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Bioenergy with carbon capture and storage: key issues and major challenges

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Abstract

Projections of the pathways that reduce carbon emission to the levels consistent with limiting global average temperature increases to 1.5°C or 2°C above pre-industrial levels often require negative emission technologies like bioelectricity with carbon capture and storage (BECCS). We review the global energy production potential and the ranges of costs for the BECCS technology. We then represent a version of the technology in the MIT Economic Projection and Policy Analysis (EPPA) model to see how it competes with other low carbon options under stabilization scenarios. We find that, with a global price on carbon designed to achieve climate stabilization goals, the technology could make a substantial contribution to energy supply and emissions reduction in the second half of the 21st century. The main uncertainties weighing on bioelectricity with carbon capture and storage are biomass availability at large scale, the pace of improvements in carbon capture technologies, the availability and cost of CO_2 storage, and social acceptance. Commercial viability would appear to depend strongly on a policy environment, such as carbon pricing, that would advantage it, given the technology costs we assume. Compared to previous studies, we provide a consistent approach to evaluate all of the components of the technology, from growing biomass to CO_2 storage assessment. Our results show that global economic costs and needed carbon prices to hit the stabilization target are substantially lower with the technology available at reasonable costs.

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1. INTRODUCTION

Emissions from fossil fuel combustion are recognized as a primary cause behind increases in global greenhouse gas (GHG) concentrations and Earth's temperature in recent decades and in projections over the next century and beyond (IPCC, 2014). Reducing GHG emissions will require drastic changes in the global energy systems as emphasized by various modeling exercises (e.g., Clarke et al., 2014; Kriegler et al., 2014). The most ambitious scenarios, those aimed at keeping the global mean surface temperature increase below 2°C above pre-industrial levels, almost always involve the use of some form of bioenergy where at least some of the carbon from the energy conversion process is captured and stored. This combination of bioenergy with carbon capture is capable of generating negative emissions (e.g., Creutzig et al., 2015; Muratori et al., 2016). The Paris Agreement (UN, 2015) increased the ambition of the desired goals to limiting the global average surface temperature to "well below" 2°C above pre-industrial level, which puts even more focus on negative emissions technologies – those that remove carbon dioxide from the atmosphere.

Bioenergy with carbon capture and storage (sometimes also referred as Bio-CCS or biomass with CCS) does not have a consistent definition throughout the literature, as emphasized by Kemper (2015). The International Energy Agency's GHG Research and Development Program (IEAGHG) describes the following six Bio-CCS pathways (Koornneef et al., 2011): four pathways in power generation, which include standalone or co-firing of biomass in power stations (with and without gasification), and two pathways in liquid transportation fuel production, which include CCS from advanced ethanol or Fisher-Tropsch biodiesel production. A negative emission potential in CCS-enabled liquid biofuel production is substantially smaller than the use of CCS in biomass-based power plants because only the CO2 released in conversion is captured (Kemper, 2015; Gough and Vaughan, 2015). We follow Gough and Upham (2010) and use the term BECCS (Bioelectricity with Carbon Capture and Storage) to refer exclusively to the process of direct or co-combustion of biomass fuels (liquid, solid or gaseous) in an electricity generation plant fitted with CCS.

The widespread characterization of BECCS's and other biomass with capture and storage options as negative CO_2 emissions technologies is often based on the premise that biomass production is carbon neutral—that is CO_2 uptake by re-growing plants equals that in the harvested crop plus any otherwise emitted as a result of biomass production. Hence the capture and storage of at least some of the CO_2 emitted during the conversion phase leads to an overall negative CO_2 balance. Considering the full production cycle, from biomass crop growth and harvest to conversion and storage there is then "a net transfer of CO_2 from atmosphere into geological layers, providing in addition a non-fossil fuel source of energy" (Fuss et al., 2014). Even if there are net GHG emissions upstream of the energy conversion process, bioenergy with CCS is a negative CO_2 technology if the amount of carbon captured and stored more than offsets those upstream emissions in carbon-equivalent terms.

Despite the importance of BECCS in many energy technology scenarios designed to achieve tight stabilization levels, there are reasons to be concerned about whether it can be a viable commercial technology. The pace of carbon capture and storage (CCS) development in power generation, in general, has been slow in recent years. There are public acceptance issues associated with CCS as some see it as stalling a needed transition to renewable energy by providing an avenue for continued use of fossil fuels. Government programs supporting CCS demonstration projects have stalled and industry has backed away, leading to a closure of a majority of the CCS-related projects. As a result, BECCS technologies are currently still missing a crucial component – reliable and relatively cheap CCS. Finally, the use of biomass for energy (with or without CCS) has raised concern about land availability and possible impacts on food price, and this concern also may affect BECCS deployment..

We contribute to the existing literature by providing a review of the current knowledge about the necessary components for BECCS technology, its global potential in terms of energy production, related costs and likely constraints. We then use a global energy-economic model, the MIT Economic Projection and Policy Analysis (EPPA) model (Chen et al., 2016), to illustrate the challenges to capture the necessary details for assessing the long-term potential of the BECCS technology. Compared to previous studies (e.g., Kemper, 2015; Gough and Vaughan, 2015), we provide a consistent approach to evaluate all of the components of the technology, from growing biomass to CO_2 storage assessment. We also offer a discussion of the key issues that need to be considered in the integrated assessment models that produce long-term scenarios of the future development.

The paper is organized in the following way. In Section 2, we start with an overview of scenarios for the 21st century to illustrate the central role BECCS plays in many climate mitigation scenarios. In Section 3, we discuss the determinants of biomass production: land requirements and agricultural yields. Section 4 focuses on bioelectricity production and Section 5 presents carbon capture technologies and their costs. In Section 6, we focus on carbon transportation and storage. Section 7 summarizes the estimates of costs for bioenergy with biomass. In Section 8 we provide suggestions for necessary components of BECCS to represent in the long-term modeling systems and illustrate the issues by providing modeling results. Section 9 offers some concluding remarks.

2. NEED FOR NEGATIVE EMISSION TECHNOLOGY

BECCS technology plays a major role in the most stringent long-term mitigation pathways. Among scenarios in the Fifth Assessment Report (AR5) of Intergovernmental Panel on Climate Change (IPCC) consistent with limiting the global temperature increase below 2°C, BECCS technologies are present in 101 of 116 (Fuss et al., 2014; Clarke et al., 2014). The potential scale of BECCS development can be illustrated in at least a couple of ways. One metric is the amount of carbon captured stored. In one model comparison exercise (Kriegler et al., 2014) BECCS technologies capture from 7 to 21 gigatonnes (Gt) of CO_2 per year by 2100 (**Figure 1)**. Current global CO_2 emissions are in the order of 30-35 $GtCO_2$. Another metric is the scale of energy production from BECCS. In the 450 ppm scenarios logged in the IPCC AR5 Database, most end up with between 150 and 200 EJ of energy supplied by BECCS in 2100, similar to the levels of gas (137 EJ), coal (168 EJ) and oil (228 EJ) production in 2015. Thus, BECCS makes a substantial contribution to both emissions abated and to energy supplied. Most models envision BECCS entry into the global energy mix in the 2030-2040 timeframe, with a more substantial deployment after 2050.

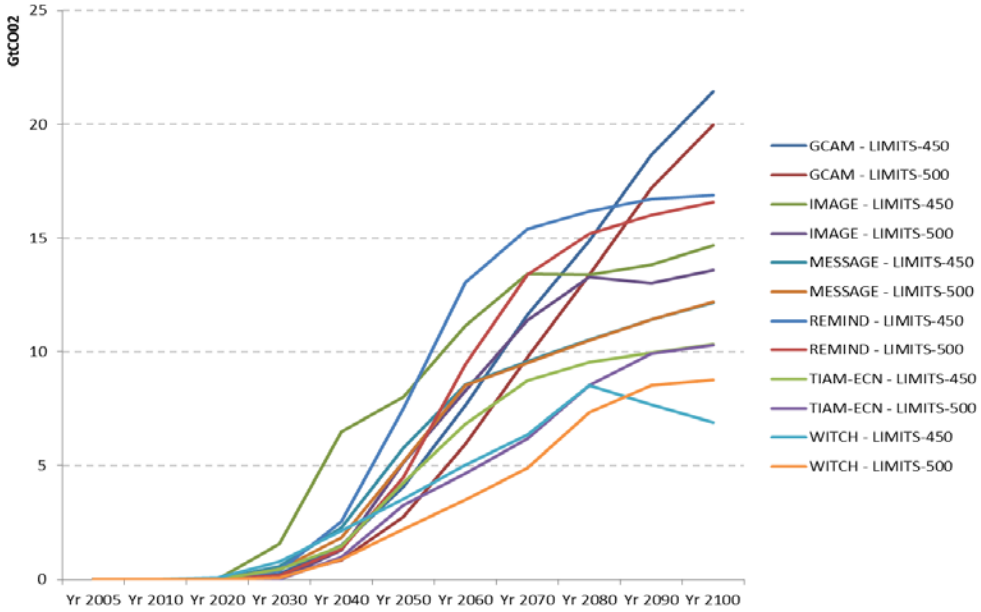


Figure 1. Carbon captured across models for the 450 and 500 ppm equivalent policies (Data source: LIMITS, Kriegler et al., 2014).

Many researchers consider the 2°C target as impossible to reach without a carbon sink, or negative emissions (provided by BECCS, afforestation, direct air capture, or other technologies). BECCS is regarded as the least uncertain and having the best potential among the negative emission generating technologies (McGlashan et al., 2012). A common theme in the mitigation literature is not only awareness about the necessity of negative emissions, but also the warnings about the huge uncertainties surrounding the availability and development of BECCS (Anderson and Peters, 2016). Indeed this technology is in its early stages of development and no commercial scale plant has been tested. Despite this, the feasibility of BECCS technologies is not the main concern and uncertainty source: biomass availability seems to be a much bigger issue as there are competing claims for this resource from food and feed production, timber production and bioenergy production. Moreover, the expansion of biomass production for energy use is a controversial subject discussed to a large extent in the land-use change (LUC) and indirect land-use change (ILUC) impacts literature (Faaj, 2015).

The second source of uncertainty is the CCS technology: even though many demonstration and pilot plant have been tested in the last decade, the number of commercial scale plants is still small. Even fewer projects inject the CO_2 in dedicated geological storage and do not use it for enhanced oil recovery (EOR). Hence, the uncertainties on the costs of CCS are still large as well as the one on the geological storage potential.

These large technical uncertainties weighing on the potential development of BECCS are met with uncertainties about the social acceptability of the technology. In Europe two CCS projects were abandoned due to a strong local opposition (the Barendrecht project in the Netherlands and the project in Jaenschwalde, Germany). BECCS also faces criticisms as this technology is sometimes viewed as a way of prolonging the use of fossil fuels and delaying mitigation actions (Smoker and Ernsting, 2012; Muratori et al., 2016). With a constant cumulative carbon budget, one can make an argument that a future carbon-negative technology reduces incentives to reduce emissions today because current emissions can be offset in the future by negative emissions. However, if negative emissions technologies do not achieve their full promise, it may then be impossible to meet stabilization goals if other near term reductions are delayed.

The range of BECCS deployment projected in stabilization scenarios implies the production of a large amount of biomass for energy use. Slade et al. (2014), in reviewing these studies, finds that they provide limited insights into the level of deployment that might be achievable for energy crops, cautioning the use of global estimates provided by them. Rose et al. (2014) conducted a comprehensive review of how well the agricultural sector is described in 15 Integrated Assessment Models (IAMs). The review revealed large diversity in the modelings approaches, large differences in regional biomass production potential explains the large differences in the estimates of biomass potential, which represent the upper limit of energy that can be obtained from biomass. Most of these modeling approaches rely on exogenous developed supply functions for bioenergy production with a maximum potential, rather than a full integration into a land use model that comprehensively treats all land uses. This may lead to inconsistencies between the biomass supply and other uses of land in the model.

Table 1. Estimates of bioenergy potential

	Imaclim	**DNE-21**	**Poles**	**Merge**	**Remind**	**Message**	**TIAM**
Bioenergy EJ	99 (75 woody biomass, 24 biomass for biofuels) (low)	40.2 (2000)	200 (2100)	188.64 (2050)	370 (2100) with 300 EJ/yr of energy crops	145	2050 technical potential: 240
	362 (302, 60) (high)	29.3 (2050)				technical potential: 160-270	2100 technical potential: 255

Source: Bibas and Méjean, 2014; Kitous et al., 2010; Marcucci, 2014; Luderer et al, 2013; Sterling and Gregg, 2013.

Slade et al (2014) review a large number of studies on biomass contribution to primary energy supply and found that the largest source of biomass are energy crops (between 22-1272 EJ), forestry (60-230 EJ), and biomass residues and wastes (25-221 EJ). While there is often hope that use of residues and waste could supply most of the biomass, thereby avoiding conflicts with food or carbon stores in natural ecosystems, the amount of residue and waste is limited as indicated by this review. Moreover, while residues and waste are often seen as “free”, there are often significant collection costs, and reliability of supply considerations that make dedicated supplies from bionenergy crops or forest preferable with large-scale bioenergy production (e.g. Winchester and Reilly, 2014). Potential biomass from crops and forests depend on the amount of land that can be devoted to bioenergy and the likely biomass yield on that land. We review these factors below, summarize estimates of biomass production potential, and discuss the concerns about sustainability of this production potential.

