Biomass Energy and Carbon Capture and Storage: unlocking negative emissions

Chapter 4

The future for bioenergy systems: the role of BECCS?

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Abstract

Many global decarbonisation scenarios suggest that bioenergy with carbon capture and storage (BECCS) is an important option for CO_2 emissions mitigation. Bioenergy has been well modelled in the TIAM-UCL model, with previous work having identified the significant impact of BECCS on the projected costs of achieving a 2°C target (McGlade et al. 2015). This chapter builds on this work, using TIAM-UCL to investigate the extent to which bioenergy with carbon capture and storage (BECCS) is critical for meeting global CO_2 reduction targets under different long-term scenarios out to 2100. The chapter also assesses the potential impacts of BECCS on mitigation costs under various scenarios at a global scale.

Though previous work has suggested that BECCs can play a crucial role in meeting the global climate change mitigation target, uncertainties remain in two main areas: one is the availability of biomass, which is affected by many factors including availability of land for biomass production; and the other is sustainability of bioenergy production including consequences for greenhouse gas (GHG) emissions. In order to assess the importance of these uncertainties, this chapter develops several scenarios by varying the availability of biomass (sustainability of the bioenergy production) and peaking year for GHG emissions under 2 °C and 1.5 °C climate change mitigation targets at a global level. Scenario analysis suggests that without BECCS, or other negative emission technologies, the targets may simply become implausible – certainly 1.5 °C but perhaps also 2 °C.

Keywords – BECCS, TIAM-UCL, uncertainty, climate change mitigation, energy system modelling, bioenergy.

4.1 Introduction

The countries that met at COP21 in Paris agreed to hold the increase in the global average temperature to well below 2 °C above pre-industrial level and also make efforts to limit the temperature increase to 1.5 °C. These are ambitious targets, and while many low carbon resources and technologies are available, there are major limitations in the plausible rate at which human societies can deploy them, due to a range of technical, financial, political and social constraints.

The challenges of meeting 2 or 1.5 °C targets are sufficiently great that many believe that low or zero carbon technologies are not enough: negative emission technologies (NETs) are required. NETs are a disparate group of methods that have been proposed for removing CO_2 from the atmosphere with the objective of limiting climate change. Some have argued that NETs are crucial to meet climate targets (Rogelj et al., 2015; Dessens et al., 2016) as the global carbon budget left during the next 85 years is very limited, and a large portion will be used up during the next few decades, due to locked-in investments. There are several negative emissions technologies discussed in the literature such as afforestation, biochar, biomass with CCS (BECCS), direct air capture (DAC), oceanic and terrestrial enhanced weathering , land use management, and ocean fertilisation, among others (McLaren, 2012).

Among negative emissions technologies, BECCS has received most attention. However, uncertainties remain in two main areas that affect the cost-effectiveness and role of this technology to meet global climate targets: one is the availability of biomass which is affected by many interlinked factors, including availability and suitability of land for biomass production; and the other is sustainability of bioenergy production. Sustainability of the biomass is not limited to GHG emissions, there are several issues around its sustainability such as environmental emissions, natural capital, social values, ecosystem services, biodiversity, etc. But, they are beyond the scope of this study. The large diversity of options and feedstocks available for bioenergy accentuates the complexity of the issue of sustainability. Biomass can only be a useful element of the energy system in the future if it is economically, socially and environmentally sustainable. Sustainability indicators include soil quality, water quality and quantity, GHG emissions, biodiversity, air quality, food competition, productivity, economic competitiveness, and global equity that are beyond the scope of this chapter. However, we develop several scenarios by varying the availability of biomass under 2°C and 1.5°C climate change mitigation targets at a global level to analyse the possible limitation on biomass production under sustainable goals.

This chapter uses the TIAM-UCL global energy system model to analyse the role of BECCS to meet global climate change mitigation targets in line with Paris agreement. This chapter has been divided into four sections. Following the introduction, Section 2 presents the tool used for modelling, presents the representation of biomass and CCS in the model, and defines the scenarios; Section 3 presents and discusses the model results, especially on the role of BECCS to meet 2°C and 1.5°C scenarios; and Section 4 concludes the findings.

Optimisation modelling of this kind provides a clear and relatively simple conceptual framework with which to explore the techno-economics of alternative possible technology options. It should be clear that neither the dynamics of the model (which assumes perfect foresight and implicitly represents the view of a single global social planner) nor the input assumptions (relating to long-term forecasts of the characteristics of technologies, which care clearly deeply uncertain) support crisp quantitative predictions. Rather, the aim of such tools is to enable insights into the potential orders of magnitude and relative importance of techno-economic factors.

4.2 Methodology

4.2.1 TIAM-UCL

TIAM-UCL is a whole energy system model covering energy resources, conversion, infrastructure and end-use sectors (Loulou and Labriet, 2007). The model has been developed under the UK Energy Research Centre (UKERC) Phase II project (Anandarajah et al., 2011) and enhanced under different projects (McGlade et al. (2015), McGlade and Ekins (2015)). It is a linear programming based partial-equilibrium model that maximises societal welfare (defined as the sum of consumer and producer surplus). The model thus identifies the optimal energy system pathway subject to constraints such as carbon targets (and 'optimal' is defined in techno-economic terms). Within the model the world is divided into 16 geopolitical regions of different size (from single nation state to group of different countries). Base-year energy-service demand is exogenous and future projections are based on drivers such as GDP, population, household size, and sectoral outputs. The base-year (2005) primary energy consumption, energy conversion, and final consumptions are calibrated to the IEA Energy Balance at sector and sub-sector levels. A simplified representation of the TIAM-UCL model structure is presented in Figure 1. The world regions are linked through the trade in crude oil, hard coal, pipeline gas, LNG (liquefied natural gas), petroleum products (diesel, gasoline, naphtha, heavy fuel oil), energy crops, solid biomass and emission credits.

Biomass is modelled in TIAM-UCL from resources to conversion to end-use devices. Regions in the model can trade energy crops, solid biomass, bio-diesel and other bio-products in addition to fossil fuels. Biomass is available for electricity and heat production with and without carbon capture and storage (CCS) and also in bio-fuel production with CCS. As presently represented in the model, biomass with CCS will always yield a negative net emission from the process when it is dedicated biomass with CCS for electricity or heat production.

End-use technologies are modelled at a detailed level in each end-use sector. For example, the transport sector is divided into passenger vs. goods transport, as well as by modes (car, bus, train, air, ship, HGV, LGV, etc.). Vehicle technologies such as internal combustion engines (gasoline, diesel, CNG, LPG), hybrids, plug-in-hybrids, electric vehicles, and fuel cell vehicles are modelled in each transport mode where appropriate. TIAM-UCL also has a climate module, which calculates impacts on atmosphere: CO_2 and other GHG emissions concentrations; radiative forcing and temperature changes, and can be constrained to a particular maximum temperature rise, such as 2 °C.

In addition to the global social discount rate of 3.5%, TIAM-UCL includes various hurdle rates. TIAM-UCL uses hurdle rates to calculate the equivalent annual capital cost (annualised capital cost) of a technology during the life time. Higher the hurdle rate higher the equivalent annual capital cost. Model will use the global discount rate to calculate the annualised capital cost for a technology If a hurdle rate was not modelled for the technology. Hurdle rates are higher than the social discount rate to represent in the model market failures, barriers, consumer preferences, etc., for sector specific technologies. These hurdle rates also vary across regions. Further details of the model are available in the model documentation (Anandarajah et al., 2011) and peer reviewed papers (Kesicki and Anandarajah, 2011; Anandarajah et al., 2013).

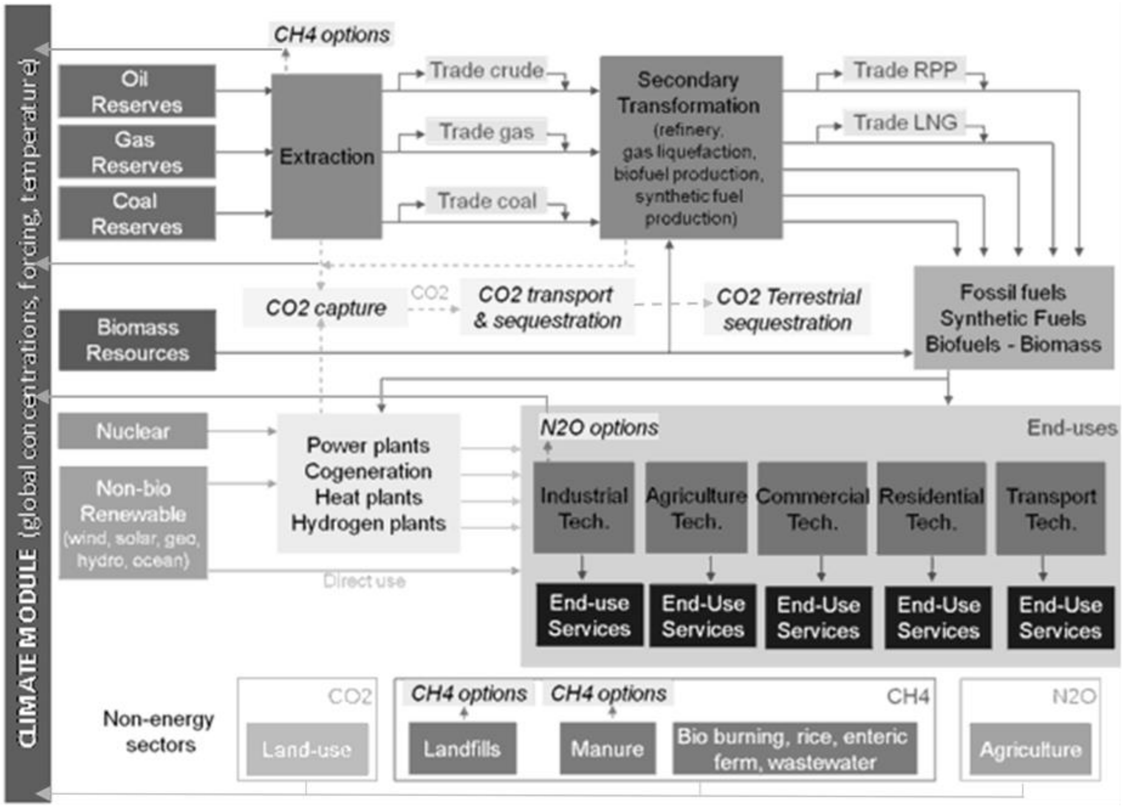

Figure 2.1. TIAM-UCL energy system structure (for more information refer to Anandarajah 2011)

