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Assessment of bio-CCS in 2°C compatible scenarios

by

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Kurzbeschreibung

Um die globale Durchschnittstemperatur auf weniger als 2°C zu begrenzen, müssen CO_2-Emissionen signifikant reduziert werden. Während in den letzten Jahren oder Jahrzehnten eine Zunahme der erneuerbaren Energien, der Energieeffizienz und anderer Klimaschutzmaßnahmen in einem notwendigen Maßstab nicht entwickelt wurden, werden weitere Optionen zur Emissionsreduzierung diskutiert. So genannte Carbon Dioxide Removal (CDR) -Technologien, die teilweise noch als "*unproven technologies*" gelten, könnten ins Spiel kommen. Bio-CCS (Carbon Capture and Storage) gehört zu den Techniken, die mit einem großen Potenzial zur Erzielung negativer Emissionen verbunden sind. Bio-CCS wird daher in einem Großteil der "Kategorie 1" -Szenarien des IPCC verwendet, die einen Temperaturanstieg von unter 2°C erreichen.

Die bio-CCS-Technologie befindet sich derzeit noch in einer frühen kommerziellen Phase und muss sich daher einigen kritischen Fragen stellen, die Fragen zur Machbarkeit der in den Szenarien der Kategorie 1 beschriebenen negativen Emissionen aufwerfen, einschließlich der potenziellen Bereitstellung von (nachhaltiger) Biomasse, der Verfügbarkeit von CO_2-Speicherpotential und die Hochskalierung auf die gewünschte CO_2-Injektionsrate. In dieser Studie wurden diese drei Aspekte anhand von Literaturrecherchen und Gutachten analysiert und bewertet.

Das Ergebnis der durchgeführten groben Machbarkeitsüberprüfung ist, dass keine der Entwicklungen für bio-CCS in den Szenarien ohne zusätzliche Maßnahmen und / oder Investitionen möglich wäre. Die Mehrheit der Szenarien erfordert eine ausgedehnte Intensivierung in Politik, Maßnahmen und / oder Investitionen in mindestens einem der drei Bereiche.

Basierend auf der Analyse kommt die Studie zu dem Schluss, dass die Anwendung von CDR-Technologien eine wichtige Maßnahme für die Erreichung einer globalen Erwärmung unter 2°C ist, ihr Potenzial jedoch voraussichtlich begrenzt sein wird. Ein zu starker Verlass auf CDR-Technologien verringert die Wahrscheinlichkeit, die globale Erwärmung auf weniger als 2°C zu begrenzen, da CDR in den erforderlichen Skalen praktisch nicht möglich ist. Eine schnelle Dekarbonisierung des Energiesektors und eine rasche Reduktion der Gesamtemissionen – zum Beispiel durch den Ausbau erneuerbarer Energien und die Steigerung der Energieeffizienz – ist von größter Priorität, um sicherzustellen, dass die begrenzte Menge an wahrscheinlich verfügbarem CDR-Potential, tatsächlich Null-Netto-Emissionen liefern kann.

Abstract

To limit global average temperature to less than 2°C, CO_2-emissions must be reduced significantly. While an increase in renewable energies, energy efficiency and other climate protection measures has not been developed to a necessary scale in the last years or decades further options are being discussed. So-called Carbon Dioxide Removal (CDR)-technologies which are currently rather "unproven technologies" could come into play. Bio-CCS (Carbon Capture and Storage) is one of the technologies that has been associated with a major potential for attaining negative emissions. Bio-CCS is therefore used in a majority of the "category 1"-scenarios of the IPCC that achieve a global temperature of below 2˚C.

Bio-CCS technology is currently still in an early commercial phase, facing some critical issues that raise questions regarding the feasibility of achieving the amount of negative emissions described in the category 1 scenarios, including the potential supply of (sustainable) biomass, the availability of CO_2 storage potential and the upscaling towards the desired CO_2-injection rate. In this study, these three aspects have been analysed and assessed based on literature reviews and expert opinions.

The outcome of the rough feasibility check is that none of the developments for bio-CCS in the scenarios would be possible without requiring additional policies, measures and/or investments. The majority of the scenarios requires even extensive intensification in policies, measures and/or investments in at least one of the three fields.