Land availability for Bioenergy

Existing studies find that land availability for energy crops is a key determinant of bioenergy potential (Rose et al, 2014; Azar et al., 2013). Most of these estimates assume that land available for bionenergy is a residual after food production needs are met (Slade et al., 2014). This requires a calculation of land needed for food crops based on an assessment of population and income growth, food demand, and future food crop yields. Relatively rapid yield growth and slow growth in food demand can lead to significant abandonment of land. However, others point out the yields may fall due to soil degradation or to local climate change (Campbell et al., 2008). Increase in demand for meat as incomes rises may put more pressure on pasture and grazing land, however, changing meat production practices toward greater intensification of may relieve some of that pressure. Economists generally see yields and intensification as at least in part driven by markets and pricing.

Figure 3 presents estimates of land availability for energy crops over the rest of the century. Given the residual nature of this estimate, it is not surprising that estimates for 2050 include a decrease from estimated present availability (to order 100 Mha from ~400 Mha) to a tripling (1200 Mha). However, there is quite range (~400-800 Mha) of estimates for the amount of land available now. A number of studies give a range of estimates, but often the ranges from different sources do not overlap. The most optimistic estimates (> 1000 Mha) are driven by a combination of high yield increases, low meat diets and high use of fertilizers to support high yields. For comparison purposes, Rosegrant and Misangi (2014) estimate that the actual area used for bioenergy production is around 30 million hectares, approximately 2% of the cultivated surface (Fischer et al., 2008).

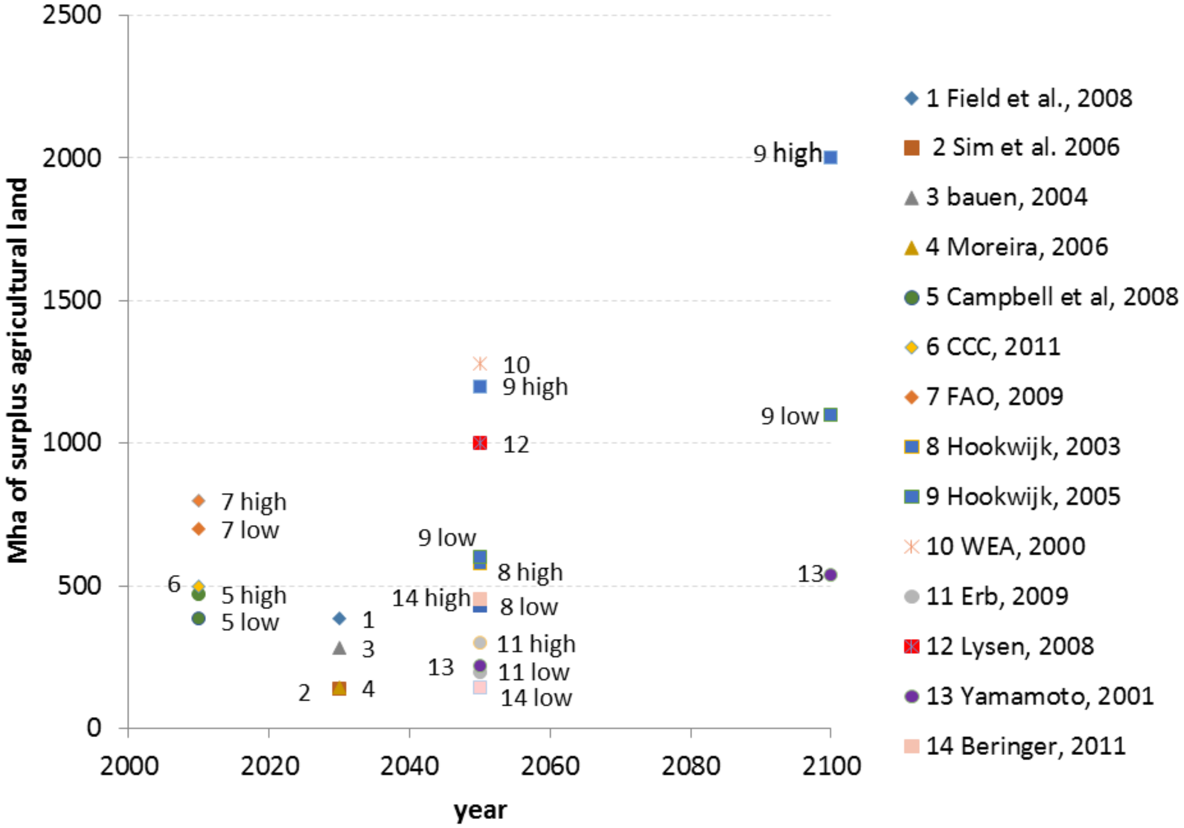


Figure 3. Land availability for energy crops estimates. Data Source: Compiled by the authors based on Slade et al., 2014, Campbell et al., 2008, CCC, 2011..

Bioenergy Yields

Assumptions on bioenergy crop yields are the other critical assumption going into bioenergy potential estimates. Most studies do not identify specific energy crop species and take a yield estimate for a crop/plant best-adapted for the climate and land type in each broad region (Slade et al., 2014). An issue that may arise with this assumption is that the residual lands assumed available for bioenergy may not be the most productive areas, so yield estimates can be overly optimistic. Harberl et al (2010) review various studies on bioenergy potential and find that yield assumptions for bioenergy crops vary from 3.5 to 32 oven dry ton/hectare (ODT/ha) (or 6.9 to 60 MJ/m^2). Slade et al. (2014) report values between 3 and 21 ODT/ha (up to 60 ODT/ha for one study) with most values in the 4 to 12 ODT/ha range. The larger values are usually found when the study consider high levels of management including irrigation (where needed) and fertilization with dedicated energy crops (e.g., short rotation willow, sugarcane). The lower values tend to be for food crop growing on rain-fed, non-fertilized lands (e.g., wheat in South America). Of course, different crops will be more or less suitable for different bioenergy conversion processes—woody crops may be most suitable for BECCS, while grain and sugar crops are more suitable for an conversion pathway the includes conversion to ethanol. Hence a single bioenergy potential estimate is likely inappropriate if one is considering multiple conversion pathways.

Johnston et al. (2009) analyze yield assumptions in a set of bio-energy studies and conclude that yields are often largely overestimated, sometimes by more than 100%. This overestimation has multiple causes: a lack of regional data, the yields are chosen on the optimistic end of the range by researchers, cultivating practices assumed are the best management practices, distinction between developed and developing countries are not made, water availability issues are not considered.

Historically many crop yields have been increasing, and many studies assume similar yield increases for bioenergy crops. These yield increases are generally attributed to a combination of technical change (crop breeding that increases yields) and gradual application of more intense management. These same factors could contribute to bioenergy crop yield increases. For example, Winchester and Reilly (2015) consider yield improvements between 0.75% and 1% per year between now and 2050, for both food crops and bioenergy crops, close to the value considered by FAO, 0.8% (FAO 2009) but lower than 1.45% to 3.5%) considered by Fischer (2009) for lignocellulosic feedstocks.. Paltsev et al. (2009) assumed yields for grass and woody crops of 6-16 ODT/ha in 2020, 11-18 ODT/ha in 2050, and 18-30 ODT/ha in 2100 (the range in each period was due to different assumption in different regions.) These are yield increases ranging from ~0.75 to 1.3% per year.

Bioenergy Potential Production

Slade et al (2014) provide a useful graphic that shows how yield and available area translate into bioenergy potential (**Figure 4).** The dashed lines map out potential assuming average yields of 5, 10, and 15 odt ha^{-1} and dots are a variety of studies in the review. To get bioenergy potential of over 1000 EJ you need land area approaching 4 Gha and yields above 15 odt. Total global cropland today is about 1.5 Gha, although there are about 3 Gha of pasture, 1.8 Gha of natural grassland, and 4 Gha of forests.

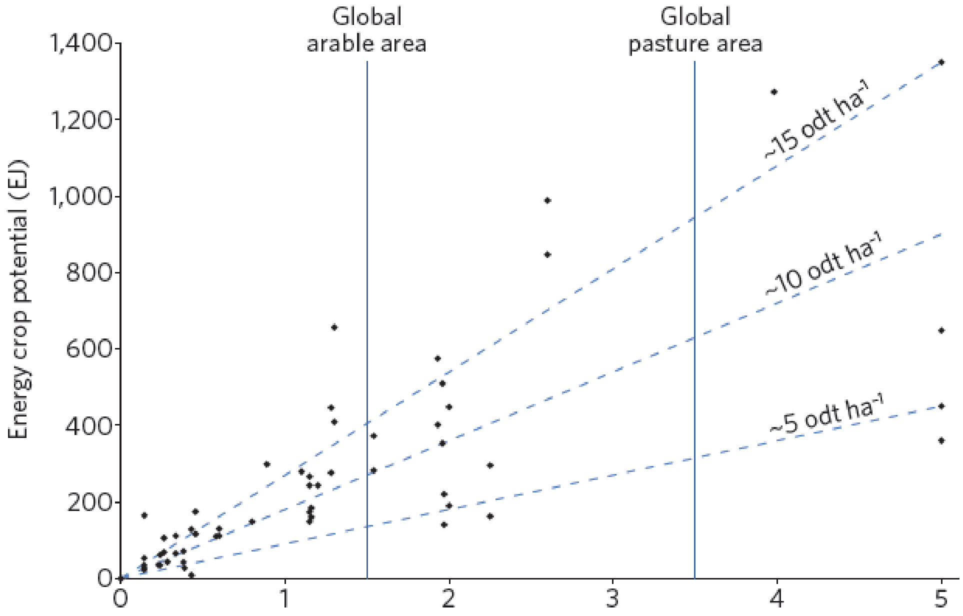


Figure 4. Estimated land area for energy crops (Gha) Source: Slade et al., 2014).

There are concerns that biomass production for energy use might result in higher food prices, additional GHG emissions, water shortages, or increased pollution (IPCC, 2014). One of the risks of increased energy crop production is that the need for more agricultural land leads to native forests clearing, thus releasing stored CO_2 into the atmosphere and threatening biodiversity. Bioenergy feedstocks can be divided in two categories: those requiring land use change (e.g., sugary, starchy, lignocellulosic and oily energy crops) and those that do not result in a substantial land use change (e.g., municipal solid waste, residues, and some wood). This is an important thing to consider in models when allowing land use change for bioenergy production purposes. One way of avoiding LUC issues when the model is not detailed enough to integrate a precise description of land, crops and GHG emissions related to LUCs, is to only consider land available for energy crop cultivation that has a LUC emission factor under a certain threshold.

Climate change, rising food demand and water pollution are three factors that could induce water scarcity and therefore limit the expansion of energy crops. There will indeed be a trade-off between high energy crop yields with irrigation or lower yields on rain-fed land. For example, Schlosser et al., (2014) found that for many developing nations water-demand increases due to population growth and economic activity have a strong effect on water stress that is amplified by climate change. By 2050, economic growth and population change alone can lead to an additional 1.8 billion people living in regions with at least moderate water stress. Of this additional 1.8 billion people, 80% are in developing countries. Uncertain regional climate change can play a secondary role to either exacerbate or dampen the increase in water stress due to socioeconomic growth.

3. BIOELECTRICITY PRODUCTION

Biomass burning is an ancient technology with a long history of development, however, the overall efficiency of converting biomass into power is still low compared to modern coal and natural gas plants. Bioelectricity is simply using biomass to generate heat (instead of coal, oil, gas, or nuclear) in a thermoelectric power plant. Much of what we know about other forms of thermoelectric generation transfers to bioelectricity. However, the properties of biomass generally lead to greater costs and lower energy conversion efficiencies. This is due to the relatively low energy density of biomass, its moisture content, impurities, and the level of pre-treatment required for firing or co-firing. Combining biomass with CCS poses similar challenges as using CCS on fossil fuels. Pilot plants of biomass with CCS as ethanol production or pulp and paper production with CCS exist but currently there are no biomass-fired power plants that have been coupled with CCS.

The economics of CCS generally assumes large-scale units and high thermal efficiency, while biomass-only fired plants are usually smaller and less efficient than coal or natural gas based plants. The bulkiness of biomass usually leads to complex logistics to maintain a consistent supply and thus high fuel handling costs. The issues of biomass availability as well as the risks of high temperature corrosion when using high temperature and pressure steam (a prerequisite for high efficiency) (Johnsson et al., 2012).

An option that can avoid some of these issues is co-firing existing fossil plants with biomass. Co-firing is possible with a large variety of biomass materials (waste, wood, etc.) and with the high thermal efficiency of a large coal fired plant the economics is often better than for the biomass-only plant. The main challenges to co-firing lie in the different properties of the fuels (calorific value, moisture content) (Gough and Upham, 2010). At low co-firing ratios, the impacts on plant performance are modest for most biomass materials. At higher co-firing ratios, concerns about impacts on plant performance increase, and this affects the flexibility of biomass fuel. In most cases burning biomass in a fossil-designed power plant would require some retrofits and added investment costs. Additionally, where co-firing has been used the rates of biomass are very low and vary significantly. They are typically in the 10-30% range defined on a percent heating value basis (Cuellar and Herzog, 2015). Some authors envision a potential for an increase in the co-firing rate in the future. For example, Koorneef et al. (2011) discuss an increase in the co-firing rate up to 50% by 2050. If the plant continues using a significant share of fossil fuel, especially coal, then the potential for negative emissions for the plant as a whole disappears.

