpha_{es}(n)ES(n,t)^{\rho_{fg}}\right]^{1/\rho_{fg}}. \tag{A.1.2}$$

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

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

$$K_g(n,t+1) = K(n,t)(1-\delta_g) + I(n,t), \tag{A.1.3}$$

where δ 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}):

$$ES(n,t) = \left[\alpha_{rd}(n)K_{rd}(n,t)^{\rho_{es}} + \alpha_{en}(n)EN(n,t)^{\rho_{es}}\right]^{1/\rho_{es}}. \tag{A.1.4}$$

"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):

$$Z_{rd}(n,t) = \varpi(n,t)\, K_{rd}^{a}(n,t)\, I_{rd}^{b}(n,t) \left\{ \left[\frac{K_{rd}(n,t)}{\sum_n K_{rd}(n,t)}\right] \left[\sum_{m\neq n} K_{rd}(m,t) - K_{rd}(n,t)\right] \right\}^{c}, \tag{A.1.5}$$

where ϖ 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.[5] New ideas are used to build the stock of knowledge capital K_{rd}:

$$K_{rd}(n,t+1) = K_{rd}(n,t)(1-\delta_{rd}) + Z_{rd}(n,t). \tag{A.1.6}$$

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

$$EN(n,t) = \left[\alpha_{el}(n)\, EL(n,t)^{\rho_{en}} + \alpha_{nel}(n)\, NEL(n,t)^{\rho_{en}}\right]^{1/\rho_{en}}. \tag{A.1.7}$$

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

$$EL(n,t) = EL_2(n,t) + \alpha_{hydro}(n)\, EL_{hydro}(n,t), \tag{A.1.8}$$

$$EL_2(n,t) = \left[\alpha_{ff}(n)FF(n,t)^{\rho_{el}} + \alpha_{nuclear}(n)EL_{nuclear}(n,t)^{\rho_{el}} + \alpha_{wind}(n)EL_{wind}(n,t)^{\rho_{el}}\right]^{1/\rho_{el}}, \tag{A.1.9}$$

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

$$FF(n,t) = [\alpha_{coal}(n)EL_c(n,t)^{\rho_{ff}} + \alpha_{oil}(n)El_{oil}(n,t)^{\rho_{ff}} + \alpha_{gas}(n)EL_{gas}(n,t)^{\rho_{ff}}]^{1/\rho_{ff}} \ , \quad \text{(A.1.10)}$$

$$EL_c(n,t) = [EL_{coal}(n,t) + EL_{coalccs}(n,t) + EL_{beccs}(n,t)] \ . \quad \text{(A.1.11)}$$

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:

$$NEL(t,n) = F_{nel,coal} + F_{nel,tradbio} + OGB(t,n); \quad \text{(A.1.12)}$$

$$OGB(t,n) = \left[\tau_{oil}\,(n)\,F_{nel,oil}(t,n)^{\rho_{ogb}} + \tau_{gas}\,(n)\,F_{nel,gas}(t,n)^{\rho_{ogb}} + \tau_{biofuel}\,(n)\,F_{nel,biofuel}^{\rho_{ogb}}\right]^{1/\rho_{ogb}} . \quad \text{(A.1.13)}$$

The final good sector purchases electricity from electric utilities that operate in the power sector using nine different generation technologies indexed with j. Different types of electricity are mixed using nested CES functions to simulate different degrees of substitutability. The final good sector also directly uses coal ($F_{fg,coal}$), oil ($F_{fg,oil}$), gas ($F_{fg,gas}$) and bio-fuels for transport ($F_{fg,bf}$). With the exception of biofuels, all fuels are purchased from the international market. The price of the final good is used as numeraire: $\phi_{fg} = 1$. Net output is equal to:

$$Y_{fg} = GY_{fg} - \sum_j p_{EL_j} EL_j - p_{F_{coal}} F_{fg,coal} - p_{F_{oil}} F_{fg,oil} - p_{F_{gas}} F_{fg,gas} - p_{F_{bf}} F_{fg,bf}, \quad \text{(A.1.14)}$$

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.[6]

A.1.2 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

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[6] 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.

of oil is $Q_{oil} = \sum_v Q_{oil,v}$. Oil is sold on a global world market. By denoting domestic aggregate consumption with $F_{oil} = F_{el,oil} + F_{fg,oil}$ I 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:

$$Y_{oil} = p_{F_{oil}} Q_{oil} \ . \tag{A.1.15}$$

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 δ:

$$Q_{oil}(t,n,v) \leq OIL_{cap}(t,n,v) \ \ \forall\, v; \tag{A.1.16}$$

$$OIL_{cap}(t+1,n,v) = OIL_{cap}(t,n,v)(1-\delta) + I_{oilcap}(t,n,v)/\phi_{oilcap}(t,n,v); \tag{A.1.17}$$

where $\phi_{oilcap}(t,n,v)$ 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). Cumulative oil extraction cannot exceed oil resources in place:

$$\sum_{s=0}^{t} Q_{oil}(s,n,v) \leq OIL_{res}(n,v) \quad \forall t. \tag{A.1.18}$$

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

$$F_{oil}(t,n) = F_{el,oil}(t,n) + F_{fg,oil}(t,n) \, . \tag{A.1.19}$$

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

$$MOIL(t,n) = \sum_v \chi_v Q_{oil}(t,n). \tag{A.1.20}$$

The cost of natural gas, coal and uranium (indexed with $f \in F$) is a function of global cumulative extraction capacity:

$$p_{F_f}(t) = \chi_f + \pi_f \left[Q_f(t-1) / \overline{Q_f}(t) \right]_f^{\xi} , \tag{A.1.21}$$

where $Q_f\left(t-1\right)=Q_f\left(0\right)+\sum_{s=0}^{t-1}\sum_n F_f\left(s,n\right)$, $\xi_f>1$ and $\overline{Q_f}$ is a threshold beyond which costs start increasing fast.