Based on the analysis, the study concluded that CDR appears to be one important measure in maintaining global warming below 2ºC, but its potential is expected to be limited. Too heavy reliance on CDR technologies reduces the likelihood of limiting warming to less than 2ºC, as carbon dioxide removal may not be practically availably at the scales required. This means rapid decarbonisation of the energy sector and rapid reductions in overall emissions are of utmost priority, to ensure that the limited amount of carbon dioxide removal potential that will likely be available can still provide net zero emissions.

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Abbreviations

bio-CCS	Bio Carbon Capture and Storage
CAP	Common Agricultural Policy
CCS	Carbon Capture and Storage
CDR	Carbon Dioxide Removal
EASAC	European Academies Science Advisory Council
EC	European Commission
EE	Energy efficiency
EPA	Environmental Protection Agency
EU	European Union
GCAM	Global Change Assessment Model
GCM	General Circulation Models
GDP	Gross Domestic Product
GHG	Greenhouse Gas
IAM	Integrated assessment model
IEA	International Energy Agency
ILO	International Labour Organisation
ILUC	Indirect land use change
IMAGE	Integrated Model to Assess the Global Environment
IPCC	Intergovernmental Panel on Climate Change
MENA	Middle East & North Africa
MESSAGE	Model for Energy Supply Strategy Alternatives and their General Environmental Impact
MMV	Measurement, Monitoring and Verification
MSW	Municipal Solid Waste
NETL	National Energy Technology Laboratory
ppm	Parts per million
RED	Renewable Energy Directive
REMIND	Regional Model of Investments and Development
RFS	Renewable Fuel Standard
RSB	Roundtable for Sustainable Biomass
UAE	United Arab Emirates
UNFCCC	United Nations Framework Convention on Climate Change

Zusammenfassung

Auf der 21. Konferenz der Vertragsparteien des Rahmenübereinkommens der Vereinten Nationen über Klimaänderungen (UNFCCC) in Paris im Jahr 2015 vereinbarten die Staats- und Regierungschefs, den Anstieg der globalen Durchschnittstemperatur auf deutlich unter 2°C bis 2100 im Vergleich zu vorindustriellen Niveau zu begrenzen. Es wurde vereinbart, Bemühungen zur Begrenzung der globalen Temperaturerhöhung auf 1,5 ° C zu verfolgen. Nach dem Fünften Sachstandsbericht (AR5) des Intergovernmental Panel on Climate Change (IPCC) müssen Treibhausgasemissionen im Vergleich zu 2010 um 40 bis 70% und bis zum Ende des Jahrhunderts um fast 100% gesenkt werden, um die globale Durchschnittstemperatur auf weniger als 2°C zu begrenzen.

Um die notwendigen Emissionsminderungen zu erreichen, ist ein Produktportfolio an Technologien erforderlich. Die bisher nicht ausreichenden Klimaschutzmaßnahmen haben die Relevanz der Debatte über Techniken, die Kohlendioxid (CO_2) aus der Atmosphäre entfernen, erhöht. Technologien, die negative Treibhausgasemissionen erzeugen sind sogenannte Carbon Dioxide Removal (CDR) -Technologien. Bio-CCS (Carbon Capture and Storage) ist eine CDR-Technologie, die mit einem großen Potenzial für die Erzielung von negativen Emissionen verbunden ist. Bio-CCS kann zum Beispiel in einzelnen Bereichen nicht-CO_2 Emissionen kompensieren, in denen Vermeidungstechnologien derzeit zu kostenintensiv sind.

Viele der Modelle, die Klimaschutzszenarien berechnen, sind ohne bio-CCS nicht in der Lage, eine wahrscheinliche Erwärmung von unter 2°C (auch als "Kategorie 1" -Szenarien bezeichnet) zu erreichen. In 104 von 116 der Kategorie 1 - Szenarien im AR5 ist bio-CCS eine wesentliche Technologie zur Erreichung der notwendigen Emissionsreduktionen.