4.2.2 Representation of bioenergy and CCS technologies in TIAM-UCL

In TIAM-UCL, biomass resources are grouped into solid biomass, energy crops, industry wastes and municipal wastes. Energy crops and solid biomass resource potentials have been modelled with three supply cost curves for each region modelled in TIAM-UCL. Aggregated regional level data for solid biomass and energy crops data (High biomass availability scenario) for 2050 is presented in Table 2.1. The regional data (costs versus availability) have been extracted originally from Smeets et al. 2004, but have been reassessed with the global values from the UKERC report (Slade et al., 2011) "Energy from Biomass: the size of the global resource". Biofuel productions (bio-refineries) are modelled to produce a range of biofuels such as biodiesel, bio kerosene, bioethanol and bio jet kerosene. Bio methane can be produced from various resources such as energy crops, solid biomass, industry and municipal wastes and landfill gas. Solid biomass, energy crops and industrial wastes can also be directly used in power and industry sectors for heat and electricity production involving various technologies including combined heat and power (CHP) technologies. Biomass technologies compete directly at energy service demand level with fossil fuel technologies to meet energy services (such as residential, industrial and commercial heating demand, transportation, and residential cooking).

The CCS technology has been modelled with various biomass technologies upstream for biofuel production (Fischer Tropsch process for biofuel productions) and hydrogen production, in the power sector for electricity and heat production, and in the industry sector with large scale heat production. Biomass is also modelled as a co-firing fuel (with coal) with CCS for electricity, heat, hydrogen and biofuel production with various technologies. CCS technologies becomes available in the scenarios from 2025 onward. The assumptions about costs of the technologies as well as the storage potential are extracted from the IEA Technology Roadmap report (IEA 2013) and the IPCC Special Report on Carbon Dioxide Capture and Storage (IPCC 2005). Finally, a growth constraint has been introduced in the model at a maximum 10% on the roll out of the CCS technologies.

Table 2.1 Solid biomass and energy crops availability in 2050 in TIAM-UCL (High Biomass scenario). Results are presented in PJ (10^{15} Joule) for 16 regions; Africa (AFR), Australia (AUS), Canada (CAN), China (CHI), etc (for full list of region please refer to: Anandarajah 2011)

	Biomass Feedstock Type (PJ)	
TIAM_UCL region	**Solid Biomass**	**Energy Crops**
AFR	19300	9000
AUS	1974	13000
CAN	2020	6000
CHI	10323	5000
CSA	15130	17000
EEU	1196	5700
FSU	2961	43000
IND	7030	5000
JPN	75	100
MEA	276	1000
MEX	1462	2000
ODA	1953	6000
SKO	105	100
UK	270	400
USA	5044	16400
WEU	4956	6400

4.2.3 Scenario definitions

Scenarios have been developed in order to examine the implications of BECCS within global decarbonisation pathways. These scenarios address the following question: What are the implications of BECCS for cost optimal global decarbonisation pathways?

The first set of scenarios explores optimal pathways to a 2 °C target, with and without BECCS. These scenarios provide a way of understanding how the use of BECCS can influence the options available to the rest of the energy system, and the cost and investment implications of BECCS availability. It is worth explaining the rationale for these scenarios, and their relationship with plausible or possible envisaged futures. In particular, one may question the realism of a scenario in which CCS is available for fossil fuels, but not for bioenergy. The point here is that these scenarios are experiments that explore the dependence of model outcomes on the availability of BECCS.

The two basic scenarios (2°C, with and without BECCS) are further explored using a range of sensitivity scenarios, which explore key uncertainties:

1. The availability of sustainable biomass for the energy system. The TIAM-UCL model adopts relatively conservative[1] baseline assumptions on the availability of bioenergy that can be sustainably used, and the literature shows a considerable range of estimates for global bioenergy availability. The relative availability of bioenergy can be expected to be an important determinant of the modelled potential for BECCS. A scenario has thus been developed to explore the implications of a more generous availability of bioenergy than is assumed in the base case, by doubling the availability of bioenergy.
2. The year in which globally co-ordinated decarbonisation efforts begin (2015, 2020 or 2025). These scenarios are a highly abstracted representation of complex global political processes. The aim of these delayed-action scenarios (is to test how the relative role of BECCS changes in the model results as effective global action to reduce emissions is delayed. The scenarios are thus designed to test the consequences of delay. They are not intended to be realistic 'storylines' as the geopolitical and practical realities of delivering global emissions reductions on such scales render such neat turning points unlikely.

The scenarios in this paper include key assumptions on climate change mitigation policies, including perfect international cooperation. This international cooperation starts in the scenarios presented in 2015, 2020 or 2025 and as consequence produce a homogenous international carbon price from this year onward. The years chosen for the starting of such global cooperation are dictated by the structure of the TIAM_UCL time representation with periodic output every 5 years from 2005. The year 2015 is a point already in the past. However large uncertainties in emissions and climate representation in the model should be taken into account and the starting dates for the mitigation policies presented should be regarded as a present-day start versus delay by 5 or 10 years. It also worth emphasising that the scenarios presented in the chapter are not forecasts as each result are built on a large number of uncertain assumptions including for example the socio-economic development of the world. The structure and philosophy of TIAM-UCL, a bottom-up cost optimisation with perfect foresight energy system model, permit to extract informed insights of the long-term energy system under specific constraints. As consequence

[1] This is in comparison with the range of estimates presented in Slade et al. 2011.

develop decisions and policy can be developed as long as the limitation of such model are acknowledged and understood.

A further set of scenarios, as presented in Table 2.2, explores the importance of BECCS in achieving a global 1.5°C target, both with and without BECCS. These scenarios have been developed in light of the agreement reached at the UNFCCC COP21 in Paris, in December 2015.

Table 2.2 Scenario descriptions

Scenario	**Scenario shorthand**	**Scenario description**
2 degree scenario	2D	The climate module in the TIAM-UCL model has been constrained to limit the temperature changes to 2°C.
2D without BECCS	2D-NoBECCS	BECCS technologies have been made unavailable in this scenario. The climate policy is same as the one applied in the 2D scenario.
2D biomass sensitivity scenarios	2D-HiBio; 2D-NoBECCS-HiBio	The 2D and 2D_NoBECCS scenarios have been run with increased biomass availability.
2D delayed action sensitivity scenarios		The 2D and 2D_NoBECCS scenarios have been run with global emissions abatement effort beginning in 2015, 2020 and 2025.
1.5 Degree scenario	1.5D	The climate module in the TIAM-UCL model has been constrained to limit global temperature changes to 1.5°C.
1.5 degree without BECCS	1.5D_NoBECCS	As the 1.5 degree scenario, but with BECCS made unavailable
1.5 Degree biomass availability sensitivity scenarios	1.5D-HiBio; 1.5D_NoBECCS-HiBio	The 1.5D and 1.5D_NoBECCS scenarios are both run with increased biomass availability.

4.3 Results and Discussions

4.3.1 2 °C scenarios with and without BECCS

Figure 2.2 shows CO_2 emissions and the marginal mitigation costs for the two 2°C scenarios (2D and 2D-NoBECCS). The results clearly show that the global energy system requires deeper CO_2 reduction in the near and medium term when BECCS is unavailable, if the 2°C target is to be achieved. The importance of BECCS is particularly clear in the near-term: the 2D-NoBECCS scenario requires an annual average CO_2 reduction rate of 2% between 2015 and 2035, whereas the 2D scenario sees emissions remaining at 2015 levels until 2030. This shows that the availability of BECCS reduces the total discounted energy system cost for the same climate target and relaxes the early mitigation requirements. However, while BECCS availability delays the need of near-term reductions, total emissions in 2055 are more or less the same under both scenarios. This is possible as BECCS can help to capture CO_2 from the atmosphere in the long-term, especially during the second half of the century, leading to near zero net global emissions by 2100. In other words, the late start is compensated by negative emissions in later years in the scenario in which BECCS is available. Unavailability of BECCS not only requires deeper early reductions but also results in much higher CO_2 mitigation costs (carbon price). BECCS can lower the marginal CO_2 mitigation cost in 2D scenario to less than half of that in the 2D-NoBECCS scenario.

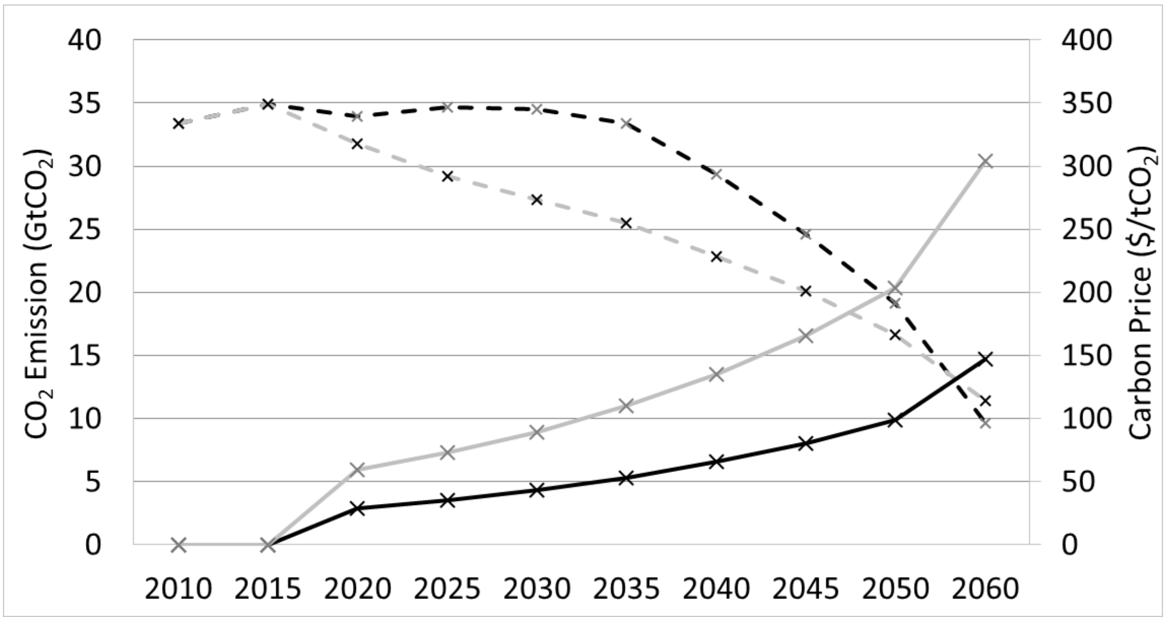

Figure 2.2. Global CO_2 emissions (dashed lines, left axes-$GtCO_2$) and marginal CO_2 abatement costs (solid lines, right axes-$/$tCO_2$) under 2D (with BECCS; black lines) and 2D-NoBECCS (grey lines) scenarios.