Existing thermal power plants could be converted to 100% biomass. With such conversions, the range of fuels that can be fired is generally limited to high quality wood materials. The principal technical concerns are associated with the increased risks of excessive ash deposition, and high temperature corrosion of the boiler tubes due to a presence of potassium, chlorine, sulphur, and/or alkaline metals in biomass feedstock (Babcock, 2013; Berlanga and Ruiz, 2013). Cuellar and Herzog (2015) report that plants converted from coal to dedicated biomass drop about 10 percentage points in efficiency (from 40% to 30% efficiency on a higher heating value basis).

4. CARBON CAPTURE

In its Fifth Assessment Report, IPCC's Working Group III worked with more than 900 mitigation scenarios. This report estimates that, relative to when CCS technologies are used, mitigation costs increase by a factor of 2.5 (median value, the 25th -75th percentile range is 1.5-3.5 if these technologies are not available/used, in the RCP2.6 scenario, and by 1.5 in the RCP4.5 scenario (IPCC, 2014)). The same kind of results are obtained by other studies: in its 2012 report (ETP, 2012), the International Energy Agency considers that achieving the 2°C target without CCS is possible but will be 40% more expensive than if CCS is available (Bassi et al., 2015). Gasser et al. (2015) have a different approach than the aforementioned studies as they use an Earth System Model and not an Integrated Assessment Model to assess the tradeoff between conventional mitigation and negative emission in RCP2.6. They reach an even more unequivocal conclusion: even in the "best" cases, CO_2 capture is required at a significant level (>1GtC per year from now on) to meet the 2°C target.

Yet, these modeling exercises are mostly prospective ones aiming to find the best solution to reach a given climate target. The reality of CCS technology deployment is less promising than these studies assume (Herzog, 2015). Another issue regarding current CCS deployment is the projects localization: most of them (2/3) are located in North America, while CCS is needed globally.

Slow deployment behind is not the only challenge faced by CCS: it also faces various criticisms. CCS detractors accuse the technology of allowing a longer use of fossil fuels and of capturing subsidies that would be better employed to fund the research on renewable energies. On the other side, CCS supporters argue that it would help avoid the stranded assets effect and that unlike renewables; power plants with CCS can provide dispatchable electricity.

Deployment of CCS requires carbon policy. There is no incentive to employ CCS if CO_2 emissions are not penalized. The main reason why CCS is not used today (in the policy environment with no or very small carbon prices) is its cost and the loss of efficiency it involves. Adding CCS to a power plant decreases the plant efficiency and at the same time increases its costs since the whole CCS process requires additional energy and large capital investments. The cost of CCS is driven by the capture technology, which is the most costly CCS element. Several capture technologies are currently available and are discussed below.

Capture Technologies

Post-combustion: This technology is used for most of the current projects. In this process (see **Figure 5**), fuel is burnt to produce power (fuel is combusted in a boiler which generates steam for a steam turbine to generate electricity) and the CO_2 is separated from combustion exhaust gases. The separation can be done with an amine-based solvent. Amines are chemicals that clean the exhaust gases by chemically binding to CO_2 (and later amines are separated from CO_2 and recycled back for further use). CO_2 is compressed, cleaned from water vapor, and then can be transported by a pipeline. The amine process and compression process requires energy. Hence the energy consumption to separate the CO_2 from the rest of the exhaust gases is quite high (Leung et al., 2014; Rubin et al., 2015). There are other ways to carbon capture like membranes (a porous structures, which different gases permeate at different rates) and cryogenics (a systems that cools off the exhaust gases to their liquefaction points). These alternative routes currently impose substantial challenges (e.g., membrane process requires energy-consuming pressure difference for the gases to flow through the membrane; and when CO_2 is cooled in a cryogenic process it forms a solid dry ice), but research activities in these areas are promising for the further advancement of post-combustion capture.

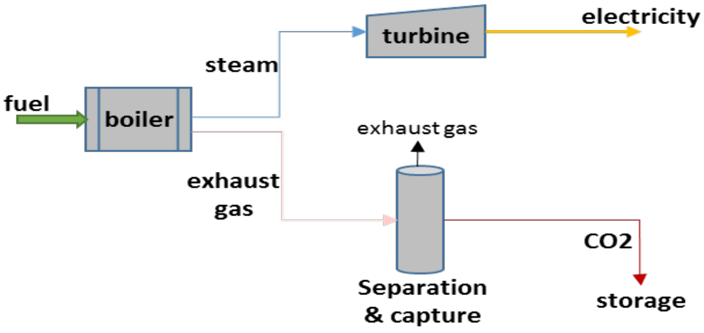


Figure 5. Post-Combustion

Pre-combustion: In this process, the fuel in gasifier is converted into a “syngas”, which is a gaseous mixture of CO and hydrogen (H_2). The syngas then goes through a water gas shift reaction in order to form a CO_2-H_2 mixture (see **Figure 6**). The high CO_2 concentration (~40%) in conjunction with high pressures (~40 atm) allows an easy CO_2 separation from hydrogen that can then be burnt without CO_2 production. The separated CO_2 is compressed and processed for transportation and storage. This technology is not used in existing power plants because the fuel pre-processing units are quite cumbersome and usually do not fit in pre-existing plants. This technology can, however, be used for new power plants, in particular for integrated gasification combined cycle (IGCC). So far, experience with recently built IGCC power plants (Edwardsport and Kemper in USA) resulted in high capital costs, which must be reduced significantly for pre-combustion capture to compete with pulverized coal power plants with post-combustion capture.

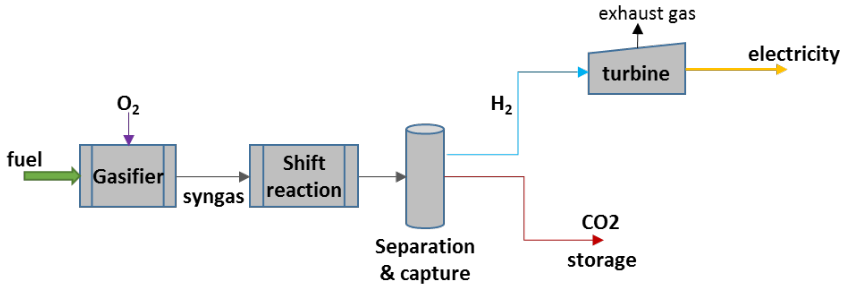


Figure 6. Pre-Combustion

Oxy-combustion: In this process, the fuel is burnt in oxygen rather than in air. The combustion exhaust gases are mainly water, CO_2, SO_2 and particulates and above all do not contain nitrogen (the major component in air that dilutes the flue gas and results in high costs for the separation step in the post-combustion case). After separation from SO_2 and particulates, the high concentrated CO_2 stream can be processed for storage (see **Figure 7**). While the O_2 production is energy-intensive and may add to the overall cost of the process, oxy-combustion has a potential to be cost-competitive. There is too little experience with this technology to date, but the elements of the oxy-combustion technology all exist and are used, for example, in the metal and glass melting industries.

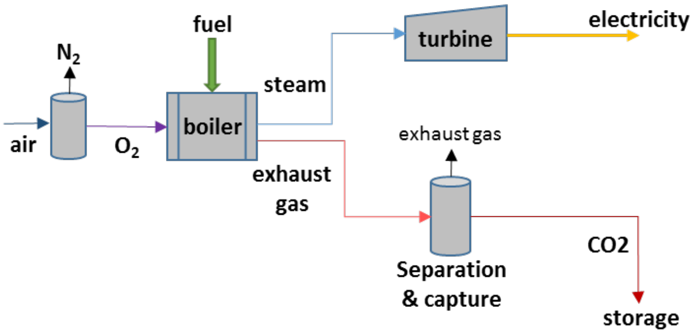


Figure 7. Oxy-Combustion

One promising route for oxy-combustion is the so called “Allam Cycle”, technology that is based on a new thermodynamic cycle that “uses a high-pressure CO_2 cycle that makes carbon capture part of the core power generation process” (NetPower, 2017). The pilot plant is under construction as of 2017. It uses a turbine that uses natural gas (methane), which is combusted with oxygen. The exhaust CO_2 gets recycled, so the working fluid inside the turbine is CO_2. The CO_2 recycling process increases the efficiency of the process and it compensates the cost penalty. If proven successful, this technology can provide a substantial change in CCS economics.

When referring to BECCS, the most discussed ideas in the literature (e.g., Koornneef et al., 2011) are co-firing biomass with coal in a “regular” power plant or to gasify the biomass in Bio-IGCC power plant (so using post and pre-combustion capture processes). The capture of CO_2 from biomass fired oxyfuel power plants has been sparsely studied. MIT (2007) and Rubin et al (2015) argue that despite the high promises of the IGCC designs, so far they failed to deliver. The high capital costs for the base IGCC plant far outweigh the relatively smaller cost savings related to carbon capture for the IGCC plant. Therefore, currently the post-combustion is the best route for BECCS.

5. CARBON TRANSPORTATION AND STORAGE

Transportation

Efficient large scale transportation of CO_2 involves pressurized pipelines both on-shore and off-shore. For large distances, oversea tanker transportation is the best solution but even though conceptual designs of such ships have been made, no CO_2 tanker ship exists at the time (IEAGHG, 2014). Transportation of CO_2 is not a technical issue as an efficient pipeline industry already exists (Bassi et al. 2015). EOR with CO_2 exists since the 1970s and in 2013 around 5000 km of pipeline transporting 60 Mt of CO_2 per year were installed around the globe (ETP, 2010). However, this infrastructure is clearly not sufficient to transport the large CO_2 amounts (up to 10 GtC/yr) that would need to be stored if CCS were to be deployed at large scale.

The issues regarding CO_2 transportation deployment are hence more regulatory and planning issues than technical ones as the scale of the needed investment is large: as a comparison the current gas pipeline infrastructure has a capacity of 1.5 GtC. The main issue regarding transportation is the fact that CO_2 sources are not necessarily located near storage capacities. A network of pipelines would hence be necessary to convey the gas in an efficient manner. A second issue is that many storages or at least admissible storages are located off-shore which implies greater transportation costs. As the technology is quite mature, the uncertainties on transportation costs are relatively small.

Storage

Of the whole CCS chain, large scale CO_2 storage and monitoring is the least developed stage. CO_2 can be stored underground in different kinds of storage reservoirs. Usually three types of storage are distinguished: active oil fields; depleted oil and gas fields; and deep saline aquifers. The principal characteristics needed for a geological formation to securely store CO_2 are the following (IEAGHG, 2014). The rock must be: porous; permeable (allow the flow of injected CO_2 into and through the formation); deep, at least 800 meters (2600 feet), the depth below which, due to high pressure and temperature conditions, CO_2 becomes a “supercritical fluid” that takes up much less space than a gas. In most cases, the formation should be covered by a layer of impermeable “cap rock” that will not allow the upward flow of the injected CO_2.

Once injected, the CO_2 will stay underground due to one or more mechanisms. The first and most obvious one is the classical geological trapping which can be structural or stratigraphic. In this case, the CO_2 is held in place by an impermeable cap rock. The second kind of trapping that can occur is the residual trapping: as the CO_2 migrates through the formation, at the tail of the CO_2 plume, the falling CO_2 concentration leads to the trapping of the gas in the tiny pores between rocks by the water capillary pressure. The third mechanism is the solubility trapping: the CO_2 dissolves in the saline water forming a dense solution that is negatively buoyant (i.e., migrates to the bottom of the reservoir). The last trapping mechanism (which is also the longest one to occur) is the mineral trapping: the CO_2 chemically combines with the reservoir rocks to form minerals. In a geological storage site, these mechanisms are usually combined which ensures that the CO_2 stays underground.

Given the diversity of reservoirs and storage mechanisms, it is not easy to determine the CO_2 storage capacity. First of all, as it is the case for fossil fuels or mineral availability estimates, CO_2 storage capacity are distinguished between resources and reserves (Bachu et al., 2007). Resources, which can be discovered or undiscovered, are the theoretical quantity of CO_2 storage estimated by geologists while reserves are the known and commercially quantity of CO_2 storage exploitable at a given time. Reserves hence fluctuate over time as technical, economic, environmental, societal and regulatory factors change while resources evolve as new discoveries are made.

Assessments of the geologic storage capacity of carbon dioxide in the current literature are incomplete and inconsistent, complicating efforts to assess the worldwide potential for CCS. Kearns et al (2017) developed a method for generating first-order estimates of storage capacity requiring minimal data to characterize a geologic formation. Their simplified method accounts for the majority of the variance in storage capacity found in more detailed studies conducted in the United States. They estimate that globally there are between 8,000 and 55,000 gigatonnes (Gt) of practically accessible geologic storage capacity for carbon dioxide. **Table 2** provides a summary of the results for the regions of the EPPA model. Additional details for the data are available in Kearns et al. (2017).

Table 2. Storage capacity estimates for regions defined by the EPPA model.