A.1.3 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}). I index power generation technologies with $j\in J$. The choice of investments in power generation capacity determines the demand for 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 $f\in F\left\{coal,oil,gas,uranium,bf,wbio\right\}$.[7] 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 biomass power plants: $CCS=CCS_{coal}+CCS_{gas}+CCS_{wbio}$. The cost of CCS ($C_{n,ccs}$) is region-specific, depends on cumulative storage ($TCCS(n,t)=\sum_{s=0}^{t-1}CCS(s)$) and is a net loss for the economy:

$$Y_{el}=\sum_j p_{EL_j}EL_j-\sum_f p_{F_{el,f}}F_{el,f}-C_{ccs}\left(TCCS\right)\ . \tag{A.1.22}$$

A.1.4 The forestry sector

The forestry sector is modeled in two distinct ways in the Thesis.

In Chapters 2 and 3 the forestry sector is build upon the assumptions from the GLOBIOM model. The forestry sector grows and harvests biomass Q_{wbio} at the region-specific cost C_{wbio} subject to the constraint $Q_{wbio}\le\overline{Q}_{wbio}$. The cost of biomass is region-specific and depends on the amount of harvested biomass in region n at time t. The cost function and the upper limit to biomass production ($\overline{Q}_{wbio}$) are derived from the model GLOBIOM (Havlik et al., 2011) and are discussed in Section B. Here I note that $C'(Q_{wbio})>0$ and $C''(Q_{wbio})>0$. In Chapter 2 the forestry sector sells biomass to BECCS power plants only domestically while in Chapter 3 it sells both domestically and abroad: $Q_{wbio}=F_{el,wbio}+\widetilde{Q}_{wbio}$, where $\widetilde{Q}_{wbio}$ denotes net export of woody biomass. 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 $p_{F_{wbio}}$.[8]

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[7] Further detail on the power generation technology is given below (see Equation A.1.27) , where I provide information on biomass electricity generation with CCS (BECCS).

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

Profits in the forestry sector are $\pi_{wbio} = p_{F_{wbio}} Q_{wbio} - C_{wbio}(Q_{wbio})$ and optimality conditions require that $p_{F_{wbio}} \geq \partial C(Q_{wbio}) / \partial Q_{wbio}$, where the latter holds with a strict equality if biomass cannot be traded internationally.[9] The output of the forestry sector is valued using the international price of woody biomass $p_{F_{wbio}}$:

$$Y_{wbio} = p_{F\,wbio} Q_{wbio} \; . \tag{A.1.23}$$

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

In Chapters 4-5 the forestry sector responds dynamically to the other sectors of WITCH through the soft-link with the GTM model. The forestry sector sells biomass to BECCS power plants at the wood international price given by GTM (see Appendix E for a detailed description of the soft-link). Therefore, I do not distinguish between domestic consumption and export of biomass. The international market of wood which include wood for both the industrial and the energy sectors must be balanced at every time period. The market clearing price of woody biomass is provided by the forestry models GTM. In this way there are not upper limits to the biomass potential available at the global level.

A.1.5 Aggregate output

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

$$\begin{aligned} Y &= Y_{fg} + Y_{oil} + Y_{el} + Y_{wbio} \\ &= GY_{fg} + p_{F_{oil}} \widetilde{Q}_{oil} + p_{F_{wbio}} \widetilde{Q}_{wbio} - \sum_{f=coal,gas,bf,uranium} \sum_{z=fg,el} p_{F_f} F_{z,f} - C_{ccs}(TCCS) \, . \end{aligned} \tag{A.1.24}$$

A.1.6 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 $L(n,t)$; total consumption is denoted with $C(n,t)$; consumption per capita is defined as $c(n,t) \equiv C(n,t) / L(n,t)$. Discounted utility is then equal to:

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[9] It is possible that the quantity constraint on biomass production binds at a lower marginal cost than the international price.

$$U = \sum_{t=0}^{\infty} u \left\{ log \left[c \left(n, t \right) \right] \right\} L \left(n, t \right) R \left(t \right), \tag{A.1.25}$$

where the discount factor $R(t)$ reflects a declining rate of pure time preference $\rho_v(t)$: $R(t) \equiv \prod_{v=0}^{t} \left(1 + \rho_v(t)\right)^{-t}$.[10]

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:

$$C = Y - I_{fg,g} - I_{fg,rd} - \sum_j I_{el,j} - \sum_j OM_j - \sum_v I_{oilcap,v} - C_{wbio} \left(Q_{wbio} \right) \ . \tag{A.1.26}$$