CO_2 mitigation in the near term takes place largely in the power sector, which reduces its emissions substantially under both scenarios, with sharper reduction in 2D-NoBECCS scenario between 2015 and 2030 (Figure 2.3). In contrast, end-use sectors such as transport, residential and industry undergo decarbonisation during the latter period of this scenario. This pattern of decarbonising the power sector first, and subsequently switching end-uses to low-carbon electricity is common to a wide range of decarbonisation scenarios at national and global scales, and the scenarios here are no exception. Power sector emissions decrease from 9.6 $GtCO_2$ in 2015 to 5.6 $GtCO_2$ in 2035 in the 2D scenario. The early mitigation requirements in 2D-NoBECCS scenario reduces power sector emissions to 1.7 $GtCO_2$ in 2035. This is equivalent to an average of 8% reduction in global power sector emissions annually from 2015 to 2035, a rate considerably in excess of the rate of decarbonisation in the UK during the well-known 'dash for gas' in the early 1990s, during which time annual reductions were less than 5% annually (CCC, 2010). The length (over 20 years) and the global character of the power sector decarbonisation in the 2D-NoBECCS scenario stretches the plausibility of this scenario, and raises the question: what kinds of political, economic or technical global developments can be envisaged that render such a scenario possible?

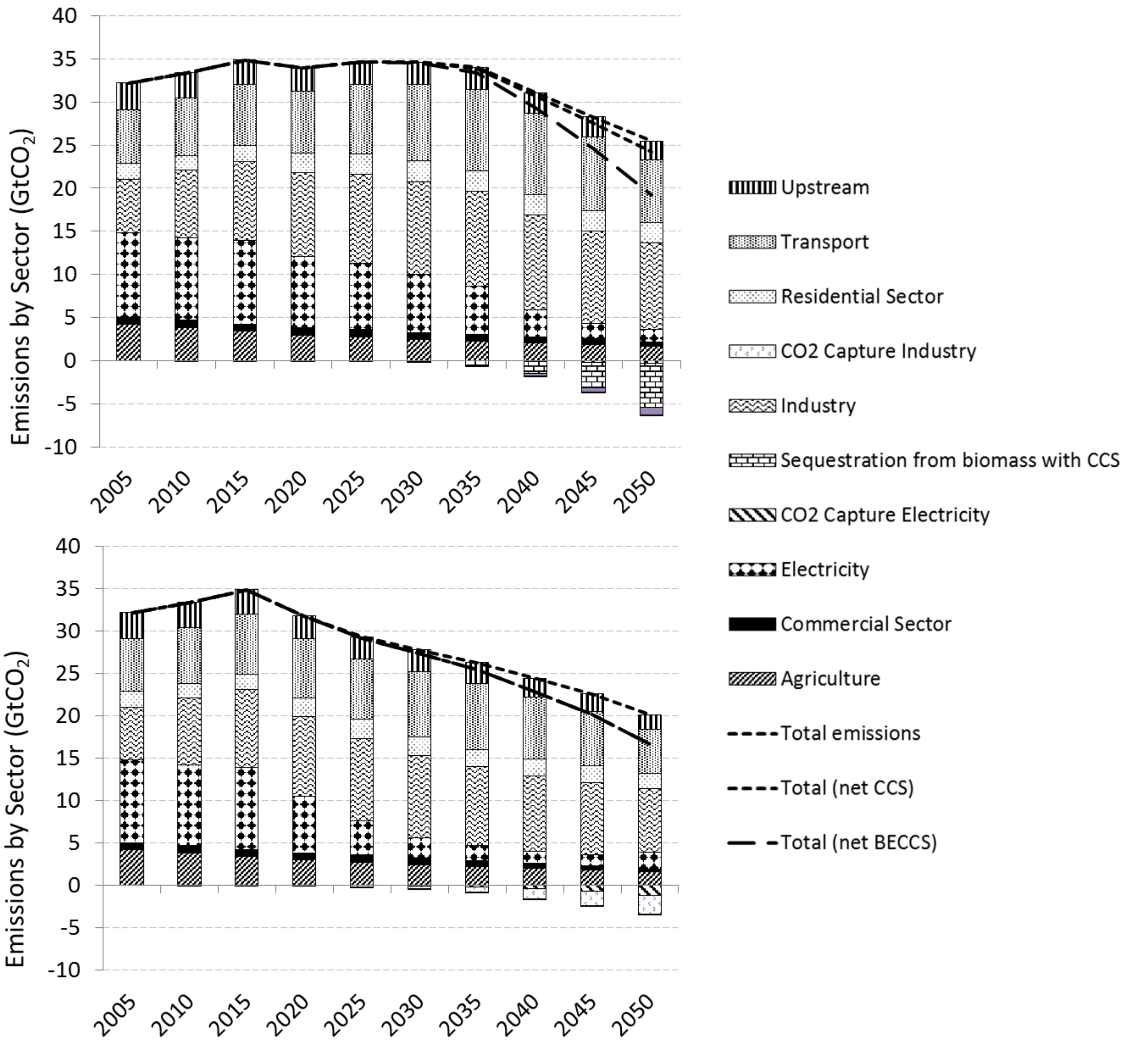

Figure 2.3. Sectoral emissions to 2050 in the 2D (top) and 2D-NoBECCS (bottom) scenarios generated using TIAM-UCL.

CCS plays a role in mitigating emissions by capturing CO_2 in both electricity and industry sectors under both scenarios. In 2050, CCS (not including BECCS) captures 1.1 $GtCO_2$ in the electricity sector and 2.2 $GtCO_2$ from industry in the 2D-NoBECCS scenario. When BECCS is available, as in the 2D scenario, the availability of lower-cost abatement via BECCS reduces pressure on industrial emissions, and as a result CCS captures only 0.9$GtCO_2$ in 2050 in the industry sector. BECCS alone captures and stores 5.1 $GtCO_2$ in 2050. This demonstrates the significance of BECCS for technology development priorities: if BECCS, under specific policy decisions (related to sustainability) or due to biomass production limitation (food prioritising), was certain to be unavailable, it would greatly strengthen the case for significant investments in the development of CCS technologies adapted to industrial processes and emissions.

Early mitigation in the power sector translates into very rapid reductions in power sector CO_2 intensity during the next 20 years. This is true in both scenarios, but the optimal rate of change in the 2D-NoBECCS scenario is extremely fast. In the 2D scenario, the CO_2 intensity of electricity halves from 520 g/kWh in 2015 to 250 g/kWh in 2035, and goes into negative values from 2045 due to BECCS (Figure 2.4). When BECCS is not available, as in the 2D-NoBECCS scenario, the CO_2 intensity of electricity must decrease sharply to 73 g/kWh in 2035, which is a seventh of the 2015 value, and 17 g/kWh in 2050. It perhaps goes without saying that this represents a global transformation that is unprecedented in the combined rate and scale of technological substitution.

In order to accomplish this transition and corresponding reductions in CO_2 intensity, the power sector needs investment in a range of low carbon technologies in the near and medium term. Figure 2.4 presents generation mix under 2D and 2D-NoBECCS scenarios. At present, in 2015, the global electricity system heavily depends on fossil fuel generation capacity, with coal and gas providing two thirds of total generation. Coal is the dominant fuel accounting for 43% of the total generation in 2015. Fossil fuel based generation decreases from 69% in 2015 to 44% in 2035 to only 7% in 2050 in 2D scenario. The fossil fuel generation is replaced mainly by hydro and solar in 2035 and by nuclear and solar in 2050. There is a rapid increase in the share of solar PV generation between 2015 and 2035 from just 1% to 16% in 2D scenario. Under the 2D-NoBECCS scenario, the share of fossil fuels in generation further shrinks to 20% in 2035 and 5% in 2050. The fossil fuels are replaced by nuclear and renewable generation especially solar PV. Nuclear and solar PV are the dominant technologies in 2050 under both scenarios, generating together more than half of the generation in 2050 with solar PV generation having a slightly higher share than that of the nuclear.

In the two scenarios presented the proportion of electricity generation from biomass reaches 18,500 PJ in 2050 (from 500PJ in 2015) representing 15% and 12% of the total generation for 2D and 2D-NoBECCS respectively. However the growth in capacity between 2015 and 2050 is different. In the absence of BECCS, biomass based technologies generate 10% of the electricity generated in 2035; at that time under BECCS availability biomass represents only 3% of generation: 1% from BECCS and 2% from biomass without CCS. From 1% in 2035. BECCS share increases rapidly to 13% in 2050 in the 2D scenario. The two scenarios present huge addition of biomass based generation during relatively short times. In the case of BECCS the addition occurs after 2030 when the model invests in 3 GW of BECCS capacity in 2030 and increases it to 39 GW in 2035, which corresponds to an annual capacity addition of 7GW. The installed capacity increases to 623 GW in 2050. Under the 2D-NoBECCS scenario the development of biomass use in power generation occurs from 2015 as the model needs to mitigate earlier to compensate the lack of negative emission with additional annual capacity addition increasing from 4 to 7GW between 2015 and 2035.