EPPA 6 Region		Estimated Storage Capacity [Gt]							
		Lower Estimate[a]				Upper Estimate[b]			
		Onshore	Offshore		Total[c]	Onshore	Offshore		Total[c]
			Technical[d]	Practical[e]			Technical[d]	Practical[e]	
AFR	Africa	1344	880	220	1563	9444	6185	1543	10986
ANZ	Australia & New Zealand	334	699	261	595	2349	4912	1835	4184
ASI	Dynamic Asia	36	115	83	119	251	806	583	834
BRA	Brazil	224	267	73	297	1572	1877	515	2087
CAN	Canada	206	514	112	318	1445	3610	790	2236
CHN	China	325	100	77	403	2286	704	544	2830
EUR	Europe (EU+)	161	492	141	302	1129	3459	991	2120
IDZ	Indonesia	96	166	67	163	672	1163	472	1144
IND	India	75	264	25	99	525	1853	172	697
JPN	Japan	4	24	5	8	26	171	34	59
KOR	Korea	0	9	3	3	0	62	24	24
LAM	Other Latin America	443	614	163	606	3111	4317	1145	4257
MES	Middle East	370	218	121	492	2603	1530	851	3454
MEX	Mexico	79	200	58	138	556	1408	411	967
REA	Other East Asia	161	377	110	272	1135	2651	776	1911
ROE	Other Eurasia	415	202	70	485	2916	1422	494	3410
RUS	Russia	1180	621	54	1234	8291	4361	382	8673
USA	United States	551	445	261	812	3872	3130	1836	5708
	Global	6003	6208	1907	7910	42181	43622	13399	55581

[a] 0.037 Gt per thouand cubic kilometers sedimentary basin

[b] 0.26 Gt per thousand cubic kilometers sedimentary basin

[c] Onshore and practically accessible offshore

[d] All offshore areas for which data is available

[e] Water depth less than 300 meters, within 200 miles of a major landmass, and outside of Arctic or Antarctic regions

Note: Totals in the table may not add up due to rounding. Source: Kearns et al. (2017). See Chen et al. (2016) for region definitions.

For most of the regions, our results discussed later indicate that storage capacity is not a limiting factor for CCS deployment through the rest of this century even if stringent emissions reductions are required.

6. ECONOMICS OF BIOENERGY WITH CCS

7.1 Cost of biomass

It is quite complex to agree on a biomass cost per region as the economics of biomass is strongly dependent upon the type of biomass considered and also upon the assumptions made for the yields, the fertilizer use, the land availability, the harvesting techniques and the transportation mode used to gather the biomass. Studies such as Perlack et al. (2011) derive supply curves for various scenarios for these parameters in the US. In this work, biomass cost is in the 40-60 $/oven-dry ton (ODT) range and decreases through time as yields are due to improve. IRENA (2012) estimates with similar prices (40-55 $/ODT) as well as (Kyle et al. 2011) who use for the GCAM models prices ranging between 35 and 65$/ODT (the price vary with the type of bioenergy crop). But in other regions the cost could be very different (lower yields, less land potential, more transportation, inferior harvesting techniques), as illustrated by the cost difference between industrial wood pellets in Europe (around 10 $/GJ) and in the US (around 4$/GJ) (IRENA, 2012). The assumptions regarding biomass cost are critical to discuss BECCS economical potential and they should be clearly exposed and the consistency of the biomass cost and the amount of biomass used in BECCS should be monitored closely (it is quite easy to forget that the cost parameters used were valid only for some part of the supply curve).

7.2 Cost of capture

CCS costs

As discussed in Section 5, CCS requires additional equipment (or different equipment in case of some technologies) and adds the cost penalty to traditional electricity production. A study by Rubin et al. (2015) compares increases in electricity cost when carbon capture system is added. For the post-combustion capture, use of capture on supercritical pulverized coal (PC) power plant increases the cost of produced electricity by 46-69%. The corresponding range for natural gas combined cycle (NGCC) plant is 27-61%. Oxy-combustion plants have 60-84% increase in electricity costs. For the pre-combustion capture, the increase for IGCC is relatively smaller (26-41% for a plant using bituminous coal), but the CCS-inclusive cost of electricity is higher due to the higher cost of gasification.

Hence, in addition to comparing the percentage increases in production costs, an informative metric is the dollar value of the CCS-inclusive cost of electricity production. Rubin et al (2015) report them in 2013 US dollars as follows. For the post combustion the costs are: PC – 94-130 \$/MWh (representative value is 113 \$/MWh); NGCC – 63-115 \$/MWh (representative value is 92 \$/MWh). Oxy-combustion costs are 91-121 \$/MWh (representative value is 110 \$/MWh). For the pre-combustion from IGCC using bituminous coal, the costs are 111-130 \$/MWh (representative value is 120 \$/MWh).

The current CCS cost estimates have a wide range (Rubin et al., 2015; Bassi et al., 2015; IEAGHG, 2015; IPCC, 2014, NETL, 2015). The hope that the uncertainty ranges on the costs narrow down and that the general level of the cost goes down is still high as most of the technologies used in CCS are still in the development or demonstration phase. Yet, the small number of the current CCS demonstration and large-scale projects would not enable the technologies to evolve rapidly. Substantial improvements in costs and performance of CCS are needed. One way or another, technology costs need to be reduced to make CCS more economic. CCS deployment is quite uncertain as it mainly relies on political decisions. If a carbon price/market were to be implemented, then CCS may be profitable. Hence a question that many researchers try to answer is: what CO_2 price level would allow CCS to emerge, or put differently, what is the cost of avoiding one ton of CO_2 emissions with CCS? **Table 3** provides carbon price ranges from different studies for different technologies. Mostly, the ranges are from \$50/tCO2 to about \$100/tCO_2.

Table 3. Overview of the CO_2 prices that make different CCS technologies economic

Abatement cost (\$2014/tCO_2)	Rubin et al. (2015)	Bassi et al. (2015)	IEAGHG (2015)	NETL (2015)
CCS coal	45-70	47-122	49	79
Coal Oxy-Combustion	45-73		81	
IGCC	52-112		126-133	86
CCS gas	58-121	87-167		

MIT (2011) notes that carbon prices provides some information, but cannot be used in isolation for determining the competitiveness of CCS technologies because the carbon price needed to make CCS profitable depends on the generation mix against which the generation with CCS is competing. The lack of CCS projects is partly due to the uncertainty about sustained climate policy. In addition, except for the

USA, where CCS is integrated with EOR, CO_2 avoidance is in most cases the only purpose of CCS. High capital requirement for CCS, in comparison to wind and solar technologies, is another reason why CCS has received less attention from developers and investors than these technologies. At the current levels of deployment of intermittent renewables, they do not pose substantial integration challenges, so the potential for CCS to be a low-cost dispatcheable technology is presently under-appreciated.

7.3 Cost of carbon dioxide transportation

Ruben et al (2015) review the studies that have examined the cost of CO_2 transportation. They report that for distance of 250 kilometers (km) the cost of CO_2 transportation in onshore pipelines of a capacity of 10 $MtCO_2$/year is in the range of 2.2-3.7 $/$tCO_2$. The corresponding number for offshore pipelines is 3.4-4.8 $/$tCO_2$. Onshore pipeline transportation costs are somewhat proportional with the distance because most of the cost is driven by investment costs in the pipeline infrastructure (which is proportional to the pipeline length). For the offshore pipelines, ETP (2011) reports substantial economy of scale with total length of the offshore pipeline. ETP (2011) also reports the CO_2 transportation costs by ship, which is about $15/$tCO_2$ for a distance of 500 km. In the case of CO_2 transportation by ship, the cost is less correlated with the distance the ship travels to transport the CO_2 to the storage site due to a dominance of the investment costs in ships and port facilities.

7.4 Cost of storage

Rubin et al (2015) discuss the variability of the costs of storage due to heterogeneity of storage reservoirs. The data on storage costs are quite sparse. In addition, it can be affected by regulations, especially related to requirements for monitoring, long-term stewardship, and liability. The onshore storage costs are estimated at 1-7 $/$tCO_2$ for the low range of the estimates and at 12-18 $/$tCO_2$ for the high range of the estimates. While CO_2 used for EOR earns some credits (provides some related revenue rather than costs for storage), typically the cost of CO_2 transport and storage is estimated to be around 10 $/$tCO_2$ for a large-scale CCS deployment (Hamilton, 2009; NETL, 2013; Rubin et al., 2015).

7. MODELING OF BIOENERGY WITH CCS in EPPA

8.1. The EPPA Model

The Economic Projection and Policy Analysis (EPPA) model is the part of the MIT Integrated Global Systems Model (IGSM) that represents the human systems (Paltsev et al., 2005; Chen et al., 2016). The EPPA model is a recursive-dynamic, multi-regional general equilibrium model of the world economy, which is built on the GTAP dataset and additional data for the GHG, urban gas emissions, taxes and details of selected economic sectors. Provision is made for analysis of uncertainty in key human influences, such as the growth of population and economic activity and the pace and direction of technical advances. It is designed to develop projections of economic growth and anthropogenic emissions of greenhouse related gases and aerosols.

The model projects economic variables (GDP, energy use, sectoral output, consumption, etc.) and emissions of greenhouse gases (CO_2, CH_4, N_2O, HFCs, PFCs and SF_6) and other air pollutants (CO, VOC, NOx, SO_2, NH_3, black carbon, and organic carbon) from combustion of carbon-based fuels, industrial processes, waste handling, and agricultural activities. Different versions of the model have also been formulated for targeted studies to provide consistent treatment of feedbacks of climate change on the economy, such as effects on agriculture, forestry, bio-fuels and ecosystems and interactions with urban air pollution and its health effects – see Chen et al (2017) for a discussion of different versions of the EPPA model.

In the EPPA model, production technologies are described using nested constant-elasticity of substitution (CES) functions (see Paltsev et al., 2005; Chen et al., 2016 for a detailed structures of production and consumption sectors of the EPPA model). Some technologies produce perfect substitutes for existing products (e.g., electricity), then their penetration is controlled by a technology specific factor (Morris et al., 2014).

8.2 The Cost of Bioenergy Generation Technologies

As described in Paltsev et al. (2005), for the EPPA model the relative costs of all technologies in the base year of the model need to be defined. This is done by using so called "markups", or the cost of a technology relative to the cost of the conventional technology (e.g., coal) against which it competes in the base year of the model. A markup of 1.5 therefore means that the technology is 50% more expensive in the base year than the conventional technology. Over time, the relative costs will change endogenously as the costs of inputs change and substitution of inputs occurs. The baseyear markups are determined based on a levelized cost of electricity (LCOE) approach, which is calculated using the equation (1) below.

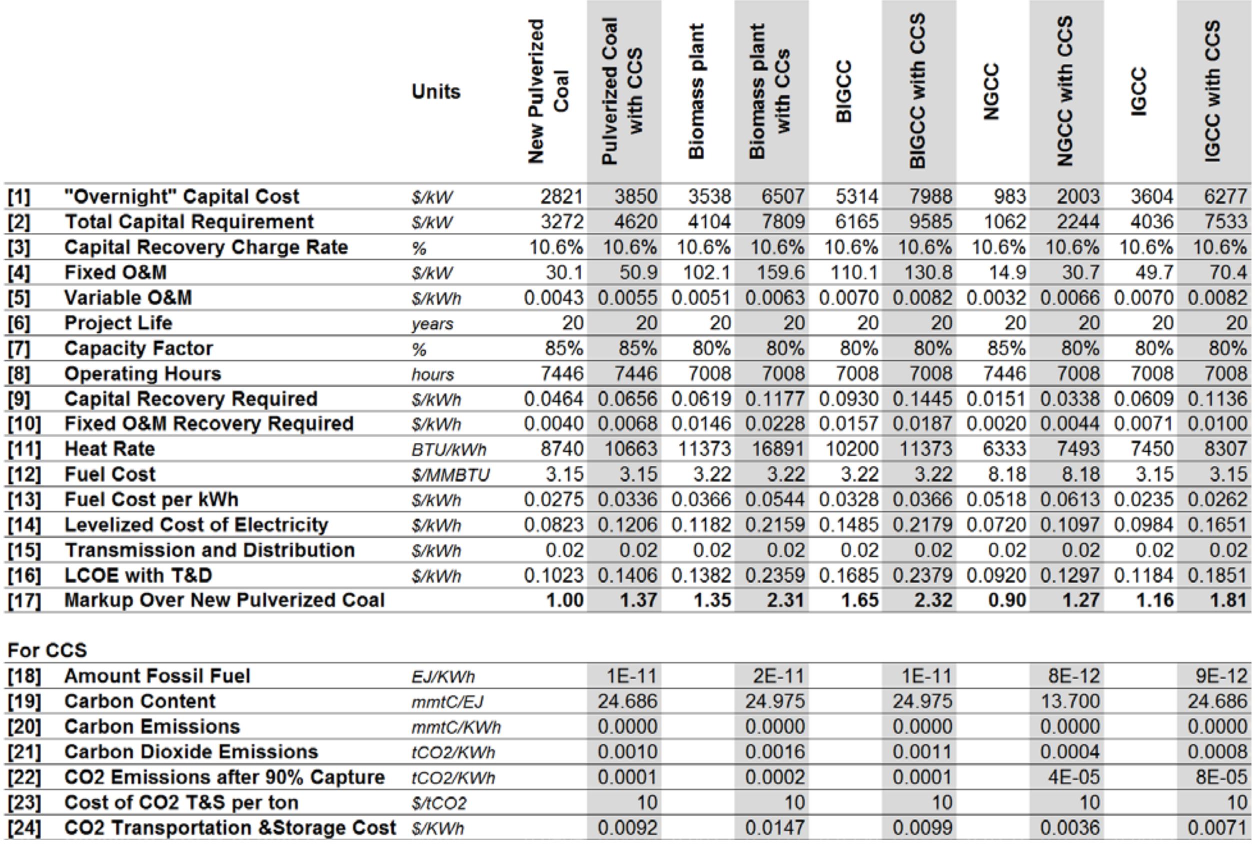
$$LCOE = \frac{TCR * CRC}{OH} + \frac{FOM}{OH} + VOM + FC + CTS \qquad (1)$$

In this formula, *TCR* is total capital requirement (overnight capital costs + construction schedule cost), *CRC* is capital recovery charge: $CRC = \frac{r}{1-(1+r)^{-n}}$; r is the discount rate, n is the project life (20 years); *OH* is operating hours (capacity factor * hours in year); *FOM* is the cost of the inputs that do not depend on the level of production (fixed O&M); *VOM* is variable O&M per kWh; *FC* is fuel cost per kWh: $/BTU * Heat Rate (BTU/kWh); CTS is the cost of transportation and storage of captured CO_2 per kWh (for CCS technologies).