A.1.7 Bioenergy with CCS power generation

Woody biomass is used only in integrated gasification combined cycle (IGCC) power plants with CCS.[11] As for all other power generation technologies, BECCS electricity generation is governed by a Leontief type production function:

$$EL_{beccs} = min \left\{ \beta_{beccs} F_{el,wbio} \ ; \ \sigma_{beccs} CCS_{wbio} \ ; \ \varsigma_{beccs} OM_{beccs} \ ; \ \eta_{beccs} K_{beccs} \right\} \ , \tag{A.1.27}$$

where $0 < \beta_{beccs} < 1$ is an efficiency parameter that determines the amount of biomass (measured in energy units) needed to generate one kWh of BECCS electricity. β_{beccs} assumes different values depending on the forestry model used for the analysis.[12] Demand for woody biomass is then:

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[10] The model is solved numerically using 30 five-year time periods without terminal conditions. The last ten time periods are discarded. The rate of pure time preference is equal to 3% in 2005 and declines to 2.3% in 2100.

[11] Several test runs have shown that when CCS is available there is no incentive to use biomass in standard pulverized coal power plant without CCS. Thus, for expositional reasons I describe only equations governing IGCC power plants with CCS.

[12] The energy content of woody biomass used in Chapters 2 and 3 is 7.5 GJ/m3 while in Chapters 4 and 5 is 9.2 GJ/m3

$$F_{el,wbio} = \frac{1}{\beta_{beccs}} EL_{beccs}. \tag{A.1.28}$$

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[13], denoted with ω_{wbio}, and on the capture rate of the power plant, denoted with e: $CCS = e\omega_{wbio}F_{wbio}$. By using equation (A.1.28) it is possible to show that $\sigma_{beccs} \equiv \beta_{beccs}/e\omega_{beccs}$. Henceforth I omit the technology subscript when no ambiguity arises. K measures BECCS generation capacity in power units. η is an efficiency parameter that regulates the number of hours of operation of BECCS power plants. Power generation capacity grows as follows:

$$K\left(t+1,n\right) = \left(1-\delta\right)K\left(t,n\right) + I_{el}\left(t,n\right)/\phi \ , \tag{A.1.29}$$

where I_{el} is the investments in BECCS in region n at time t, δ is the depreciation rate of power plants and ϕ is the investment cost of BECCS generation capacity.[14] Finally, operation and maintenance costs (OM) are needed to run power plants and their demand is regulated by ς.

In Chapter 3, if the country is a net importer of biomass, BECCS power plants also pay the cost for transporting biomass TC, proportional to distance D from major production regions. The transportation cost is paid on the share of imported biomass of total consumption, denoted with γ: $\gamma = 0$ if the region is a net exporter, $\gamma = 1$ if a region imports 100% of biomass.[15] By denoting the interest rate of the economy with r, the cost of generating one unit of electricity with BECCS is thus equal to:

$$C\left(EL\right) = \left[\frac{1}{\beta}p_{F_{wbio}} + \frac{1}{\beta}\gamma\, TC\cdot D + \frac{1}{\sigma}C_{ccs}\left(TCCS\right) + \frac{1}{\varsigma} + \frac{1}{\eta}\left(r+\delta\right)\phi\right]EL. \tag{A.1.30}$$

BECCS power generation firms maximize profits $\pi_{EL} = p_{EL}EL - C(EL)$. Optimality conditions require that $\partial\, C(EL^*)/\partial\, EL^* = p_{EL}$. Thus:

$$p_{EL} = \frac{1}{\beta}p_{F_{wbio}} + \frac{1}{\beta}\gamma\, TC\cdot D + \frac{1}{\sigma}C_{ccs}(TCCS) + \frac{1}{\varsigma} + \frac{1}{\eta}\left(r+\delta\right)\phi\ . \tag{A.1.31}$$

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

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[13] The carbony content of woody biomass used in Chapters 2 and 3 is 0.096 Mt C per Twh of bio-energy while in Chapters 4 and 5 is 0.10 Mt C per Twh of bio-energy

[14] Investment cost in other technologies may vary across regions and time: $\phi_{el_j}\left(t,n\right)$. δ varies by technology.

[15] Transportation costs enter the BECCS version of equation (A.1.22) as a net loss. Transportation costs should also appear in equation (A.1.24).

j power technologies. Thus, the following condition must hold: $(\partial GY/\partial EL_{beccs})/(\partial GY/\partial EL_j) = p_{EL_{beccs}}/p_{EL_j}\ \forall j$.

A.2 GHG emissions and climate policy

WITCH considers emissions of CO_2 from fossil fuels, from the international transport of woody biomass (only in Chapter 3), 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 (ω_j) of each fuel F_j. CO_2 emissions from the international transport of woody biomass (MTR) are determined by the carbon intensity of maritime transport (ξ) and the distance from major centers of production (D).[16] Emissions from oil extraction ($MOIL$) are obtained summing emissions from the extraction of each oil type. Abatement of CO_2 emissions from fuel combustion is endogenously determined by changing the energy mix and the mix of capital, labor and energy. In Chapters 2 and 3 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 both LULUCF emissions and other GHG is also endogenous but relies on abatement cost curves. In Chapters 4 and 5 LULUCF are from the forestry model GTM and take into account the change in land use due to the demand for woody biomass and timber from the industrial sector. In Chapters 4 and 5 I do not include abatement of LULUCF as the only incentive to change the use of land is the demand for wood from the energy and the industrial sectors ($ALU = 0$).