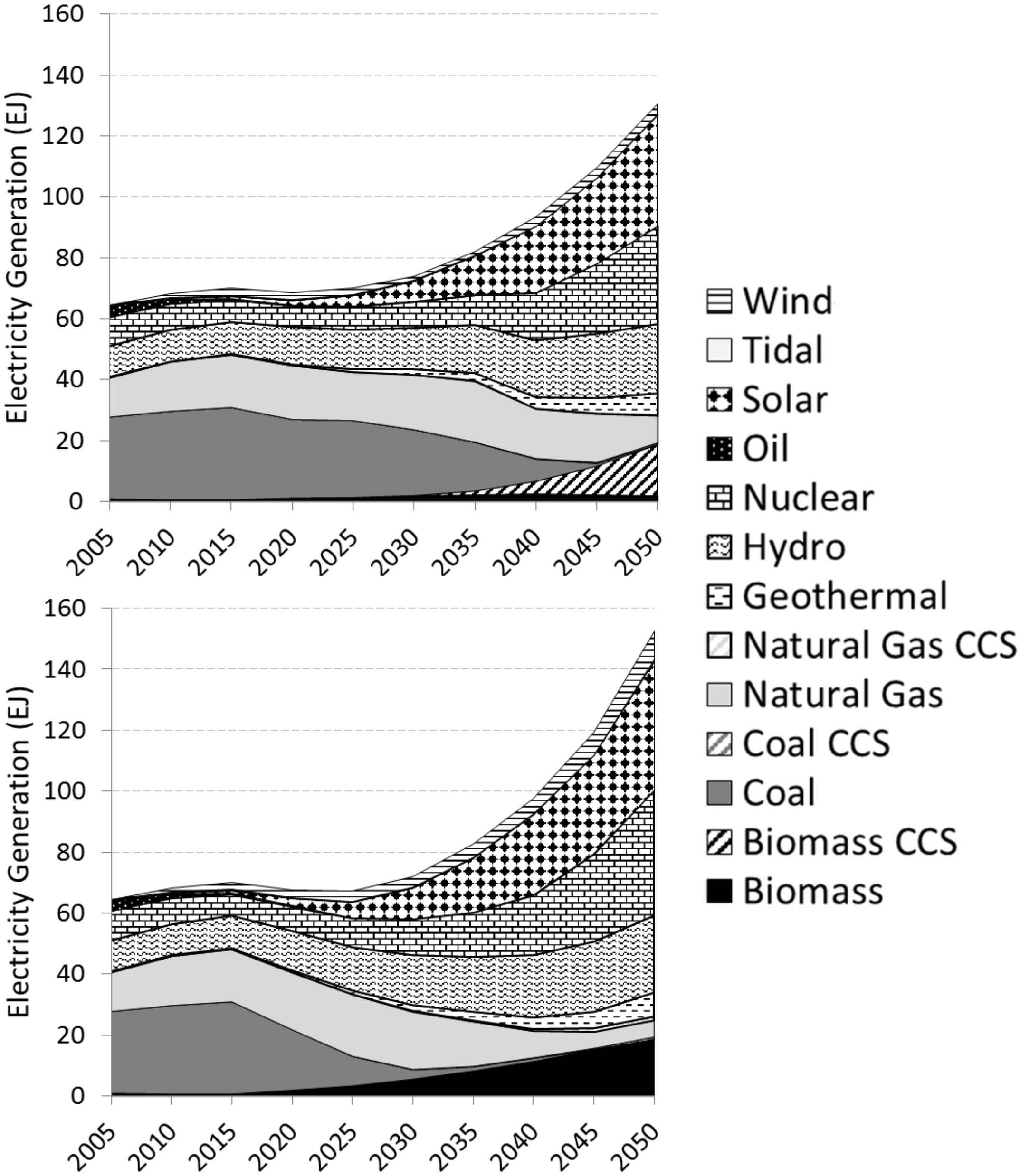

Figure 2.4. Electricity generation mix (PJ) under 2D (top) and 2D-NoBECCS (bottom) scenarios

There is not much difference in the total electricity demand between the scenarios until around 2025. However, in the absence of BECCS, the global energy system needs 17% more electricity in 2050 under the 2D-NoBECCS scenario compared to that in the 2D scenario. This clearly shows that, in order to offset the emissions captured in power and industry sectors by BECCS in 2D, the 2D-NoBECCS scenario decarbonises end-use sectors by means of electrification – that is, by shifting to low carbon electricity and away from fossil fuels. This happens in all major end-use sectors: transport, residential, industrial and commercial. The transport sector consumes 32% more electricity in the 2D-NoBECCS scenario compared to that in 2D in 2050. The respective figure for all other end-use sectors is about 10%.

Differences in the near term and long term generation mix between the scenarios are reflected in the primary energy consumption of the respective scenarios (Figure 2.5). There are notable differences in coal and natural gas consumption in the near and medium term between the scenarios. In long-term, total primary energy production in the 2D-NoBECCS scenario is slightly lower than that in the 2D scenario. Lower primary energy consumption in the 2D-NoBECCS scenario in 2050 is driven by a larger share of nuclear and solar in the generation mix replacing gas and also end-use sector electrification.

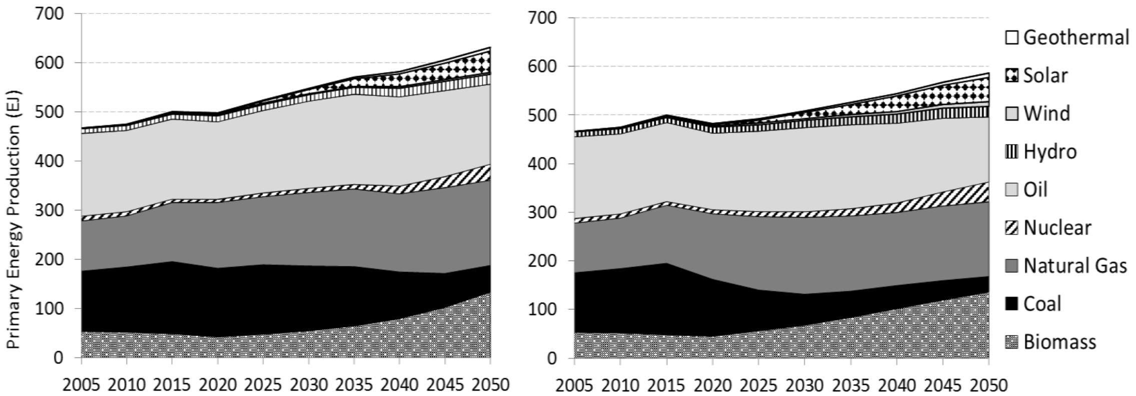

Figure 2.5. Primary energy production under 2D (left) and 2D-NoBECCS (right) scenarios.

4.3.2 Sensitivity around availability of sustainable bioenergy

As discussed previously, the relative availability of bioenergy can be expected to be an important determinant of the perceived importance of BECCS. However, it is not intuitively obvious how changes in bioenergy availability might influence the importance of BECCS. Greater availability of bioenergy might be expected to increase the apparent benefit of BECCS in the model results, since it is possible that the deployment of BECCS might be limited by the available bioenergy. On the other hand, greater availability of bioenergy could directly offset the consumption of fossil fuels, reducing the need for more-expensive negative emissions technologies such as BECCS.

The sensitivity scenarios presented here explore the implications of a more generous bioenergy resource than assumed in the earlier runs, with a doubling of the available potential biomass. The scenario is named 'high biomass'. The change in resource has been applied to the scenarios with BECCS and without-BECCS.

A second sensitivity experiment is conducted looking at the impact of delaying the start of mitigation policies (or the peaking year for CO_2 emissions) between 2015 (as in the previous Section) and 2020 or 2025. This has created a set of 12 different scenarios summarised in the Scenarios Definition Table in Section 4.2.3.

Figure 2.6 presents the CO_2 emissions pathways (net of all carbon capture and sequestration) of the 12 different sensitivity scenarios for the 2 °C target. Within the pathways three different behaviours in CO_2 emissions can be described. The six no-BECCS scenarios are grouped in one lower emissions trajectory after 2030; the 2035 emissions in these scenarios are limited to 25 Gt(CO_2). A second set corresponds to the scenarios combining BECCS with low biomass availability (with 2035 emissions 20% higher than those without BECCS). Finally, the case of BECCS with high biomass availability allows emissions to be around 10% higher during the first part of the pathway (2015 to 2035) compared to the previous set, and almost 30% higher than in the scenarios in which BECCS is unavailable. The higher early emissions that occur in the BECCS scenarios are compensated later in the century (after 2070) by larger negative emissions keeping the total carbon budget within the overall constraint. The inflexion point (from higher emissions during the first half of the century to lower during the second half) occurs in 2055. A key message from Figure 2.6 is that, when BECCS is unavailable and global action is delayed until 2020 or 2025, reductions must happen with great speed if the carbon budget is not to breach the 2°C target. This occurs regardless of the amount of bioenergy available (though of course a much less generous amount of bioenergy would bring the BECCS cases closer to the no-BECCS resulst, as opportunities for negative emissions via BECCS would be constrained by resource limits).

Figure 2.7 presents the annual mean reduction in emissions needed between the peaking year and 2035 in the 4 scenarios created by combining the high and low biomass with the BECCS availability. The figure shows the rate at which emissions need to be reduced during the period 2015 and 2035. The no-BECCS scenarios all reach a common level of 25 Gt(CO_2) in 2035, but the CO_2 reduction rate needed to reach this level is of course much higher for the delayed case, reaching 3.5% per year. In these no-BECCS scenarios, the amount of biomass available does not affect the rate of reduction. When BECCS is available, the amount of bioenergy does influence the optimal decarbonisation rate: with high biomass the mean annual rate of change to 2035 decreases to a more manageable -0.2% if global action begins in 2015, rising to only -1% per year if global action is delayed. With low biomass, the optimal rate of decarbonisation needed to achieve the 2°C target rises from -1.5% to -3.5% for the early and late policy respectively, as shown in Figure 2.7. It is useful to compare these rates of decarbonisation to estimates of what might be a plausible upper bound on the rate at which global decarbonisation could be achieved. Den Elzen et al., (2011) for example has suggested that 3.5% is the maximum possible annual global reduction rates of CO_2 that could be achieved, taking into account assumptions about technological development, economic costs, and socio-political factors. This makes clear the importance of early global mitigation action in the case of BECCS failure in the future as in this case any delay would bring the reduction rate close to the maximum value that Den Elzen et al. view as plausible.