The LCOE and markups used in the study are shown in **Table 4** for the bioenergy generation technologies and the main technologies against which it competes. The markups for other technologies in the EPPA model are described in Chen et al (2016). The data sources used for the bioenergy generation technologies include EIA (2015), Cuellar and Herzog (2015), and Bibas et al. (2014). For the overnight capital for biomass with CCS, we start with the overnight cost for Biomass (from EIA, 2015) then add an additional capital cost for CCS ($888 in 2014$, from Cuellar & Herzog, 2015), and then adjust for the decrease in efficiency from adding CCS, which we assume drops from 30% to 20.2%. This assumption is based on applying the 9.8% efficiency penalty Rubin et al. (2015) found for adding CCS to pulverized coal and the 30% biomass efficiency from Cuellar and Herzog (2015).

Efficiencies are converted to heat rates by dividing the number of BTUs in one kWh of electricity (3412) by the efficiency. Fixed costs and variables costs come from EIA (2015) for biomass and from Cuellar and Herzog (2015) for biomass with CCS. The overnight cost and fixed costs for BIGCC with CCS are from Bibas and Mejean (2014), scaled by the ratio between EIA's costs for IGCC with CCS and those from Bibas and Mejean, which is 2.27 for overnight costs and 1.55 for fixed costs. The overnight cost and fixed costs for BIGCC are then the costs for BIGCC with CCS minus the difference in cost between IGCC with CCS and IGCC (from EIA, 2015). Variable costs for BIGCC are set equal to those for IGCC and for BIGCC with CCS are set equal to variables costs IGCC with CCS. The heat rate for BIGCC with CCS is from the 30% efficiency in Bibas and Mejean (2014), while the heat rate for BIGCC is equal to the heat rate of BIGCC with CCS divided by the ratio between IGCC with CCS and IGCC (1.12). The cost of transportation and storage of captured CO_2 is assumed to be $10/t$CO_2$, consistent with Hamilton (2009), NETL (2013) and Rubin et al (2015). The CO_2 transportation and storage cost per kWh is added to the LCOE.

Table 4. LCOE and Markups of Bioenergy Generation and Main Competing Technologies in EPPA (in 2007$)



		Units	New Pulverized Coal	Pulverized Coal with CCS	Biomass plant	Biomass plant with CCs	BIGCC	BIGCC with CCS	NGCC	NGCC with CCS	IGCC	IGCC with CCS
[1]	"Overnight" Capital Cost	*$/kW*	2821	3850	3538	6507	5314	7988	983	2003	3604	6277
[2]	Total Capital Requirement	*$/kW*	3272	4620	4104	7809	6165	9585	1062	2244	4036	7533
[3]	Capital Recovery Charge Rate	*%*	10.6%	10.6%	10.6%	10.6%	10.6%	10.6%	10.6%	10.6%	10.6%	10.6%
[4]	Fixed O&M	*$/kW*	30.1	50.9	102.1	159.6	110.1	130.8	14.9	30.7	49.7	70.4
[5]	Variable O&M	*$/kWh*	0.0043	0.0055	0.0051	0.0063	0.0070	0.0082	0.0032	0.0066	0.0070	0.0082
[6]	Project Life	*years*	20	20	20	20	20	20	20	20	20	20
[7]	Capacity Factor	*%*	85%	85%	80%	80%	80%	80%	85%	80%	80%	80%
[8]	Operating Hours	*hours*	7446	7446	7008	7008	7008	7008	7446	7008	7008	7008
[9]	Capital Recovery Required	*$/kWh*	0.0464	0.0656	0.0619	0.1177	0.0930	0.1445	0.0151	0.0338	0.0609	0.1136
[10]	Fixed O&M Recovery Required	*$/kWh*	0.0040	0.0068	0.0146	0.0228	0.0157	0.0187	0.0020	0.0044	0.0071	0.0100
[11]	Heat Rate	*BTU/kWh*	8740	10663	11373	16891	10200	11373	6333	7493	7450	8307
[12]	Fuel Cost	*$/MMBTU*	3.15	3.15	3.22	3.22	3.22	3.22	8.18	8.18	3.15	3.15
[13]	Fuel Cost per kWh	*$/kWh*	0.0275	0.0336	0.0366	0.0544	0.0328	0.0366	0.0518	0.0613	0.0235	0.0262
[14]	Levelized Cost of Electricity	*$/kWh*	0.0823	0.1206	0.1182	0.2159	0.1485	0.2179	0.0720	0.1097	0.0984	0.1651
[15]	Transmission and Distribution	*$/kWh*	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
[16]	LCOE with T&D	*$/kWh*	0.1023	0.1406	0.1382	0.2359	0.1685	0.2379	0.0920	0.1297	0.1184	0.1851
[17]	Markup Over New Pulverized Coal		**1.00**	**1.37**	**1.35**	**2.31**	**1.65**	**2.32**	**0.90**	**1.27**	**1.16**	**1.81**
For CCS												
[18]	Amount Fossil Fuel	*EJ/KWh*		1E-11		2E-11		1E-11		8E-12		9E-12
[19]	Carbon Content	*mmtC/EJ*		24.686		24.975		24.975		13.700		24.686
[20]	Carbon Emissions	*mmtC/KWh*		0.0000		0.0000		0.0000		0.0000		0.0000
[21]	Carbon Dioxide Emissions	*tCO2/KWh*		0.0010		0.0016		0.0011		0.0004		0.0008
[22]	CO2 Emissions after 90% Capture	*tCO2/KWh*		0.0001		0.0002		0.0001		4E-05		8E-05
[23]	Cost of CO2 T&S per ton	*$/tCO2*		10		10		10		10		10
[24]	CO2 Transportation &Storage Cost	*$/KWh*		0.0092		0.0147		0.0099		0.0036		0.0071

The fuel costs for the bioenergy technologies are based on the baseyear feedstock costs in the EPPA model. These feedstock costs vary by region as the biomass crop yields vary by regions (see Section 8.3). Table 5 includes the fuel cost for the U.S. as an example. The base year fuel costs for other EPPA regions are given in **Table 5**. For this study, no other costs are assumed to vary by region. These data result in the LCOEs found in line 16 (which includes transmission and distribution costs) and the markups in line 17 of Table 4, which are used in the EPPA model.

Table 5. Baseyear biomass fuel costs in the EPPA model (in 2007$)

EPPA Region	Biomass Fuel Cost $/MMBTU
AFR	2.85
ANZ	2.91
ASI	3.25
BRA	2.67
CAN	2.87
CHN	3.99
EUR	3.19
IDZ	3.25
IND	6.07
JPN	10.86
KOR	3.25
LAM	2.85
MES	4.62
MEX	3.74
REA	3.73
ROE	3.43
RUS	2.83
USA	3.22

8.3 Modeling of biomass production

In this study, we introduce a dedicated bioenergy crop representation for the use in bioelectricity (with and without CCS). Our parametrization of feedstock costs assumes that a representative energy crop is grown in each region and follows Winchester and Reilly (2015). Based on a literature review of switchgrass and *Miscanthus* yields in the US, these authors assign a base energy grass yield of 16.8 oven dry tons per hectare (ODT/ha) in this region. Base yields for other regions are calculated by multiplying the US yield by net primary productivity for C3-C4 grasslands estimated by the Terrestrial Ecosystem Model (TEM, see http://ecosystems.mbl.edu/tem/) divided by net primary productivity for the same grasslands in the US.

As several yield estimates surveyed by Winchester and Reilly (2015) involved field trials and we wish to evaluate large-scale bioelectricity production, we classify energy crop yields used by these authors as a "high yield" scenario and consider two alternative cases with lower yields. Thomson et al. (2009) estimate that on all continental US cropland, the average switchgrass yield of 5.6 ODT/ha. Mann and Spath (1997) estimate yields between 9 and 11 ODT/ha in most part of the US, while Perlack et al. (2011) use yields for energy crops around 5-7 ODT/ha (with low scenarios around 2-3 ODT/ha and high ones at 11-12 ODT/ha for the US). Informed by these estimates, we multiply the base yields estimated by Winchester and Reilly (2015) by one-half in a ‘medium yield’ case and one-third in a ‘low yield’ case.

For each case, base yields are combined with cropland rents to estimate land costs per ODT. Production cost for other inputs required for delivered biomass – including growing, storage and transportation – are assigned using estimates from Duffy (2008). The production structure for the representative energy crop is shown in **Figure 8**. The nesting structure facilitates endogenous yield responses to changes in land prices by allowing substitution between land and the energy materials composite (e.g., fertilizer) and between the resource-intensive bundle and the capital-labor aggregate. The model also includes compounding exogenous yield improvements of 1% per year for all crops (including food crops), which is applied to the base yields in each case and is consistent with estimates by Ray et al. (2013).

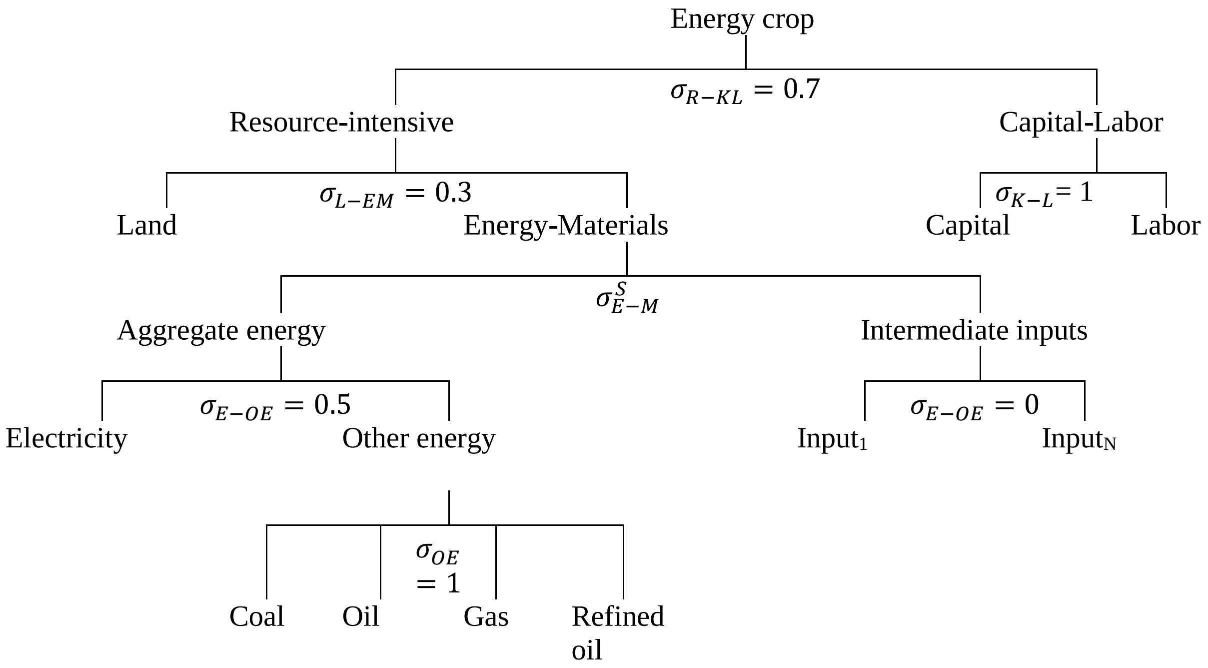


Figure 8. Nesting structure for production of energy crop in the EPPA model.

8.4 Modeling of electricity from biomass

Electricity from biomass produces a perfect substitute for other technologies that do not require additional requirements for integration to the grid. We assume that it can be used for baseload and peaking generation. The rate of penetration of the bioelectric technology is determined by the technology specific factor that is described in Morris et al. (2014). **Figure 9** illustrates the nesting structure for the production of bioelectricity. Adding CCS to bioelectricity leads to a technology with negative emissions, with growing biomass crops scrubbing CO_2 from the atmosphere, which is then stored instead of released.

The technology represents electricity production using the energy crop, capital and labor inputs. The input shares are parameterized based on information in Table 4 and Table 5. The red-colored portion in Figure 9 represents the addition of the CCS component. With CCS, the technology generates emission allowances (and "earns revenue") by storing carbon dioxide released in the process of biomass combustion. The amount of CO_2 is calculated based on the fuel input amount. In this study, we represent four biomass based generation technologies: Biomass (based on pulverized technology), Biomass Integrated Gasification Combined Cycle (BIGCC), Biomass-based with CCS, and BIGCC with CCS. The nesting structure for all technologies is depicted in Figure 9, while input shares and markups are based on information provided in Tables 4 and 5.