Die bio-CCS-Technologie befindet sich derzeit noch in einer frühen kommerziellen Phase und muss sich daher einigen kritischen Fragen stellen, die Fragen zur Machbarkeit der in den Szenarien der Kategorie 1 beschriebenen negativen Emissionen aufwerfen:

- Was ist das verfügbare Potenzial an (nachhaltiger) Biomasse?
- Was ist das Potential zur CO_2 -Speicherung sowohl aus fossilen als auch aus Biomasse?
- Was ist der Zeitpunkt für diese Technologie und was sind realistische CO_2-Injektionssraten?

Um diese Fragen zu beantworten, wurden die 104 bio-CCS Szenarien beurteilt. Um eine fokussierte Bewertung zu ermöglichen, wurde eine Auswahl von fünf Modellen erstellt, die fast 75% der Szenarien der Kategorie 1 abdecken:

- Global Change Assessment Model (GCAM, including MiniCAM)
- Integrated Model to Assess the Global Environment (IMAGE)
- Model for Evaluating the Regional and Global Effects (MERGE)
- Model for Energy Supply Strategy Alternatives and their General Environmental Impact (MESSAGE)
- Regional Model of Investments and Development (REMIND)

Um Einblicke in die Machbarkeit von bio-CCS-Szenarien zu geben, wurde ein dreistufiger Ansatz gewählt: *erstens*, wurden die zugrunde liegenden Annahmen in den ausgewählten Modellen und Szenarien identifiziert und bewertet; *zweitens* wurden die Annahmen auf der Grundlage von Literatur und / oder Expertenansichten hinsichtlich ihrer Machbarkeit und Nachhaltigkeit kritisch überprüft und bewertet; *drittens* wurden die Ergebnisse von Schritt 1 und Schritt 2 verglichen, um Einblicke in die Erreichbarkeit der einzelnen Szenarien zu geben und um zu bewerten ob zusätzliche Maßnahmen erforderlich sind.

Im ersten Schritt wurden die zugrundeliegenden Annahmen und Szenario-Ergebnisse der ausgewählten Modelle identifiziert und bewertet. Dabei werden allgemeine Indikatoren (Bevölkerungswachstum und Wirtschaftswachstum), die Entwicklung von Biomasse (Biomasse-Nachfrage, Biomasse-Arten und Landnutzung)

und (bio-)CCS-Entwicklung (Einsatz von bio-CCS und Entwicklung der CO_2-Abscheidung und -Speicherung) betrachtet. Basierend auf der IPCC-Datenbank wurden Erkenntnisse in der Entwicklung von Primärenergie aus Biomasse, dem Einsatz von CO_2-Lagerstätten (sowohl fossile als auch biogene) und der CO_2-Injektionsrate bereitgestellt:

- Alle Szenarien gehen von einem **Anstieg des Primärenergiebedarf aus Biomasse** auf 100-350 EJ/Jahr im Jahr 2100 aus. Ein kleiner Teil der Szenarien geht von einem Primärenergiebedarf zwischen 100-150 EJ/Jahr aus, die Mehrheit der Szenarien von 175-275 EJ/Jahr. Ein paar der Szenarien nehmen einen Anstieg von über 300 EJ/Jahr an.
- Bei der **Entwicklung von bio-CCS** zeigen die ausgewählten Szenarien eine große Bandbreite bis 2100: zwischen 50-300 EJ/Jahr. Einige der Szenarien bleiben unter 100 EJ/Jahr, während die meisten Szenarien einen wachsenden Trend zu 125-175 EJ/Jahr zeigen. Ein bedeutender Teil der Szenarien zeigt ein Wachstum bis zu 205-300 EJ/Jahr. Interessant ist der Anteil von bio-CCS am gesamten Primärenergiebedarf aus Biomasse. Im Jahr 2100 zeigen alle ausgewählten Szenarien einen bio-CCS-Anteil von 50% oder mehr, von denen etwa die Hälfte im Bereich von 75% oder mehr liegt. Einige Szenarien gehen von einem bio-CCS-Anteil von 100% aus.
- Die Entwicklung der **CO_2-Abscheidung und -Speicherung** zeigt ebenso eine große Vielfalt zwischen den ausgewählten Szenarien. Ab 2010, wo im Grunde noch kein CO_2 eingespeichert wird, gehen die Szenarien davon aus, dass im Jahr 2100 die CO_2-Injektionsrate (biogene und fossile) zwischen10-60 Gt CO_2 pro Jahr liegt. Die Szenarien gehen davon aus, dass bis zum Jahr 2100 zwischen 614.000 und 2.300.000 Gt CO_2 eingespeichert werden.