A common pathway in the three major cases discussed above (no-BECCS, BECCS low biomass, BECCS high biomass) is reached after 2035. The pathways diverge again after 2070 (not shown), with respectively lower emissions for the delayed mitigation scenarios (a difference reaching 10% for the year 2080 emissions between a pathway peaking in 2025 and 2015). This difference compensates the added emissions of CO_2 from the start of the simulation in the delay in mitigation policy case.

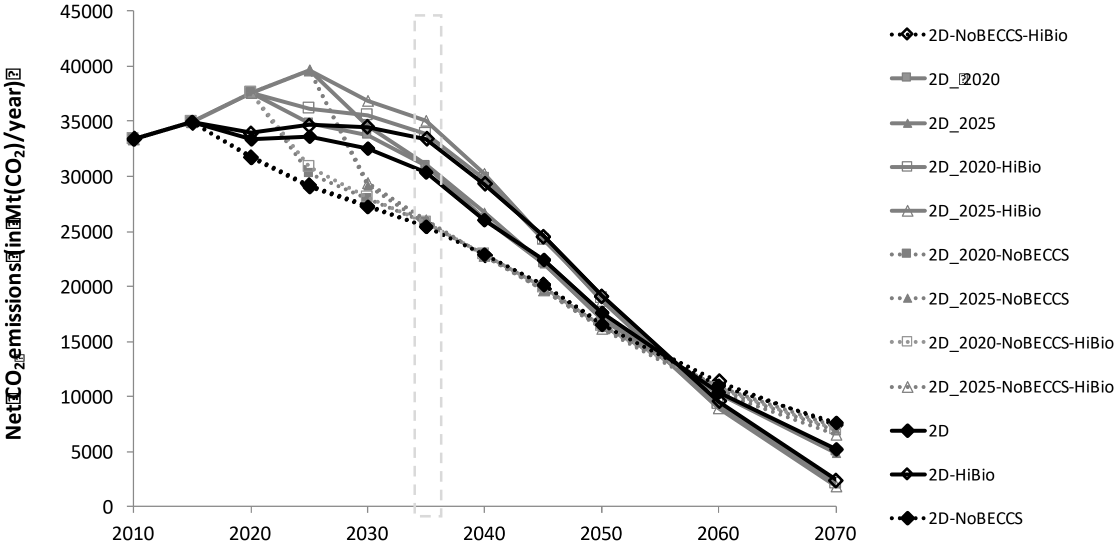

Fig2.6: CO_2 emissions until 2070 under different scenarios for the 2°C target (list of scenarios presented in the Scenario table chapter 2.2.3).

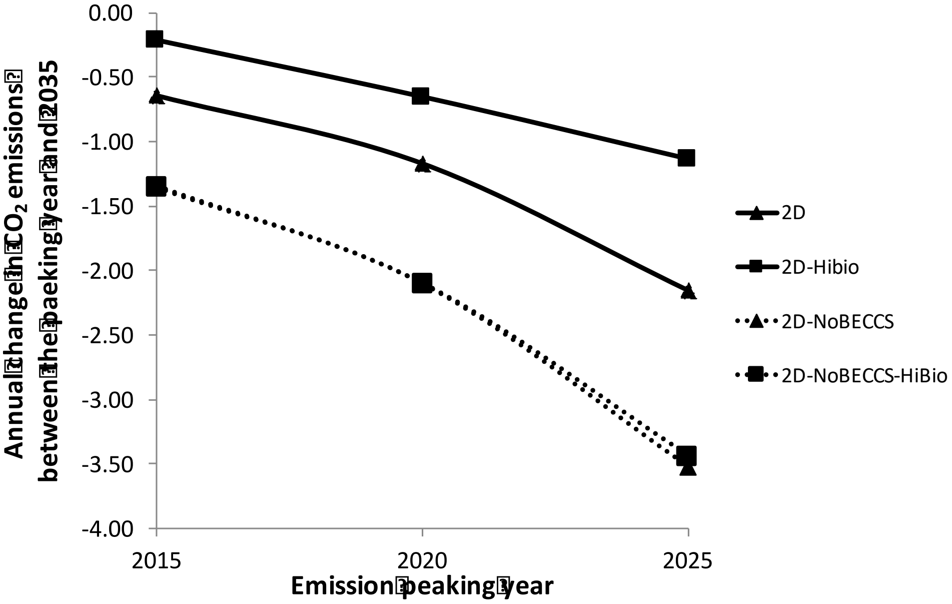

Figure 2.7: Year 2035 annual mean reduction in global CO_2 emissions between the peaking year (2015, 2020 and 2025) for the 4 families of scenarios incorporating the amount of biomass and the availability of BECCS.

The carbon prices calculated for the 12 different scenarios are presented in Figure 2.8. In almost all cases the peaking year for emissions is important in determining the carbon price level. When BECCS is available in the scenarios the carbon price stays below $150 per tonne of CO_2 in 2050. However, when BECCS is available and bioenergy is abundant, the peaking year makes little difference to mitigation costs to 2050: such scenarios provide a large potential for removing emissions via BECCS during the second part of the century. In the case of low biomass availability, late action matters: the increase in carbon price is 5% if starting the mitigation in 2020 and 15% if only starting in 2025 compared to the 2015 scenario as negative emissions are becoming more restricted by biomass production.

As expected, the no-BECCS scenarios show a significant impact on carbon prices. When BECCS is unavailable, carbon prices range from $200 to $280 per tonne of CO_2 in 2050. The exclusion of BECCS technology in the scenarios increases the carbon prices by 75%, 80% and 95% (mitigation policy starting in 2015, 2020 and 2025 respectively) under normal biomass production and 105%, 115% and 145% under high biomass (this is due to the fact that high biomass with BECCS scenarios present the lowest carbon prices of the 12 pathways calculated) as seen in Figure 2.9. Finally, the changes in carbon price from the impacts of not having access to BECCS increase as global action is delayed.

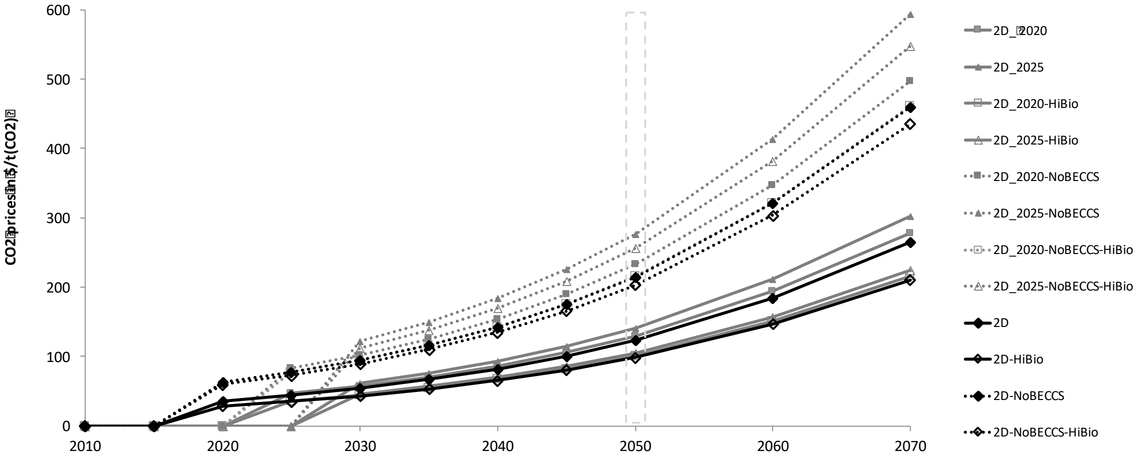

Figure 2.8: Carbon prices until 2070 (in $/t($CO_2$)) under different scenarios as in Figure 2.6.

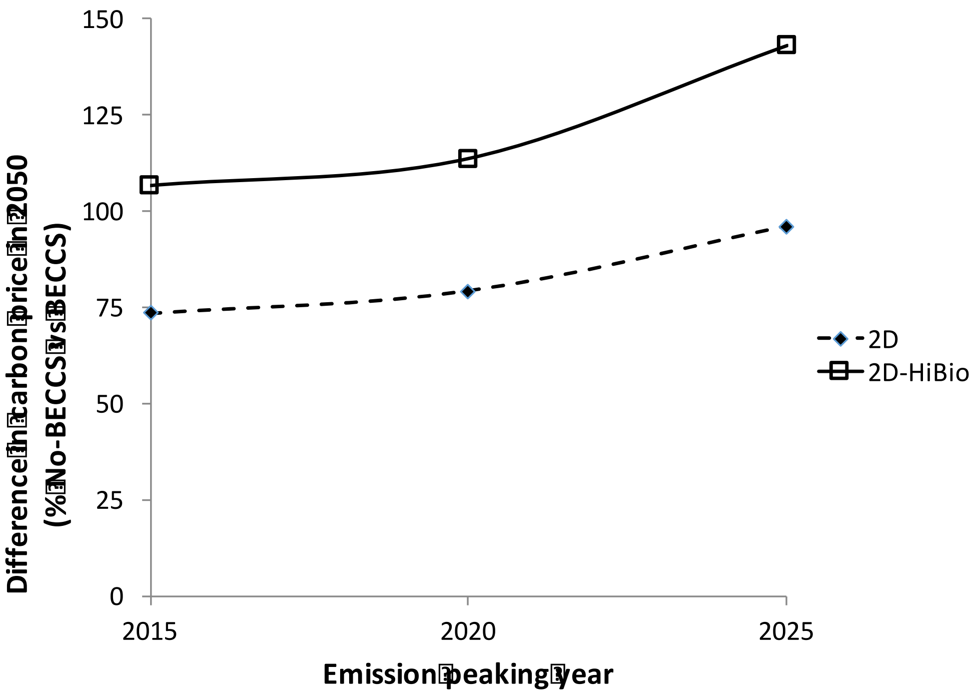

Figure 2.9: Difference in carbon prices between no-BECCS and BECCS scenarios for the year 2050, as a function of emissions peaking year (2015 to 2025) under low and high biomass availability.