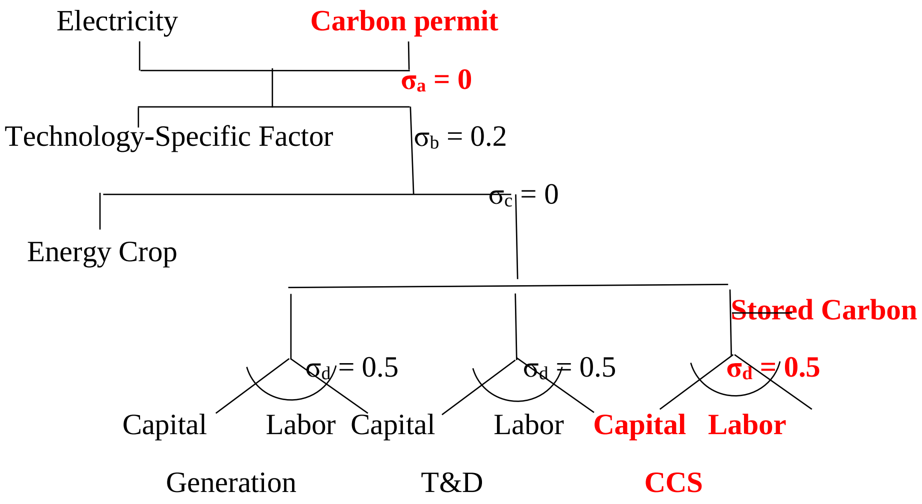


Figure 9. Nesting structure of bioenergy generation with CCS (BECCS). Red colored portion of the diagram represents the CCS addition.

8.5 Scenarios

In this study we assess the impact of the introduction of BECCS technology on the de-carbonization pathways under climate constraints. We also evaluate the sensitivity of the results to various uncertainties, such as biomass availability, biomass feedstock yield variations, and variations in the costs of bioelectricity production, CCS and c renewables (which are an alternative way to generate low-carbon energy). **Table 6** lists the core scenarios considered in our analysis.

Table 6. Main Scenarios

Policy	Description
Reference	No Climate Policy
Policy	2°C above Pre-Industrial by 2100 with the reference assumptions about the costs of technologies
Policy- Optimistic Bio CCS Costs	2°C above Pre-Industrial by 2100 with low costs for bioelectricty production and CCS, and high biomass yields
Policy- Pessimistic Bio CCS Costs	2°C above Pre-Industrial by 2100 with high costs for bioelectricty production and CCS, and low biomass yields
Policy- No Bio CCS	2°C above Pre-Industrial by 2100 with no biomass with CCS available

The 2°C scenarios are modelled by applying an economy-wide carbon price in all regions of the world starting in 2030 (after the expiration of the current submissions to the Paris Agreement). The cumulative GHG emissions that are allowed to reach the 2°C target are based on Sokolov et al. (2017), and the carbon is chosen endogenously in each scenario to meet these targets. The optimistic and pessimistic bioenergy and CCS costs are based in IEA (2015) and expert judgement.

8.6 Results

Macro-indicators

In our scenarios, the carbon price leads to changes throughout the economy. **Figures 10-12** present the carbon intensity of energy, the carbon intensity of GDP, and the energy intensity of GDP.

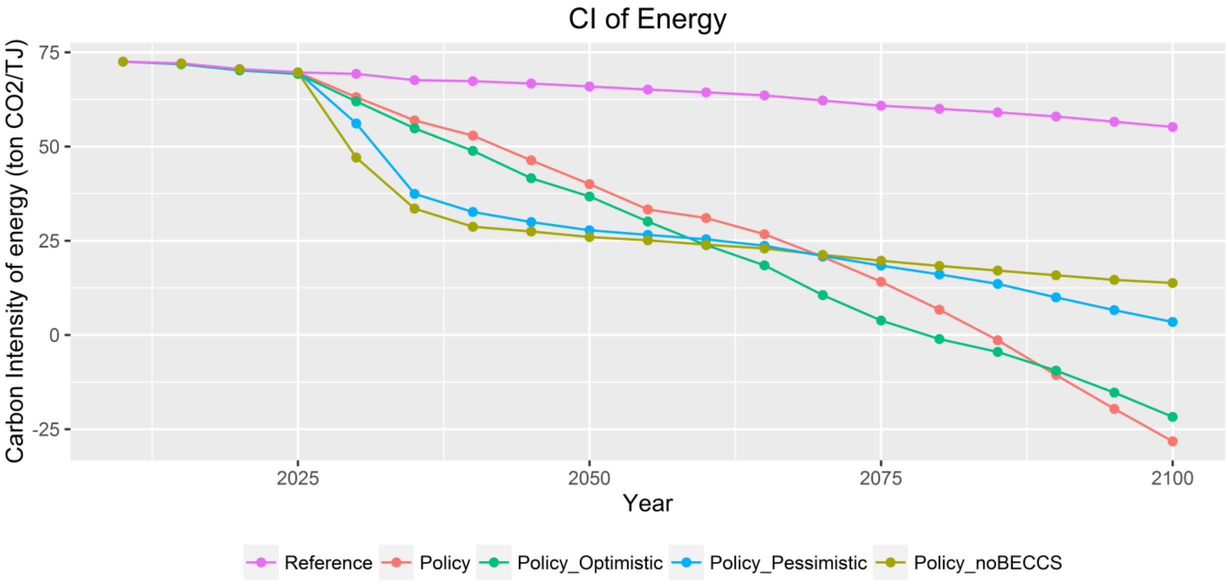


Figure 10. Carbon intensity of energy

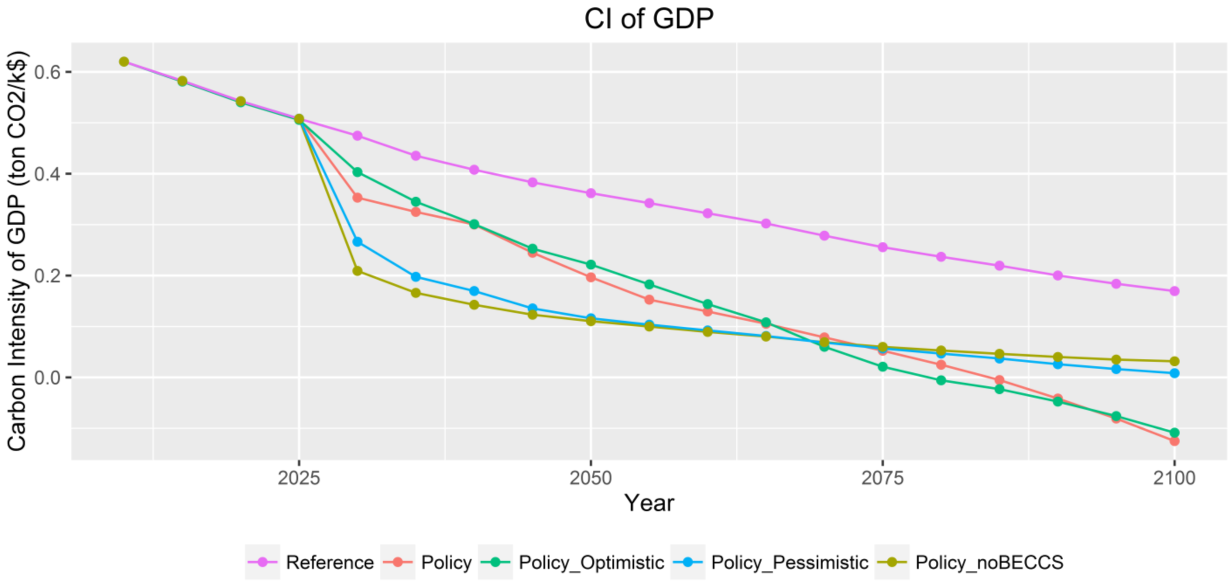


Figure 11. Carbon intensity of GDP

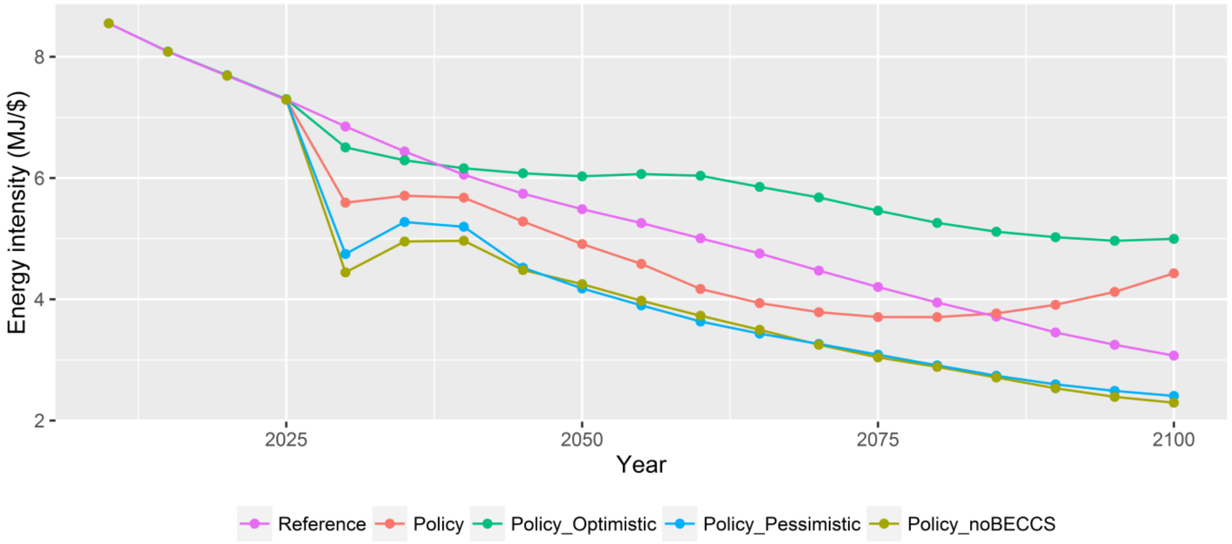


Figure 12. Energy intensity of GDP

In order to comply with the carbon constraint (or rather because of the increasing price of CO_2), the carbon intensity decreases sharply for the policy cases and become negative at the end of the time horizon in some scenarios due to bio-CO_2 storage. On the contrary, in the *Policy_Pessimistic* and the *noBECCS* scenarios, the energy intensity of the economy decreases sharply to comply with the carbon constraint, and there is a different adaptation strategy to high CO_2 prices. When BECCS are relatively inexpensive, at the end of the century the energy intensity of GDP is substantially higher than in other scenarios, reflecting the increased overall use of energy.

CO_2 emissions and storage

Figure 13 presents carbon emissions for various scenarios. For the policy runs where BECCS are available, emissions decrease rapidly and become negative around 2085, while for the *NoBECCS* case emissions have to stay positive because a negative emission technology is not avaiable. In this scenario and in the *Policy_Pessimistic* case, emissions have to be reduced dramatically in the first part of the century. An availability of BECCS allows for a delay in the near-term reductions in emissions.

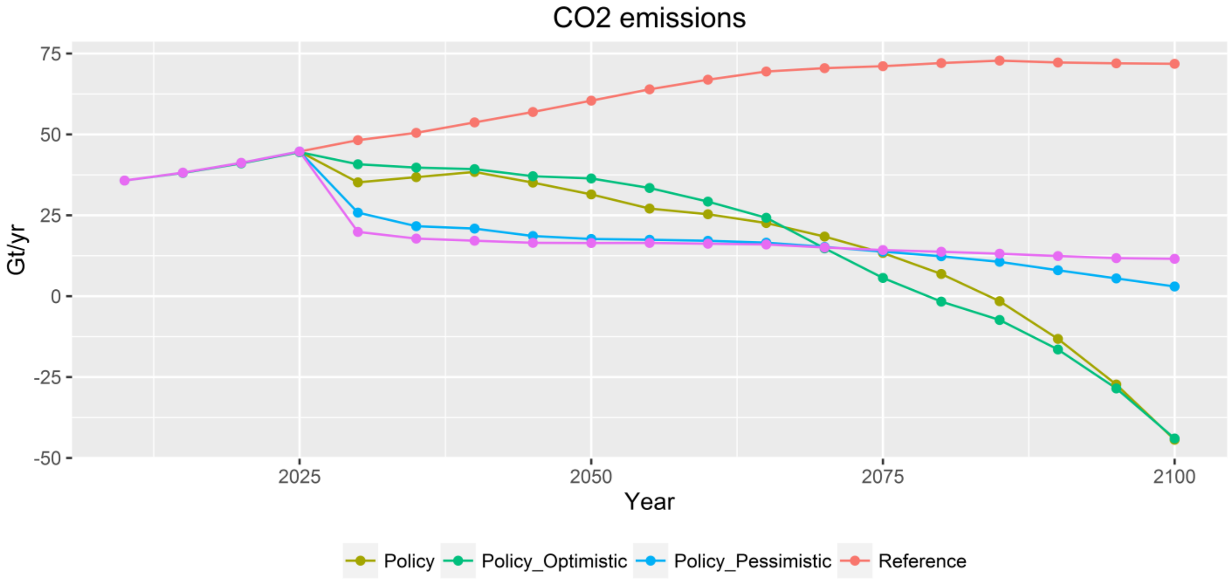


Figure 13. CO_2 emissions for different scenarios

Figure 14 provides the results for the amount of the annually stored carbon (in Gt of CO_2) by fossil fuel CCS (the figure combines the results for coal with CCS and natural gas with CCS) and BioCCS (the results are combined for Biomass with CCS and BIGCC with CCS). The use of CCS and the resulting stored carbon increase notably through the century for the *Policy* and *Policy_Optimistic* cases. Except for the *Policy_Optimistic* scenario, CCS is adopted first on the fossil-fuel power technologies, and then, at the end of the century, BECCS becomes the dominant technology.