Im zweiten Schritt wurden die Modellergebnisse mit Hilfe von Literaturrecherche und Expertenmeinungen überprüft. Dies führte zu folgenden Erkenntnissen:

- Um eine ausreichende Versorgung mit Biomasse zu gewährleisten, sind nachhaltiger Anbau und Nutzung von Biomasse eine Voraussetzung. Bisher sind Nachhaltigkeitskriterien jedoch erst in der Vorbereitung. Dazu gehören die Formulierung und Umsetzung von Maßnahmen zur Sicherung der biologischen Vielfalt, der Ernährungssicherheit, der Wasserknappheit und der Bodendegradation.
- Eine globale primäre Bioenergieproduktion von bis zu 100 EJ/Jahr kann aus Abfällen und Rückständen und auf aufgegebenen landwirtschaftlichen Flächen ohne Verbesserungen über autonome Trends realisiert werden. Eine nachhaltige globale Nachfrage nach Primärenergie aus Biomasse von über100 EJ/Jahr, würde die Umsetzung zusätzlicher Nachhaltigkeitsmaßnahmen erfordern. Je höher der Einsatz von Biomasse vorgesehen ist, desto umfangreichere und strengere zusätzliche Maßnahmen sollten ergriffen werden. Die primäre Bioenergieproduktion von über 300 EJ/Jahr kann realisiert werden, erfordert aber eine deutliche Verbesserung des globalen Agrar-Nahrungsmittelsystems, unter anderem durch die Überbrückung von Ertragslücken und die Verbesserung der Lieferketten-Logistik.
- Das theoretische CO_2-Speicherpotential wird zwischen 8.000-15.000 Gt CO_2 geschätzt. Die praktische CO_2-Speicherkapazität wird auf 3.900 Gt CO_2 geschätzt. Diese Bewertung umfasst sowohl Onshore- als auch Offshore-CO_2-Speicherkapazitäten in tiefen Kochsalzlösungen, erschöpften Gasfeldern sowie Ölfeldern und nicht abbauwürdige Kohleflözen.
- Die IEA-Roadmaps 2009 und 2013 zu CCS beschreiben die erwartete CO_2-Menge, die bis zum Jahr 2050 gespeichert werden kann. Zwischen den beiden Roadmaps wurde ein rückläufiger Trend festgestellt: 2009 wurde die CO_2-Menge auf 145 Gt CO_2 geschätzt, während im zweiten Bericht die Schätzung auf 120 Gt CO_2 gesenkt wurde. Die Schätzung wurde aufgrund der Verzögerungen und Schwierigkeiten bei der Entwicklung der CCS-Industrie reduziert.
- Die aktuelle Entwicklungsrate von CCS-Projekten ist niedriger als in den meisten Szenarien dargestellt. Die Projektpipeline zeigt, dass in den kommenden 15 Jahren neue CCS-Projekte entwickelt werden, jedoch ist die eingespeicherte Menge geringer als in den Szenarien angenommen.

- Die IEA-Roadmaps 2009 und 2013 beschreiben auch die erwarteten CO_2 Injektionsraten bis 2050. Ähnlich wie bei der eingespeicherten CO_2-Menge wurde ein Rückgang bei den Injektionsraten zwischen den beiden Roadmaps festgestellt: Im Jahr 2009 wurde die Injektionsrate auf 10 Gt CO_2 geschätzt, während im Jahr 2013 diese Schätzung auf 8 Gt CO_2 pro Jahr reduziert wurde.