The discussion now will focus on use of the available bioenergy across the scenarios. In a global energy system model, the optimisation procedure identifies the least-cost allocation of bioenergy feedstocks across a wide range of possible technologies, sectors and end-uses. When BECCS is available starting from year 2025 there is an increase in biomass use reaching 10% in the energy system in 2050 compared to the low-biomass availability scenario. However, at a later period in the pathway under high-biomass combined with CCS availability there is a strong uptake of biomass in the model, reaching an increase of 60% after 2070 compared to the low-biomass configuration (Fig 2.10). In contrast when BECCS is not available the quantity of biomass used in the energy system increases regularly to achieve 45% higher quantities in the case of high availability after 2070.

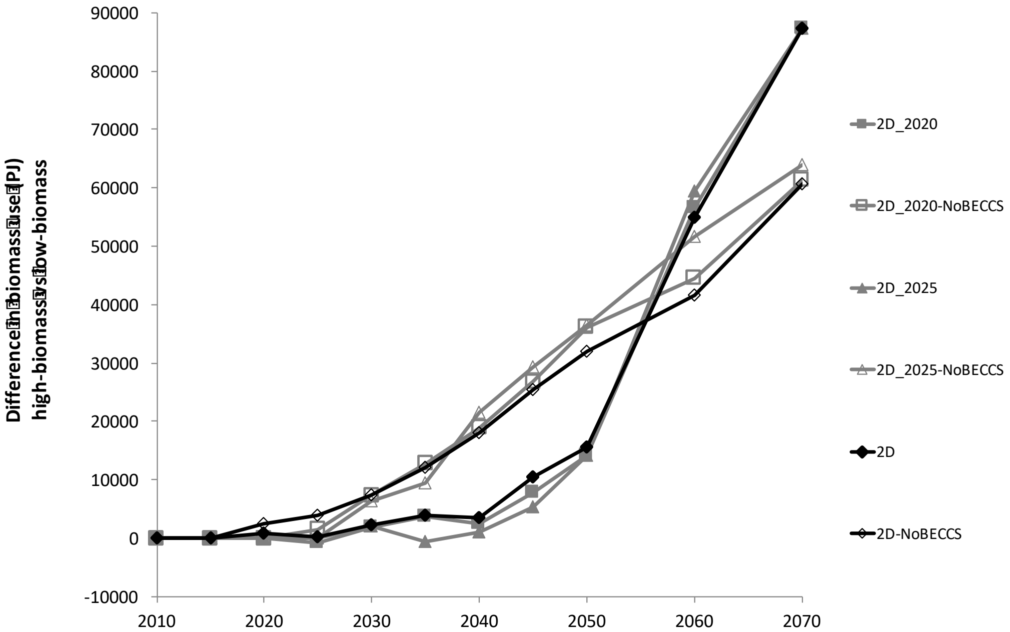

Fig2.10: Change in bioenergy use in 2°C scenarios until 2070: High-biomass vs Low-biomass availability

In terms of peaking year, the changes from no-BECCS to BECCS availability is plotted in Figure 2.11. As seen before, the implication of a failure in BECCS increases the pre 2050 biomass use (positive difference), peaking in 2035 to 2040 depending on the scenario and reduces it after 2050 when biomass can contribute to negative emissions using BECCS. In all cases, delaying the peaking year from 2015 to 2025 increases the amount of biomass under the no-BECCS scenarios around 2035 from 20 to 30% in the low biomass case and 30 to 45% in the high biomass case. These increases in conjunction with other low carbon sources (nuclear and variable renewable) compensate for the reduction in fossil fuel (coal and gas) involved in the electricity generation.

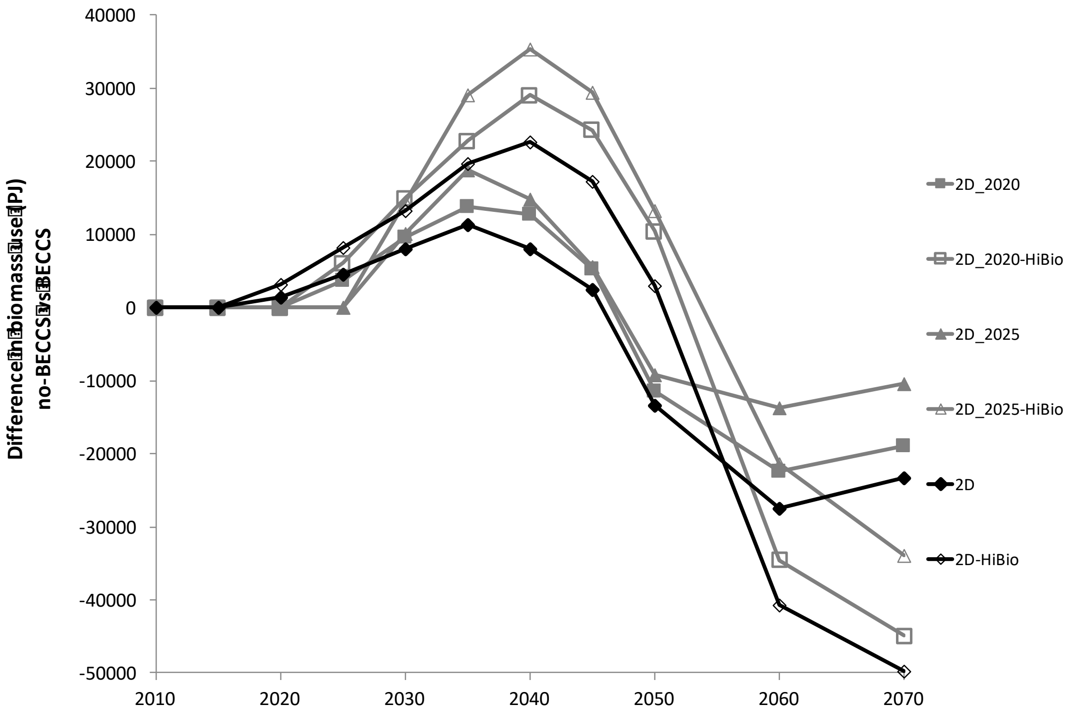

Figure 2.11: Change in bioenergy use in 2°C scenarios until 2070: no BECCS versus with BECCS scenarios.

Figure 2.12 presents the change in primary energy resources used for electricity generation between the high and low biomass availability scenarios for two years of interest: 2035 and 2050. Negative values represent a decrease in the use of the resource under high biomass availability when positive values display a higher share in the electricity generation mix. The cases BECCS is available or not are treated separately for each year. The larger availability of biomass during the scenario is translated into an increase in use of biomass in the generation mix. Under the 2°C constraint and no BECCS availability scenario, coal is rapidly removed from the electricity mix; almost totally by 2035. This corresponds to an immediate global effort to convert power stations, and establish global bioenergy supply chains. The realism of such a rapid supply chain emergence is unclear. Coal can have a more prolonged role when BECCS is available (still present in 2035 mix) and biomass is almost not changed under the high availability scenarios. BECCS creates stronger carbon removal in the later part of the pathway allowing prolonged use of coal and fewer stranded assets. In this scenario, the persistence of coal is accompanied with a slower implementation of natural gas fired power stations that is noticeable only after 2050. The increase in biomass use around the mid-century period mostly reduces the more expensive wind, solar, hydro and nuclear generation (respectively 1.0 EJ, 3.5 EJ, 2.5 EJ and 1.5 EJ under no BECCS or 2.7 EJ, 2.1 EJ, 1 EJ and 5.5 EJ under BECCS availability in 2050). It is noticeable that the largest increase in biomass use as feedstock for electricity generation under higher biomass availability (with or without BECCS) occurs only after 2050.

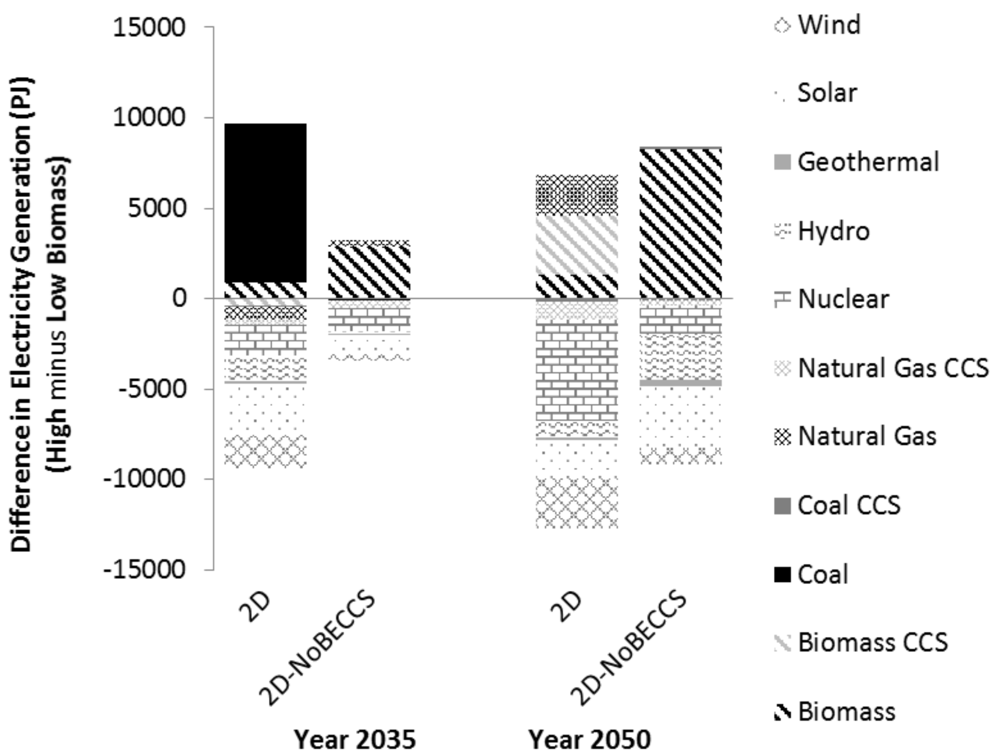

Fig2.12: Difference in electricity generation by technology under 2°C scenarios between high and low biomass scenarios. Only years 2035 and 2050 results are presented from the pathways with no delaying in mitigation policies (peak emissions 2015); negative values convey a reduction and positive values an increase in the use of technology under high biomass availability.