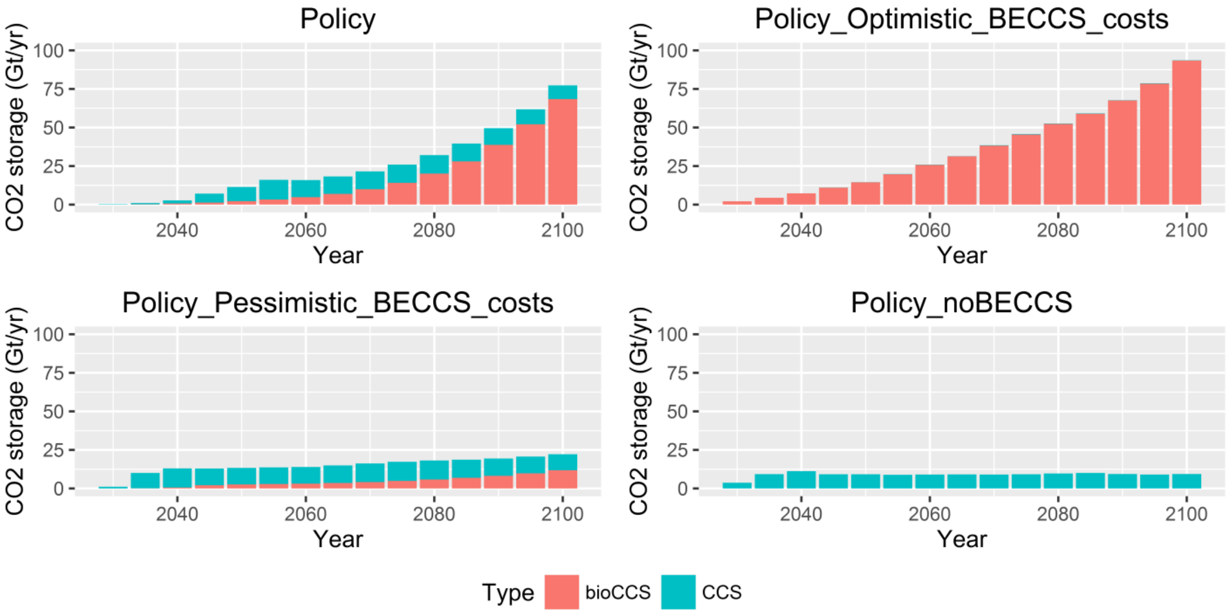


Figure 14. CO_2 stored by type of technology

The results show that at the end of the time period, between 10 and 100 Gt of CO_2 would be stored every year, which represent a very sizeable amount given that the current global anthropogenic CO_2 emissions are around 30 Gt/yr.

Electricity generation

Global electricity production by generation type in the *Reference* scenario is presented in **Figure 15**. It shows a substantial increase from about 20 PWh in 2005 to about 70 PWh in 2100. No CCS technologies are present in the *Reference* scenario because there is no policy mechanism that makes them economic. In the policy scenarios, the use of fossil fuels is penalized and provides an incentive for CCS. As represented in **Figure 16**, policy scenarios result in a substantial demand response and energy efficiency improvements. Electricity production by BECCS increases sharply after 2050 (in the *Policy* and *Policy_Optimistic* cases), when more and more negative CO_2 emissions are needed.

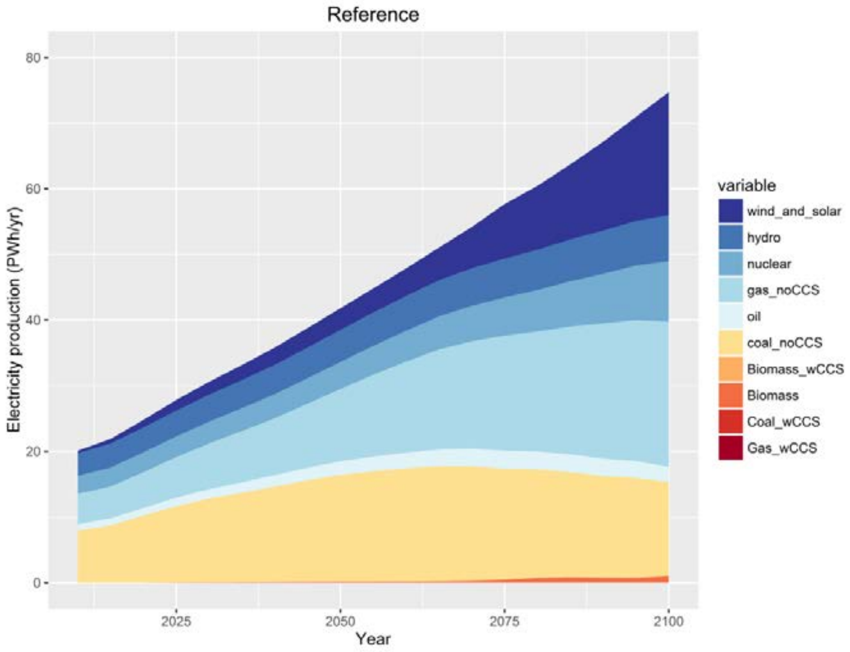


Figure 15. Electricity Production by Type in the Reference case

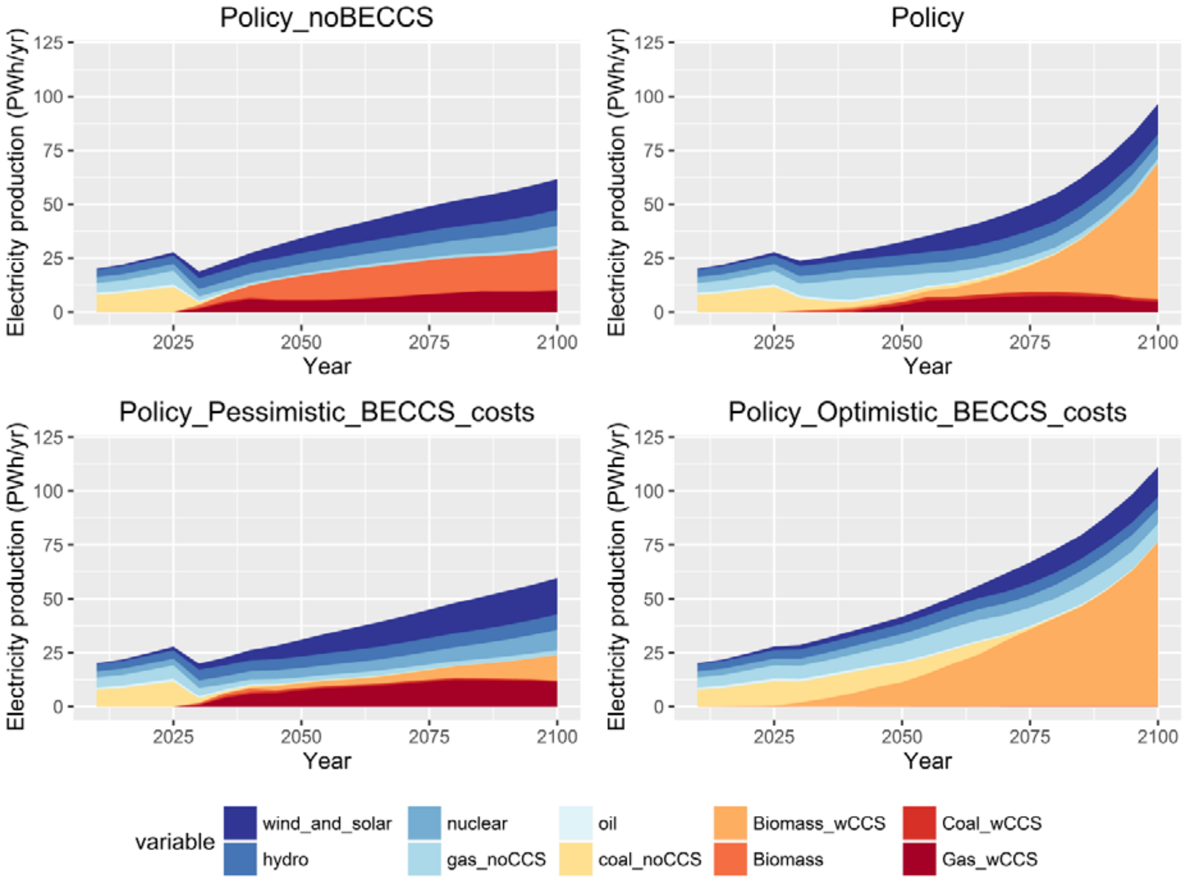


Figure 16. Electricity Production by Type in the Policy Scenarios

BECCS deployment: parameter sensitivity

We perform sensitivity analyses regarding the alternative assumptions about the costs of renewable energy (wind and solar), bioenergy crop yields, the costs of bioelectricity, and the costs of the CCS. **Figure 17** displays the difference in the cumulative CO_2 storage over the century between the *Policy* scenario with our core assumption and when one sensitivity parameter is varied at a time.

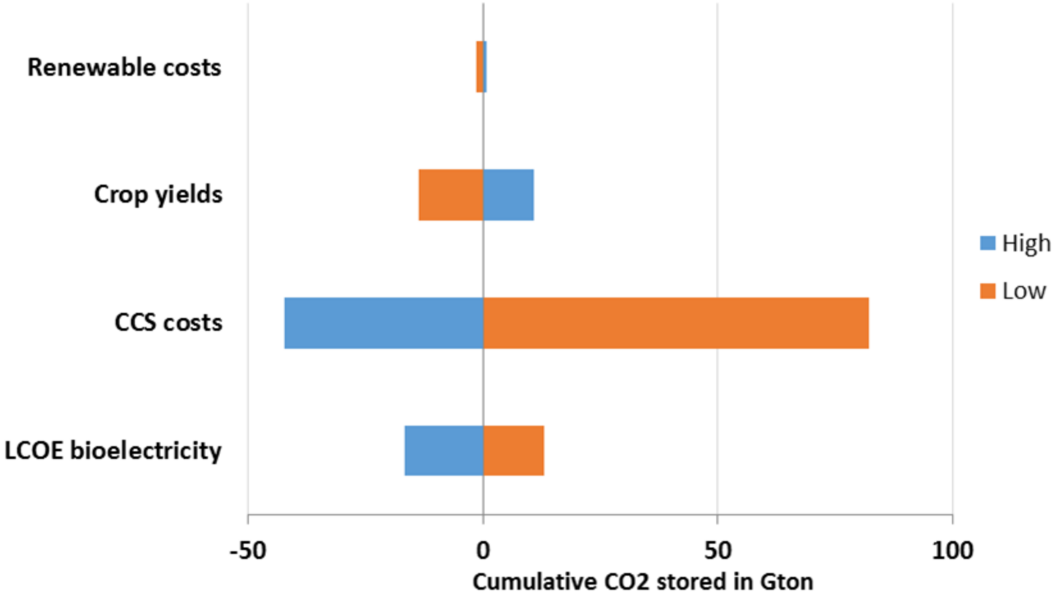


Figure 17. Sensitivity of bioCO_2 storage over the century to various parameters

Our preliminary exploration of the sensitivities shows that the uncertainty about the CCS costs has the largest impact on the results. Uncertainly about the bioenergy crop yields and the cost of power generation from biomass also has a sizeable impact. In the current setting, deployment of BECCS is relatively insensitive to the change in the cost of renewables. We continue to explore the fuller set of parameters that impact the BECCS development.

Land use for bioenergy crops

One concern regarding BECCS is their competition for land use for other purposes, such as food crops, livestock, and forestry. Indeed, the amount of land dedicated for BECCS grows substantially in the policy scenarios. In the *Policy* scenario, the global amount of land for BECCS approaches 1.4 Gha (see **Figure 18**), which is about the same amount of land that is currently used as cropland.

In the *Policy* scenario, land use productivity is improving by 1% annually, which is consistent with historic improvements (see Section 3). In the *Policy_Optimistic* scenario, higher yields (discussed in Section 8.3) result in lower land requirements (about 1 Gha globally by 2100) even though the amount of generation in this scenario is larger (75PWh vs 65 PWh in 2100).