By denoting abatement of LULUCF emissions with ALU and abatement of non–CO_2 GHG with AM_{ghg} where $ghg \in G\,\{CH_4, N_2O, S_2O, SLF, LLF\}$, respectively 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:

$$M = \sum_i \omega_i F_i + MTR + MOIL + LU + \sum_{ghg} M_{ghg} - CCS - ALU - \sum_{ghg} AM_{ghg}. \tag{A.2.1}$$

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 et al 2007).

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

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

GHG emissions from 2015.

A.2.1 Carbon tax

In the carbon tax policy framework all countries agree to implement 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. I assume that firms in the final good sector pay taxes on and manage abatement technologies of land use emissions and non-CO_2 GHG. 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:

$$G\left(n,t\right)=T\left(t\right)M\left(n,t\right)-LS\left(n,t\right). \tag{A.2.2}$$

The government must run a balanced budget in every period: $G\left(n,t\right)=0\ \forall\, t$ and $\forall\, n$. The output of the final good sector and the budget constraint of the economy are transformed as follows:

$$\begin{aligned} Y_{fg}=GY_{fg}-\sum_j p_{EL_j}EL_j-p_{F_{coal}}F_{fg,coal}-p_{F_{oil}}F_{fg,oil}-p_{F_{gas}}F_{fg,gas}-p_{F_{bf}}F_{fg,bf}-\\ -T\left(LU+\sum_{ghg}M_{ghg}-ALU-\sum_{ghg}AM_{ghg}\right)-C_{lu}(LU)-\sum_{ghg}C_{ghg}(AM_{ghg})\ , \end{aligned} \tag{A.2.3}$$

$$C=Y-I_{fg,g}-I_{fg,rd}-\sum_j I_{el,j}-\sum_j OM_j-\sum_v I_{oilcap,v}-C_{wbio}\left(Q_{wbio}\right)+LS\ , \tag{A.2.4}$$

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.

A.2.2 Cap-and-trade

In the cap-and-trade policy framework (used in Chapter 3) governments agree on a global maximum level of emissions $\overline{GM}(t)$ that is consistent with the desired long term temperature 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. I assume that the government manages emission allowances endowed to the region. The government auctions emission allowances both domestically and internationally at the price $P_{ep}(t)$. If demand for permits from the domestic economy is higher than the emission endowment, the government buys credits from the international market. Revenues from emission permits sales are recycled lump sum. With a global cap-and-trade scheme the government budget constraint reads as follows:

$$G\left(n,t\right)=P_{ep}\left(t\right)M\left(n,t\right)+P_{ep}\left(t\right)\left[\,\overline{M}\left(n,t\right)-M\left(n,t\right)\,\right]-LS\left(n,t\right). \tag{A.2.5}$$

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

A.2.3 BECCS under climate policy

CO_2 emissions released during the combustion of woody biomass were recently captured by the plant during the growth process. Therefore, it is standard convention to assume that burning biomass generates zero GHG emissions. However, emissions from fertilizers use (N_2O) and management activities represent a net contribution to the stock of GHG in the atmosphere. Thus biomass is exempt from carbon taxes. This implies that a power plant that generates 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 from the international transport of woody biomass (when is included in the analysis). In addition, in Chapters 4 and 5 I assume that biomass power plants receive credits for the extra forest sequestration equal to the carbon tax for each extra ton of carbon stored in forest with slash and soil (a) (see Appendix F).

The price of BECCS electricity is obtained by modifying equation (A.1.31) as follows:

$$p_{EL_{beccs}}=\frac{1}{\beta}p_{F_{wbio}}+\frac{1}{\beta}\gamma TC\cdot D+\frac{1}{\sigma}C_{ccs}(TCCS)+\frac{1}{\varsigma}+\frac{1}{\eta}\left(r+\delta\right)\phi-e\omega\frac{1}{\beta}T-a\frac{1}{\beta}T+\frac{1}{\beta}\gamma\xi D\cdot T\,. \tag{A.2.6}$$

BECCS power generation firms are willing to demand biomass subject to the optimality condition imposed by equation (A.2.6). This result implies that, for a given price of electricity, the higher is the tax, the higher is the price of biomass that they are willing to pay.

In Chapter 3, this result implies that the regional social planner may be willing to pay a price higher than the global marginal cost of biomass production if the global demand for biomass exceeds the global maximum endowment. As the carbon tax increases the marginal production cost of biomass remains the same when there are constraints to production. However, 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 capture the rent. This is a peculiar outcome of my non-cooperative solution. In a different setting, with strategic coalition formation, a group of importing countries would have the incentive to form a cartel to extract part of the rents from the forestry sectors of exporting regions.

B. ASSUMPTIONS - CHAPTERS 2-3

In this section I explain how I model BECCS power plants and I describe the assumptions on the cost and availability of biomass in Chapters 2 and 3. There are many uncertainties associated with the BECCS technology. First, there is uncertainty on the cost of large-scale power plants with CCS and on 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 for 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). I are therefore forced to make some discretionary choices in my modeling exercise.