Availability of BECCS can bring down the near-term mitigation costs up to 2-3% depending on assumptions on biomass availability (Figure 2.13). This translates in to a saving, on annual energy system costs, of up to $5.8 trillion under 2D_Highbio scenario and up to $7 trillion under 2D-Lowbio scenario if action to reduce emissions is postponed until 2025. Effects of this cost reduction due to BECCS on carbon prices are significant (Figure 2.9), i.e., required carbon prices to meet the 2-degree target under a no-BECCS scenario will be at least twice as high as compared to that in a corresponding BECCS scenario with low biomass availability. However, there are challenges as BECCS (or CCS) is not yet a commercially viable technology and a considerable amount of investment for research, development and deployment will be necessary to make CCS technology commercially viable. Further, global cooperation among the leading nations, who develop and deploy CCS technologies, is required to make this technology development a success.

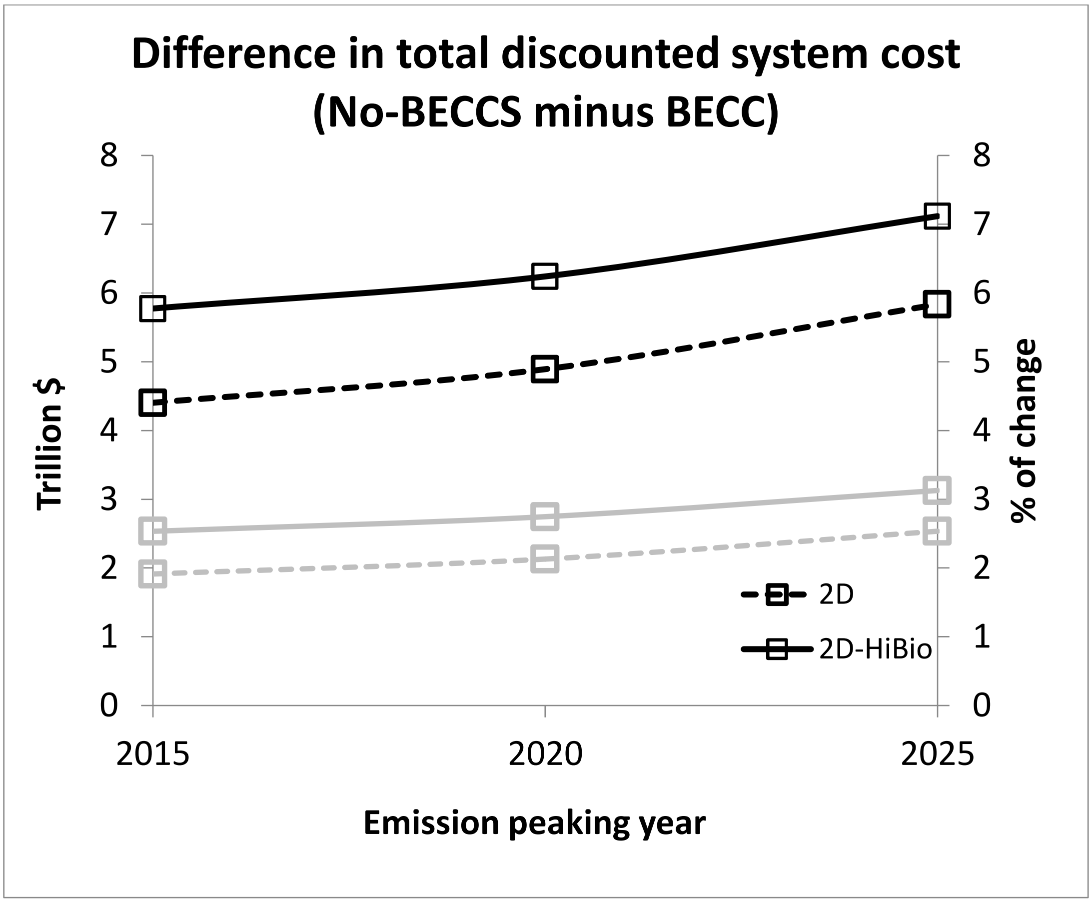

Figure 2.13: Difference in total discounted system cost between scenarios with no-BECCS and scenarios with BECCS to meet 2°C targets function of biomass availability (Black line = absolute change; Grey line = relative change).

4.3.3 1.5⁰ C scenarios

Four scenarios have been developed with a climate policy of achieving 1.5°C target by the end of the century. Figure 2.14 presents CO_2 emissions pathways under different 1.5°C target scenarios. All scenarios require an even more rapid early reduction of CO_2 between 2015 and 2020 than were observed in the 2°C scenarios, especially the two scenarios without BECCS. The results, presented in Figure 2.14, show that, in order to meet the 1.5°C target without BECCS, CO_2 emissions should decrease at a rate of 11% annually between 2015 and 2020 while the scenarios with BECCS require annual reduction rates of 4-7% depending on the scenario. Achieving a reduction rate as high as that in the BECCS scenario appears to be impossible. As den Elzen et al. (2011) argued, the energy system cannot develop and invest in low carbon technologies to reduce

CO_2 emissions at such rates due to very short lead time required for development and installation of low carbon technologies for both supply and demand sectors.

Indeed, even ignoring many of the behavioural and social issues that Den Elzen et al. considered, the TIAM-UCL model is only able to meet the 1.5°C target when 'backstop' technologies are available when BECCS is not available. These are dummy technologies modelled in TIAM-UCL to avoid infeasibility, they produce negative emissions when a certain level in carbon price is achieved (for this chapter the level chosen is 5000 $/t(CO2)). Due to this high cost the processes are only starting-off very late in the scenarios after 2070 to keep the global temperature just below the 1.5°C limit. To a certain degree these 'backstop' processes could represent unspecified and uncertain negative emission technologies such as direct air capture, enhanced weathering or ocean fertilisation for example. This strongly suggests that BECCS appears to be essential to meet the 1.5°C target in absence of alternative negative emissions technologies.

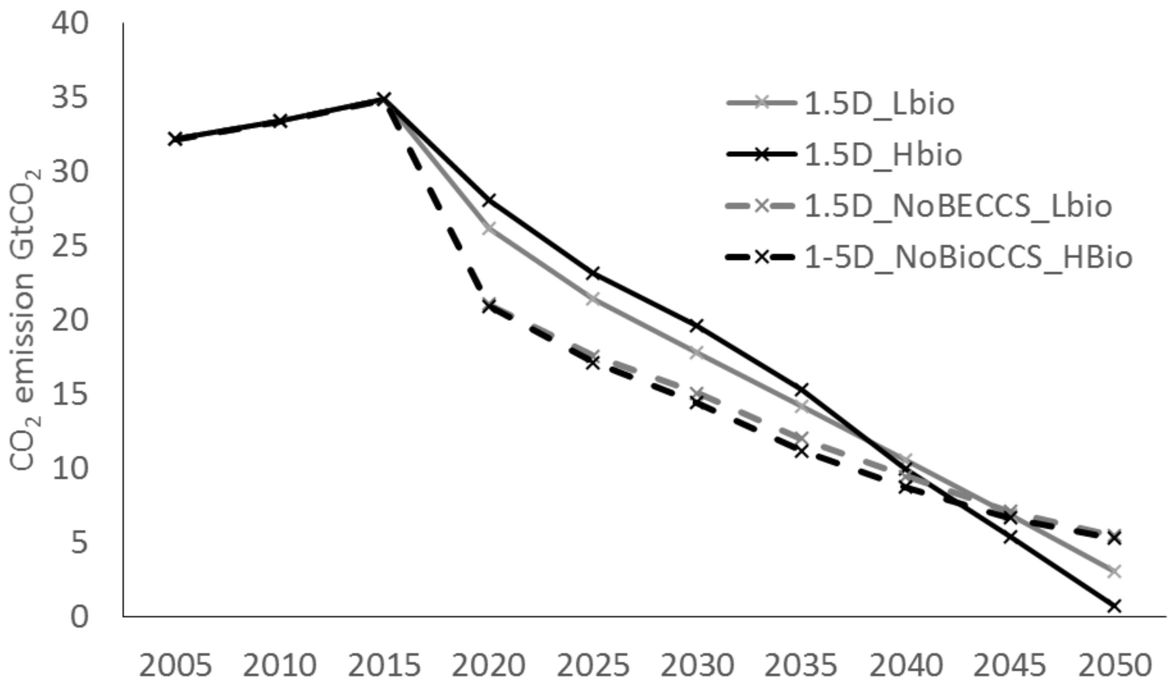

Figure 2.14: Emissions ($GtCO_2$) under different 1.5°C scenarios

The BECCS scenarios require a relatively low CO_2 reduction rate (about half) during 2015-2020 compared to the No BECCS scenarios, allowing more emissions in the early period, as these emissions can be offset by BECCS at a later period (post 2050), reaching net CO_2 emissions negative during the 4th quarter of the century. Net CO_2 emissions in 1.5D_LBio and 1.5D_HBio scenarios are -2.5 tCO_2 and -6.8 tCO_2 in 2100.

The scenarios with BECCS also require a rapid early reduction, which leads to rapid investments in expensive low carbon technologies in the early period, leading to higher marginal CO_2 abatement costs compared to those in the 2D scenarios. Figure 2.15 presents the marginal CO_2 abatement costs under different 1.5°C scenarios. This clearly shows that meeting the 1.5°C target is infeasible without BECCS as it needs a carbon price of over a thousand USD per tonne of CO_2 in 2020.