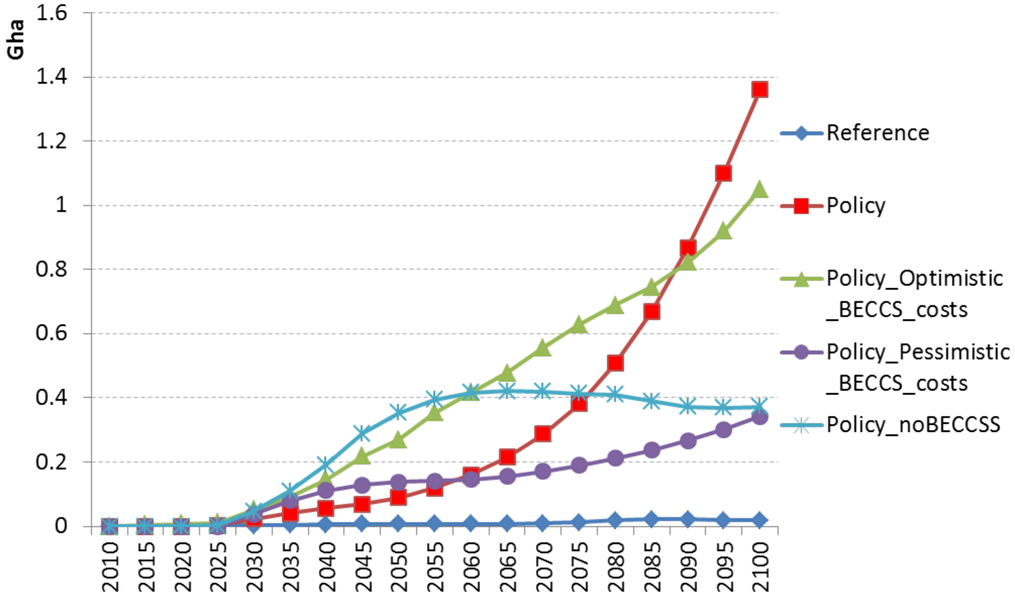


Figure 18. Land use for biocrops

Primary energy consumption

The results for global primary energy use are presented in **Figure 19** for the *Reference* case. Global energy consumption grows from about 500 EJ in 2005 to about 1300 EJ in 2100. In this scenario the world relies on fossil fuels for its energy needs.

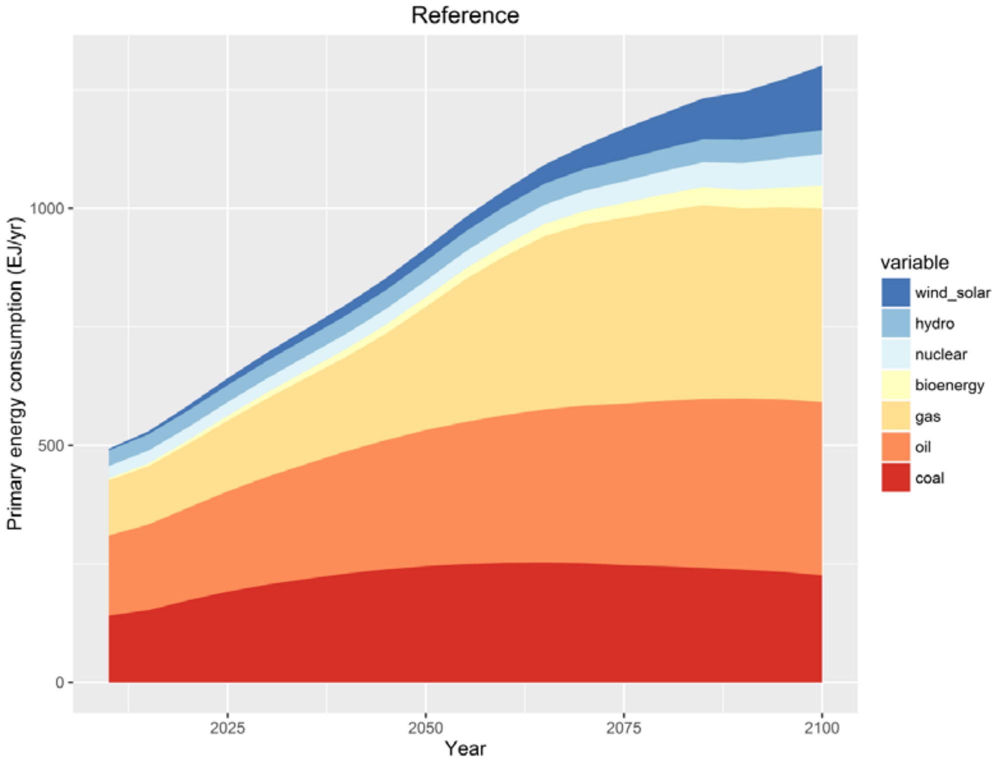


Figure 19. Primary energy consumption - Reference case

Changes in the global primary energy in the policy scenarios are represented in **Figure 20**. In the policy case, when negative CO_2 emissions are not allowed (*noBECCS)*, bioenergy, wind & solar and nuclear are used to reduce CO_2 emissions (comparison with the reference case) while the use of coal, oil and gas decreases notably. With the BioCCS option, the direction of changes in energy by source is the same as when this technology is unavailable, but the proportional changes are different. Bioenergy use increases significantly, while the impact on nuclear and renewable is very small. Around 2070, the consumption of oil in the *Policy* scenario is around 300 EJ higher than in the *no BECCS* case (around 40% higher) which confirms the fact that using negative emission technologies allows for a longer use of fossil fuels.

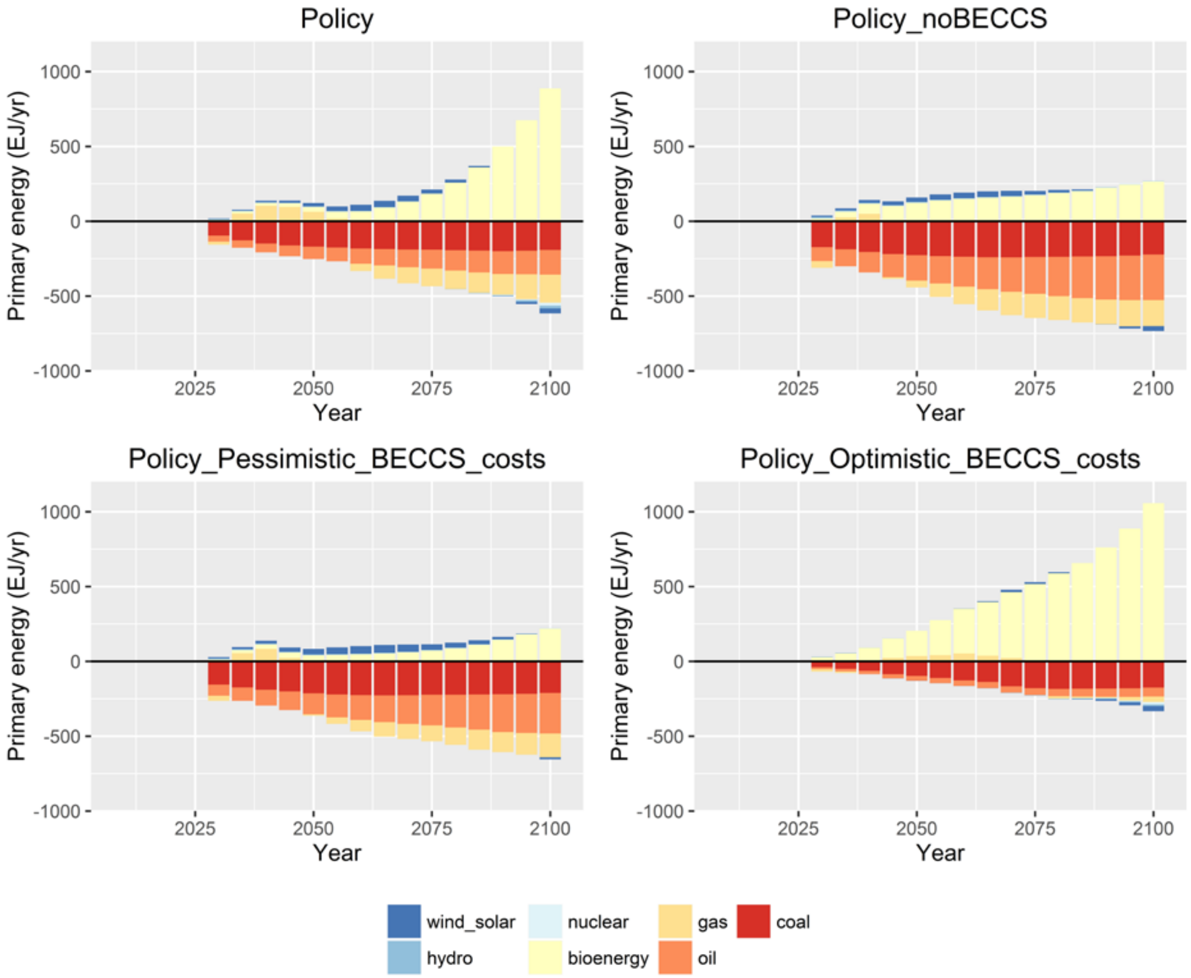


Figure 20. Primary energy consumption differences with the reference case

Economic impacts

The economic impact of the various policies is quite diverse. As shown in **Figure 21**, with the *Policy_Optimistic* scenario, the change in GDP is small (at the end of the century, the world GDP is only 4% lower than it would have been without climate policy). Yet, for the three others scenarios, the long term impact is much higher, around 15% in 2100. What is interesting there is the difference in the GDP trajectories: for the *Policy_Pessimistic* and the *NoBECCS* scenarios, the effort has to be realized when the policy is implemented (2030).

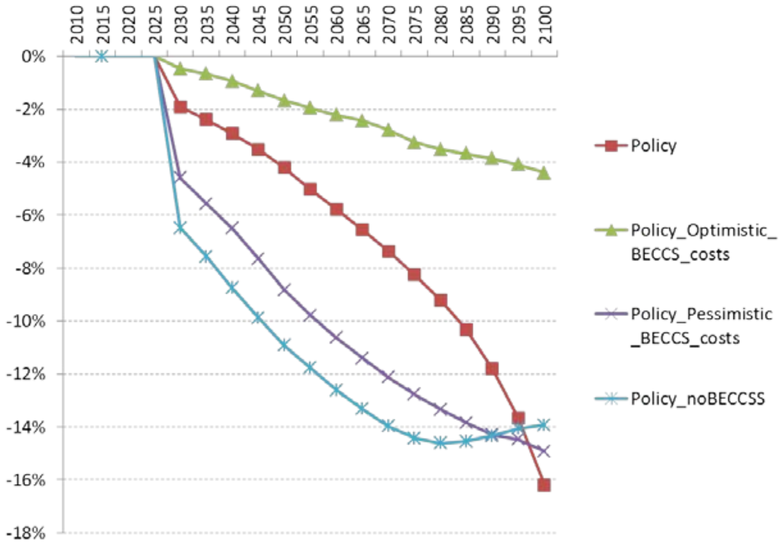


Figure 21. Welfare change in the policy scenarios relative to the reference case

The carbon price profiles that are needed to reach the 2°C target are also differ dramatically. In the *Policy* scenario (when BECCS are available), carbon prices are about \$70/tCO$_2$ in 2030, \$100/tCO$_2$ in 2050, rising to about \$300/tCO$_2$ by 2100. When BECCS are not available, to reach the same cumulative emission target, much higher carbon prices are required: about \$200/tCO2 in 2030, \$350/tCO2 in 2050, and rising to about \$900/tCO2 by 2100.

8. CONCLUSIONS

The ultimate goal of the agreement achieved at the UN climate conference in Paris in 2015 is to hold "the increase in the global average temperature to well below 2°C… and to pursue efforts to limit the temperature increase to 1.5°C above preindustrial levels…." A majority of the scenarios in the UN FCCC database (IIASA, 2014) designed to achieve such an outcome requires negative emission technologies. However, it seems that for the BECCS technology logistics and land use constraints will limit BECCS to less than what is needed.

The main uncertainties weighing on BECCS development are bioenergy availability, CCS development, policy incentives and social acceptance. Bioenergy availability is subjected to many uncertainties such as the rate of improvement in agricultural management, choice of crops and their yields, changes in food demands and human diets, use of degraded land, competition for water, use of agricultural/forestry by-products, protected area expansion, water use efficiency, climate change impacts, carbon neutrality of the biomass.

CCS is a proven technology, but it is not a mature one yet. The costs performance is expected to improve but some aspects of the CCS chain are still unknown, such as global CO_2 storage capacity, maximum annual rate of CO_2 storage, the BECCS/CCS deployment rate. Policy incentives and social acceptance is a large driver of BECCS development but here again many uncertainties remain, such as CO2 price, negative emissions accounting, global governance system, clear framework for the storage and monitoring of CO_2, and regional differences in attitude towards carbon storage. The efforts to improve public knowledge about CCS projects should be enhanced as in many cases the opposition is based on inaccuracy in understanding the nature of CO_2 properties and its storage. To overcome these challenges, policy makers may need to consider supporting the accelerated development of BECCS, including the advanced methods to increase biomass productivity.

In our study, we provide a consistent outlook of the whole technology chain related to BECCS: energy crop production, power generation, carbon capture, carbon transportation and storage. Our modeling of BECCS, as any modeling up to date, allows capturing only the key components and major challenges. While our results show that global economic costs and carbon prices are substantially lower when BECCS technology is available, the policy makers should not treat this result as a signal for postponing emission reduction in the near future due to a prospect of a negative-carbon technology. There is a substantial risk of relying on any particular technology. Instead, the policy makers should provide investors a certainty about the emission goals and their time profiles, and establish the flexible mechanisms for achieving the emission targets. The emission markets will then choose the most economic emission reductions from any source, including the development and use of BECCS.

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