B.1 Power plants

I 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 equal to 4,170 USD/kW.[1]

The capture rate of carbon dioxide is equal to 90%[2]. Both the efficiency and the capture rate are consistent with other studies in the literature (Luckow et al. 2010, Krey and Riahi, 2009).[3]

The cost of storing CO_2 underground is region-specific. The cost varies according to the estimated size of reservoirs and it increases exponentially as cumulative storage increases.[4]

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[1] Efficiency of coal IGCC power plants is equal to 40% and the investment cost is equal to 3,170 USD/kW.

[2] According to GLOBIOM, on average 1 Twh of bio-energy releases 0.096 Mt C previously stored during the growth of trees of which 90% is captured through the CCS.

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

[4] Capturing and storing 20 Gt of CO_2 underground costs about 4 USD/tCO_2 for LACA, 5 USD/tCO_2 for EASIA, 6.7 USD/tCO_2 for the USA, WEURO, KOSAU, India and China, 7.3 USD/tCO_2 for SSA, 12.8 USD/tCO_2 for MENA and TE and 21.6 USD/tCO_2 for CAJAZ.

B.2 Woody biomass

I use regional biomass supply cost functions derived from the Global Biosphere Optimization Model (GLOBIOM) (option 3 in Havlik et al. 2011).[5] Cost functions are derived in GLOBIOM assuming that woody biomass production cannot substitute agricultural or forestry activities. Woody biomass is obtained either from forest logging residues or from short rotation tree plantations on marginal land, which is productive land that is not necessary to support agricultural and forestry production.

The cost of biomass includes planting and harvesting costs, collecting costs and terrestrial transportation costs. It does not include the opportunity cost of land because biomass production does not directly compete with other land uses. 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 in that year. The literature assumes that the highest cost of biomass is generally lower: Magne et al. (2010) estimate a 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) use a cost equal to 7 USD/GJ. The energy content of woody biomass is assumed to be equal to 7.5 GJ per cubic meter.

GLOBIOM also provides the maximum biomass production potential for each region until 2050 by projecting the extension of marginal land. 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). Global biomass potential is equal to 158 EJ/yr in 2010 and decreases to 147 EJ/yr in 2050. After 2050 I assume that the potential remains constant. The literature presents a large variation in the estimates of biomass production potentials with a range of 70-420 EJ/yr in 2050 and 140-600 EJ/yr in 2100 (see among all Reilly and Paltsev 2007; Gillingham et al. 2008; Calvin et al. 2009; Luckow et al. 2010; Magne et al. 2010; Popp et al. 2011). The divergence in the estimates is mainly due to the types of biomass included (residue, grass, plants, trees) and to the assumptions on land use change.[6]

Biomass supply cost functions and maximum biomass production potential are not the result of a fully coherent linkage between WITCH and GLOBIOM. Therefore I cannot exclude inconsistencies between economic activity in WITCH and agricultural and forestry demand in GLOBIOM. However, the constraint to the expansion of woody biomass at the cost of agriculture and forestry

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[5] GLOBIOM provides the marginal cost supply functions as step functions. I converted them in quadratic functions: $MC(Q_{wbio}) = a(n)Q_{wbio}^2 + b(n)Q_{wbio} + c$, where a and b are region-specific and c is the minimum marginal production cost, equal to 3 USD/GJ.

[6] 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.

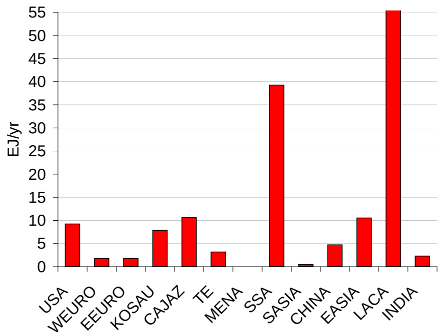

Fig. B.1: Regional biomass potential in 2050

reduces possible inconsistencies. I also cannot exclude inconsistencies between biomass cost functions, LULUCF baseline emissions and LULUCF abatement cost functions. LULUCF emissions and abatement cost functions used in WITCH were generated by IIASA for the Eliasch Review (Eliasch 2008) using a cluster of models that includes GLOBIOM and G4M (Kindermann 2008), a forestry model that provides information to GLOBIOM. Woody biomass supply cost functions were generated instead after the Eliasch Review. However, the inconsistencies should be limited because the same cluster of models was used. In addition, inconsistencies are minimized by restricting biomass plantations on residual land.

B.3 International transportation costs

In Chapter 3 I include the international transportation costs for woody biomass. Following Hansson and Berndes (2009) I 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.[7] 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.[8]

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[7] Main harbors 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.

[8] I 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.

C. POLICY SCENARIOS - CHAPTERS 2-3

In 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 1,013 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 the concentration of GHG in the atmosphere is equal to 951 ppm CO_2-eq and radiative forcing is equal to 6.6 W/m^2, with an increase of the global mean temperature above the pre-industrial level equal to 4 °C.

In the policy scenarions, I assume that all world regions credibly commit to reduce all GHG emissions from 2015. In the carbon tax policy framework[1] all countries agree on a uniform global tax $T(t)$. Taxes are equal to 2, 7 and 14 USD/tCO_2 in 2015 and reach 158, 576 and 1,161 USD/tCO_2 in 2100.[2] I 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 Chapter 2 I run the same carbon tax scenarios with and without the use of BECCS in order to assess the effect of the technology on emissions abatement and the power sector for a given CO_2 price. In Chapter 3 I run instead the same carbon tax scenarios with and without the international trade of woody biomass in order to analyze the effect of the trade on the policy.