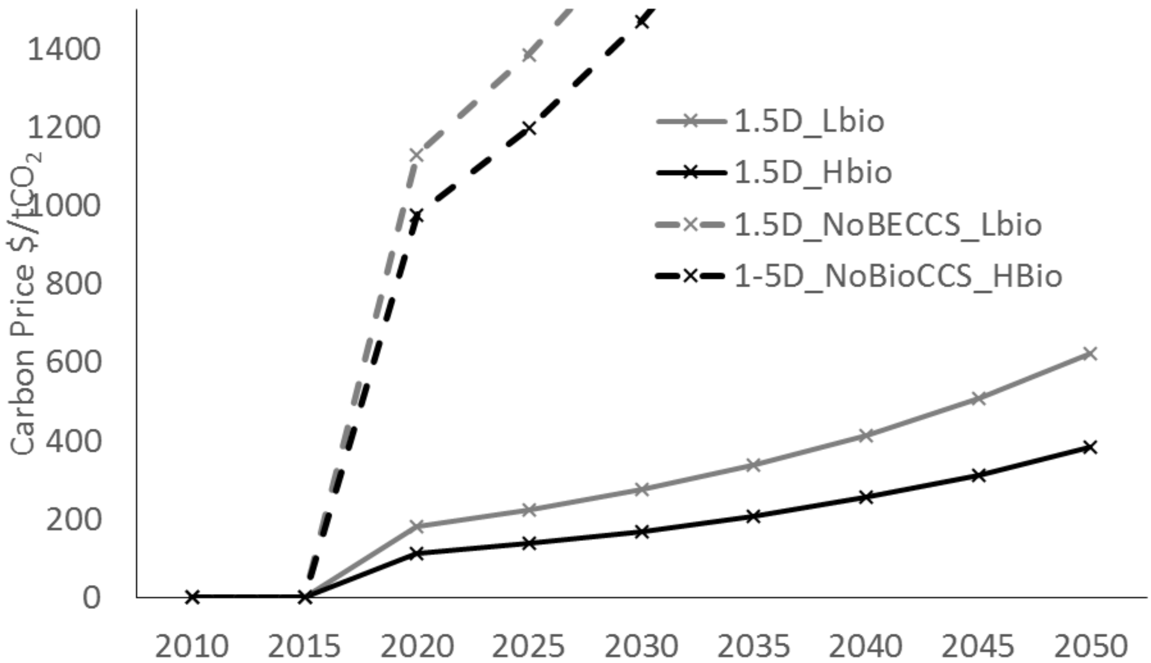

Figure 2.15. Marginal CO_2 prices ($/t$CO_2$) under different 1.5°C scenarios

The model heavily invests in BECCS from 2025 to meet the deep climate policy of 1.5°C target (Figure 2.16). In order to meet the stringent climate policy, depending on the scenario, installed capacity of BECCS varies from 134 GW in 1.5D_HBio scenarios to 142 GW in 1.5D_LBio scenario in 2025 (Figure 2.16) generating at least 5% of the total electricity generation from BECCS. Further, a two-fold increase in the installed capacity is required during the following 10 years between 2025 and 2035 in low biomass scenario to meet the climate target. The respective figure for the high biomass scenarios is at least a four-fold increase. This is clearly a very challenging level of investment as BECCS is not a fully commercialised technology yet. On the other hand, without BECCS it is also not possible to meet the stringent target of 1.5°C.

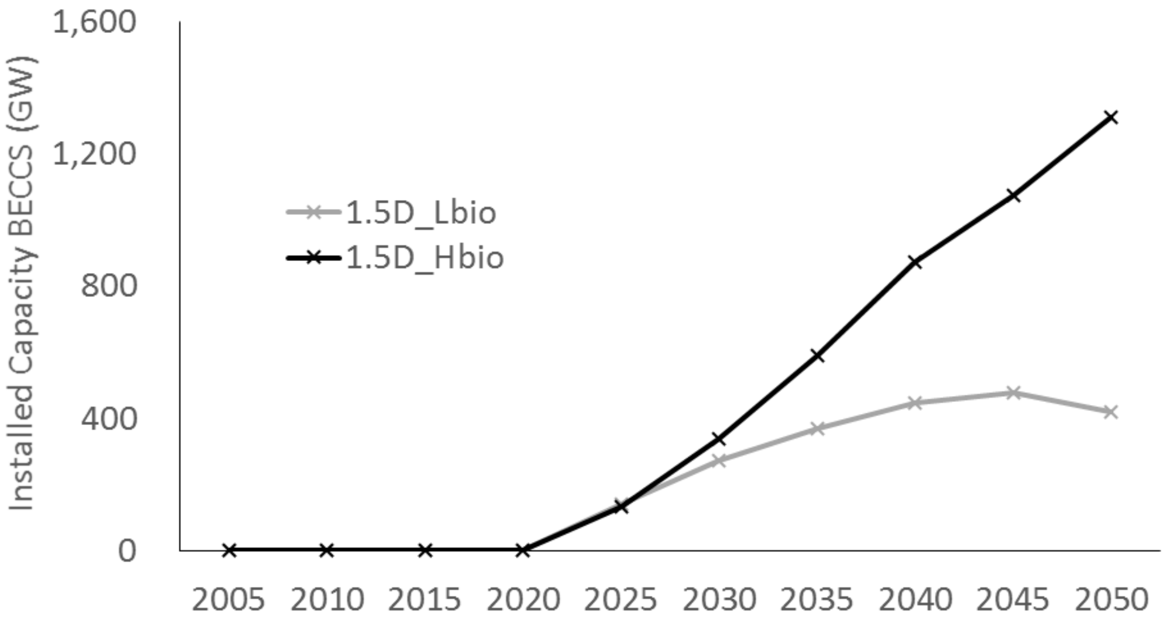

Figure 2.16. Installed Capacity of BECCS (GW) under different 1.5°C scenarios

Electricity generation from BECCS is at least 60% more in 2035 and three times more in 2050 in high bioenergy scenarios compared to that in the low energy scenarios. Additional investment in BECCS capacity in high bioenergy scenarios, mainly reduces generation from gas CCS plants, and also nuclear and wind generations to certain extent compared to that in low bioenergy scenarios.

4.4 Discussion and Conclusions

This chapter investigates the extent to which BECCS is critical for meeting global CO_2 reduction targets under different long-term scenarios during 2005-2100 using the TIAM-UCL global energy system model. We generated and analysed 16 scenarios by varying the availability of biomass in terms of quantity (resource potential) and time (delayed availability) in mitigation action for GHG emissions under 2°C and 1.5°C climate change mitigation targets at global level.

Analysis shows that availability of BECCS can reduce the pressure on near-term mitigation requirements under a 2°C scenario as BECCS can be used to capture CO_2 from the atmosphere in the long-term, especially during the second half of the century, leading to near zero net global emissions by 2100. It especially reduces pressure on the power sector: the CO_2 intensity of electricity halves from 520 g/kWh in 2015 to 250 g/kWh in 2035 under the 2D_BECCS scenarios while it must decrease sharply to 73 g/kWh in 2035 under the 2D-NoBECCS scenario. BECCS alone captures and stores 5.1 $GtCO_2$ in 2050 with an installed capacity of 623 GW. Unavailability of

BECCS doubles the carbon price required in 2050 to meet the 2°C target from 150 to 300 $/t($CO_2$). Sensitivity analysis shows that later action combined with no-BECCS (delaying the peaking year to 2025) can further double the carbon price required to meet the target. Unavailability of BECCS requires the almost complete removal of coal from electricity production by 2035. The realism of such a rapid global supply chain decline is unclear. In return, the availability of BECCS creates stronger carbon removal in the later part of the pathway allowing longer use of coal and lower stranded assets.

In order to meet the 1.5°C target, the model results show that without BECCS, CO_2 emissions should decrease at a rate of 11% annually between 2015 and 2020 resulting in a carbon price of \$1000/tCO_2 in 2020. Moreover, in this case negative emission technologies, other than BECCS, are still needed at the end of the century to achieve the stringent target. But, the BECCS scenario requires relatively low CO_2 reduction rate (about half, ~5%) during 2015-2020 compared to the No-BECCS scenarios. This requires an installed capacity of at least 134GW of BECCS in 2025 generating 5% of the total electricity generated globally. This is clearly a very challenging level of investment, as BECCS is not a commercialised technology yet. On the other hand, without BECCS (or other process producing negative emission) it appears to be impossible to meet the stringent target of 1.5°C.

Many pathways developed here involve extremely rapid reductions in global emissions, implying a degree of global cooperation that is unprecedented. Such a task requires not only agreement between nations, but also it requires the capacity of national governments to effect such a dramatic energy-system transformation. The plausibility of such pathways—in political and socio-economic terms—is highly uncertain, and there may be valid disagreements about whether such pathways represent possible futures or not. In this context, the model outcomes can be regarded as techno-economically optimal (though their optimality even in narrowly defined techno-economic terms is highly uncertain), but their socio-technical plausibility remains open to question. This generates two possible interpretations of some of the principal results of these scenarios.

First, results appear to suggest that the availability of BECCS provides some 'breathing space' to enable globally co-ordinated mitigation efforts to ramp up to the required level. Such an interpretation could be read as reducing the need for near-term action. This would be a mistake. The model formulation, based as it is on optimisation using linear-programming, implicitly assumes a world in which co-ordination barriers are low or non-existent, and technology deployment can proceed without being held up by the behavioural, institutional or political factors that result in slow technology adoption in the real world.

Alternatively, one can understand the scenarios as suggesting that without BECCS, the targets simply become implausible – certainly 1.5 degrees but perhaps also 2 degrees. The social, political and economic conditions under which such rapid global transformation may occur are difficult to even imagine. Such an interpretation puts BECCS—or other NETs—as being absolutely essential for avoiding dangerous climate change, and it suggests that the urgency of investment and learning around BECCS technology is extreme. Even with BECCS, the temperature targets require unprecedented global action such that this interpretation sees BECCS as neither a ‘get-out-of-jail-free-card’ nor as ‘silver bullet’, as – but as a last hope.

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