In addition, in Chapter 3 I simulate a cap-and-trade scenario. In particular, I assume that all regions agree to achieve a global level of radiative forcing equal to 3.8 W/m^2 from 2015, as in the t2 scenario. Each region receives an allocation of emission permits and is entitled to buy or sell

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[1] For convenience I refer to the tax on all GHG emissions as the "carbon tax" even if this tax is on all GHG emissions.

[2] I solve the model using a cap-and-trade policy tool with borrowing and banking with a 460 ppm CO_2-eq target in 2100. With both when and where flexibility I 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 I avoid unnecessary assumptions on the distribution of emission allowances and thus separate efficiency from equity considerations.

permits from other regions at the international market clearing price.[3] Since the price of emission permits does not change under alternative distribution rules (Coase, 1960), I use a representative equal-per-capita distribution of permits to study how trade changes the carbon price and global mitigation costs.

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

D. THE GLOBAL TIMBER MODEL - GTM

In Chapters 4 and 5, I rely on the dynamic Global Timber Model (GTM) Sohngen et al. (1999). This model has recently been used to study woody biomass in the US (Daigneault et al. 2012).

The forest model contains 200 forest types in 16 regions. The 200 forest types can be aggregated into four broad categories: boreal, temperate hardwood, temperate softwood, and tropical. The intensity of forest management is determined endogenously. Low valued forests are managed lightly with minimal inputs. Moderately valued forests are managed more actively including replanting after harvest. High-value forests are managed as plantations with intensive forest management inputs. Finally, inaccessible forests are left in a natural state unless global timber prices are high enough to justify creating access. The model finds that generally, high valued forests are located in the subtropics, moderate valued forests are in the temperate softwood zone, and low valued forests are in the boreal and tropical forests.

The model also captures the age of the timber on each piece of land (and thus resembles a vintage capital model). The stock of timber on the land is determined by a site specific growth function depending on the underlying productivity of land in each region, the type of forest, and management intensity. The supply of timber is consequently also a function of time since it takes time to grow a forest.

The model captures the behavior of a competitive forest industry. Land that is set aside for conservation is taken out of timberland. However, one weakness of the model is that it does not capture segments of the forest sector that are not competitive. The model does not reproduce the fact that governments constrain harvests on public forestland. The model also does not reproduce the fact that there is too much harvest on most common property forests. Although it is clear that both practices are inefficient, it is not clear what net effect these two phenomena have on global timber supply. That is, it is not clear what bias the model has introduced because it assumes the timber market is universally efficient.

In the original model (Sohngen et al. 1999), forestry demand is represented by a single aggregate demand function for industrial wood products.[1]. This demand function is assumed to grow over

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[1] Industrial wood products are inputs into products like lumber, paper, plywood, and other manufactured wood

time as the global economy grew:

$$Q_t^{ind} = AZe^{\phi\eta t}P_t^{\omega}, \tag{D.0.1}$$

where A is a constant, Z is income which grows exponentially over time at rate η, ϕ is income elasticity, P_t is the international price of timber and ω is the price elasticity. Empirical evidence suggests that ϕ is equal to 0.9, ω is equal to 1.1, and η is equal to 1% (Sohngen et al 1999; Daigneault et al. 2012).

In this work, I introduce a required amount of woody biomass for energy, Q^{bio}, which is determined by the energy model for each period given the implied price of biomass. The amount of biomass requested by WITCH is then fixed in GTM.

The total global demand for wood Q^{tot} in GTM is therefore:

$$Q_t^{tot} = Q_t^{ind}(P_t) + Q^{bio}, \tag{D.0.2}$$

The total wood supply comes from a host of regions that all have forest. I assume there is an international market for timber that leads to a global market clearing price. I further assume that there is also an international market for woody biomass. If woody biomass is going to directly compete with wood products, competition for supply will equilibrate their price. The timber model solves for the price of biomass given the quantity that is desired.

Following Sohngen et al (1999), the model solves a dynamic problem that equates supply with this aggregate demand. For example, the model chooses the age class (a) to harvest trees in each forest [2]. Hence, the total quantity of timber, Q^{tot}, depends upon each hectare harvested in each age class, H(a), and the growth function V which is a function of age class and management intensity[3] (m_{t0}) such as:

$$Q_t^{tot} = \sum_{a=1}^{A}[H_{a,t}V_{a,t}(m_{t0})], \tag{D.0.3}$$

The model also chooses management intensity and planting. There are a host of costs for management intensity, additional land, and transportation to markets. In particular, the costs of accessing, harvesting, and transporting timber to markets in accessible and highly valuable plantation forests are assumed to be constant marginal costs. While the costs of accessing new forests at the inaccessible margin are assumed to rise with additional harvests. The costs of planting

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products.

[2] Timber shifts from one age class to the next, unless harvests occur.

[3] Management intensity for forests is decided at the time of planting, or t0.

forests in accessible regions are assumed to be constant for each hectare planted in a given time. Similarly, the costs of replanting existing highly valuable plantation forests are constant but the costs to establish new hectares in inaccessible area are assumed to increase as additional hectares are established. Finally, the costs of establishing new plantations are assumed to be fairly high as new plantations require substantial site preparation efforts to obtain the desired high growth rates (Daigneault et al. 2012).

The final major cost component is the cost of renting land for forestry. The model takes into account the competition of forestland with farmland using a rental supply function for land. So, for example, if timber prices rise relative to farm prices, the model predicts that timber owners will rent suitable farmland for at least a rotation. Similarly, if timber prices fall relatively to farm prices, suitable forest land will be converted back to farmland upon harvest. The total amount of forestland is therefore endogenous.

The carbon analysis used in Chapters 4 and 5 was described by Sohngen and Sedjo (2000) and updated by Daigneault et al. (2012). I assume that the total ecosystem carbon is given by the aboveground forest, slash, forest products and soil carbon. First, aboveground carbon (C) accounts for the carbon in all tree components (including roots) as well as carbon in the forest understory and the forest floor. It is in function of the growth function V and the management intensity (m_{t0}):

$$C_{a,t} = \omega V_{a,t}(m_{t0}), \tag{D.0.4}$$

Second, slash carbon is the carbon left over after timber harvest and removal of carbon in products. Annual additions to the slash carbon pool (AS) depend upon each hectare harvested in each age class, $H(a)$, the growth function V and the aboveground carbon (C) such as:

$$AS_t = C_{a,t}H_{a,t} - kV_{a,t}H_{a,t}, \tag{D.0.5}$$

where the parameter k is the proportion of harvested timber volume that is carbon (typically around 0.25 tC per m^3). Third, carbon in timber harvests is estimated by tracking forest products (for the industrial sector) over time. Finally, for soil carbon I assume that carbon is constant unless there is land use change. For instance, when land use change occurs, I track net carbon gains or losses over time

The model solves assuming there is a social planner maximizing the present value of the difference between consumer surplus and the costs of holding timberland and managing it over time. It is an optimal control problem given the aggregate demand function (which contains the required biomass for energy), starting stock, costs, and growth functions of the model. It endogenously solves for timber prices and the global supply of both woody biomass and industrial timber and optimizes the harvest of each age class, management intensity, and the area of forest land at each moment in time. The timber model is forward looking with complete information.

E. THE SOFT-LINK OF WITCH AND GTM

In Chapters 4 and 5 I rely on a soft link between WITCH and GTM. GTM has been soft linked with integrated assessment models before to calculate optimal sequestration programs (Sohngen et al. 2003 and Tavoni et al. 2007). In this study, I soft link WITCH and GTM to study woody biomass. This link was first implemented by Tavoni et al. (2007). However, both models have been modified since this earlier research. First, the option of combining biomass with carbon capture and storage (CCS) has been introduced recently in WITCH. Second, I introduce the demand for biomass in the forestry model.

WITCH calculates the global quantity demanded of woody biomass over time for each policy scenario. The quantity demanded for woody biomass from WITCH is then added to the demand for industrial wood products in GTM. The timber model then solves for the international price of wood. The price is then entered back into WITCH which generates a new quantity demanded of woody biomass. The two models iterate back and forth until demand equals supply.

The two models are assumed to be linked when the quantity of woody biomass demanded by WITCH changes less than 5% between iterations. The equilibrium is achieved after 12-20 interactions depending on the policy scenario. This equilibrium is actually a set of distinct equilibrium conditions in each time period.

For each mitigation strategy, WITCH assures that the outcome takes into account a dynamic carbon price trajectory and the competition between woody biomass and other mitigation options. The forest model takes into account the competition between industrial wood products and woody biomass, the intensity of forest management, the competition for land between forestry and agriculture, and the price of forest products. The forestry model also predicts the price of industrial wood products, forestland area, and the carbon sequestered in those forests over time.

F. ASSUMPTIONS CHAPTERS 4 AND 5

The forestry model GTM assumes that wood products are traded in a global market so that there is one international price for wood at each moment in time. Prices are allowed to change over time. Demand and supply equilibrate at the global scale. Demand and supply are not constrained within any region: trade is permitted across regions so biomass does not have to be produced in the region it is consumed. WITCH has 5-year time steps and the forestry model has 10-year time steps. To link the two models, I average the 10 years price steps from GTM to yield 5 year price steps for WITCH.

I assume that only wood can be used to meet the demand for biomass. Neither biomass from crops nor biomass from forest residues (branches and leaves normally left at the forest site) is included. On average, 1 m^3 of timber produces approximately 8.8 MMBtu of energy (Daigneault et al. 2012). Also the carbon content of woody biomass is included in WITCH: I assume that on average 1 Twh of bio-energy releases 0.16 Mt C previously stored during the growth of trees and produces extra sequestration[1] of 0.10 Mt C in soil, slash and market.

I assume that woody biomass is used only in integrated gasification combined cycle (IGCC) power plants with CCS. [2] Technically, residences also use woody biomass for heat and cooking but I assume this use remains fixed over time and across policies. The efficiency of the IGCC power plants is assumed to be 35%. Carbon capture and storage technology is assumed to be able to capture 90% of emissions[3] (Bosetti et al. 2006). That is, 90% of above ground carbon stored during the growth of the trees and then released at the burning time will be captured and

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[1] The extra carbon sequestration is defined as the difference between the amount of carbon stored in forests soil and slash and wood products in the baseline scenario and the amount of carbon stored in forests soil and slash and wood products in the policy scenario.

[2] Several test runs have shown that when the CCS technology is available there are no incentives to use biomass in standard pulverized coal power plants without CCS. For this reason I describe the model assuming that biomass is used only in IGCC power plants with CCS.

[3] Similar assumptions have been found in the literature, in Luckow et al. (2010) the efficiency of biomass IGCC plant is equal to 41.6% while for Koornneef et al. (2012) is 43-50%. Luckow et al. (2010) assume a CCS capture rate of 91% in 2020, growing to 94% in 2095, Krey and Riahi (2009) assume a capture rate of 90% and Koornneef et al. (2012) a capture rate of 90-95%

sequestered via CCS.

Finally, the capital cost for biomass-fired IGCC power plants is assumed to be 4170 USD/kW. The cost of storing CO_2 underground is region-specific, it varies according to the estimated size of reservoirs and it increases exponentially as cumulative storage increases (Bosetti et al. 2006).

G. POLICY SCENARIOS - CHAPTERS 4 AND 5

In this study I use a baseline scenario and three mitigation scenarios. The baseline scenario is a Business As Usual (BAU) scenario with no greenhouse gas mitigation policies over the century. According to WITCH, the average global GDP per capita grows from 6,900 USD in 2005 to 18,000 USD in 2050 and to 39,634 USD in 2100. Global total primary energy supply is 436 EJ/yr in 2005, 820 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. This corresponds to a level of GHG concentration in the atmosphere in 2100 of 951 ppm and therefore radiative forcing equal to 6.6 W/m^2.

I then examine three mitigation scenarios that lead to radiative forcing levels of 3.7, 3.2 and 2.5 W/m^2. The purpose is to show how the demand for biomass would change depending upon the mitigation scenario. The long term objectives correspond to GHG concentrations of 560, 500 and 450 ppm CO_2 -eq respectively.

I solve WITCH using a global carbon price as the tool. Carbon prices force mitigation to be cost effective across sectors and countries providing when and where flexibility. WITCH solves for the optimal level and growth rate of the carbon price given the target concentration. WITCH predicts the least cost carbon price would be 4, 7 and 14 USD/tCO_2 in 2015 and would reach 158, 576 and 1161 USD/tCO_2 in 2100 across the three scenarios. I assume no sequestration policies (other than carbon capture and storage) are available in this analysis.

H. APPENDIX REFERENCE

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ESTRATTO PER RIASSUNTO DELLA TESI DI DOTTORATO

L'estratto (max. 1000 battute) deve essere redatto sia in lingua italiana che in lingua inglese e nella lingua straniera eventualmente indicata dal Collegio dei docenti. L'estratto va firmato e rilegato come ultimo foglio della tesi.

Studente: Alice Favero **matricola:** 955690

Dottorato: Science and Management of Climate Change

Ciclo: 24

Titolo della tesi[1] : Carbon mitigation with woody biomass and CCS: an economic assessment

Abstract (Italian)

Questa tesi analizza il contributo della biomassa da legno con CCS (BECCS) nel mitigare le emissioni di gas serra. Lo strumento utilizzato e' l'IAM WITCH. Nei capitoli 2-3 ho usato le curve di biomassa da GLOBIOM. Mentre nei capitoli 4-5 ho collegato WITCH a GTM. Gli scenari di policy sono tre carbon tax. I risultati mostrano che, al crescere della carbon tax aumenta la domanda di BECCS (66-90 EJ/anno nel 2100). Includendo il trade internazionale della biomassa e' possibile aumentare l'abbattimento delle emissioni di 120-323 GtCO2 e ridurre i costi cumulativi della *policy* del 14% entro il 2100. Collegando WITCH a GTM, si mostra che la domanda di bioenergia avra' grandi effetti sull'uso della terra. La domanda raggiungera' 8-15 mld m3/anno, mentre il prezzo del legno aumenter 4-9 volte rispetto alla BAU nel 2100. Tale incremento ridurra' la domanda di legno industriale dell80-90%. Le foreste si espanderanno del 70-95% rispetto al BAU e lo stock di CO2 accumulato aumentera' del 685-1279 GtCO2 entro il 2100.

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[1] Il titolo deve essere quello definitivo, uguale a quello che risulta stampato sulla copertina dellelaborato consegnato.

Abstract (English)

This Thesis analyzes the contributions from woody biomass with CCS (BECCS) in mitigating GHG emissions. I used the IAM WITCH tool. In Chapters 2-3 I use biomass supply curves from GLOBIOM. In Chapters 4-5 I instead link WITCH to GTM. The policy scenarios consist of three carbon taxes. Results show that as the carbon tax increases the demand of BECCS will reach 66-90 EJ/yr in 2100. The introduction of international trade of biomass in WITCH makes it possible to increase the emissions abatement by 120-323 GtCO2 and reduce cumulative policy costs by 14% over the century. Linking WITCH to GTM, I show that bio-energy demand will have implications for land use. The demand will reach 8-15 billion m3/yr while the price of wood will increase 4-9 times relative to the BAU by 2100. This increase would shrink the demand for industrial wood from 80-90%. Forest area will expand by 70-95% relative to the BAU and increase the global stock of forest carbon by 685-1,279 GtCO2 by 2100.

Firma dello studente