Die Ergebnisse von Schritt 1 und Schritt 2 wurden in einer groben Machbarkeitsüberprüfung verglichen, um die Erreichbarkeit der einzelnen Szenarien mit Bezug auf einzelne Indikatoren zu überprüfen. Abhängig von den Unterschieden zwischen den Modellannahmen und den Ergebnissen sind zusätzliche Maßnahmen erforderlich, um die Szenarien zu realisieren. Es gibt drei mögliche Ergebnisse:

- Politiken, Maßnahmen und / oder Investitionen, wie sie in der Literatur beschrieben sind, sind ausreichend, keine zusätzlichen Maßnahmen erforderlich.
- Die Szenarien gehen von einer verstärkten Entwicklung eines Indikators aus und erfordern zusätzliche Politiken, Maßnahmen und / oder Investitionen;
- Die Szenarien erfordern eine umfangreiche Intensivierung von Politiken, Maßnahmen und / oder Investitionen.

Die Ergebnisse der Machbarkeitsüberprüfung sind wie folgt:

- Ohne Änderungen der Politiken, Maßnahmen und / oder Investitionen in nachhaltige Biomasse und / oder die Realisierung von ausreichend CO_2-Speicherkapazitäten ist keine bio-CCS Entwicklung wie in den Szenarien beschrieben realistisch.
- Die Mehrheit der Szenarien (82) erfordert eine umfangreiche Intensivierung der Politiken, Maßnahmen und / oder Investitionen in mindestens einem der drei Indikatoren. Ohne solche Maßnahmen scheint die Erreichbarkeit dieser Szenarien unwahrscheinlich.
- Ein kleinerer Teil der Szenarien (17) erfordert zusätzliche Politiken, Maßnahmen und / oder Investitionen:
  - Alle Szenarien erfordern zusätzliche Maßnahmen zur Sicherstellung der Nachhaltigkeit der Biomasse.
  - Die meisten dieser Szenarien erfordern Investitionen und konzertierte Aktionen zur Steigerung der Entwicklung der CCS-Infrastruktur. Nur eine Handvoll Szenarien erfordert keine zusätzlichen Maßnahmen.
- Für die verbleibenden 5 Szenarien gab es nicht ausreichend Daten über den Primärenergieverbrauch aus Biomasse, um ins Gesamtergebnis aufgenommen zu werden.

Die Ergebnisse führen zu folgenden wesentlichen Schlussfolgerungen:

- CDR (negative Emissionen) kann eine wichtige Maßnahme für die Einhaltung der globalen Erwärmung unter 2°C sein. Jedoch wird das Potenzial voraussichtlich begrenzt sein. Ohne zusätzliche Maßnahmen nimmt die Wahrscheinlichkeit ab, dass diese Szenarien einen machbaren Entwicklungspfad für eine globale Erwärmung um maximal 2°C darstellen.
- Bei den Szenarien, die sehr stark auf negativen Emissionen basieren, verringert sich die Wahrscheinlichkeit einen realistischen 2°C Entwicklungspfad zu beschreiben, da die CO_2-Einspeicherung in den erforderlichen Skalen praktisch nicht verfügbar ist.
- Der Vergleich der derzeitigen Verfügbarkeit von Bioenergie und (bio-)CCS mit der prognostizierten Entwicklung in den ausgewählten Szenarien zeigt, dass in einigen Szenarien davon ausgegangen wurde, dass der Einsatz von (bio-)-CCS bereits jetzt weiter fortgeschritten ist, als dies tatsächlich der Fall ist. Obwohl man davon ausgehen kann, dass aktuelle Abweichungen zwischen Szenarien und der aktuellen Entwicklung ausgeglichen werden können, ist festzustellen, dass dies für Szenarien, die einen erheblichen Anteil an bio-CCS beinhalten, kritisch sein kann. Diese Szenarien basieren (sehr stark) auf der Realisierung negativer Emissionen in der Zukunft, um aktuell relativ hohe CO_2-Emissionen zu kompensieren. Wenn die Realisierung von bio-CCS sich weiterhin nur sehr langsam

entwickelt und umgesetzt wird, wird die Machbarkeit des 2°C Ziels mit diesen Technologien immer ungewisser.

- Der Mangel an Übereinstimmung zwischen Biomassequellen und CO_2-Speicherressourcen könnte möglicherweise die Erfassung und Speicherung von biogenem CO_2 einschränken. Voraussichtlich müsste Biomasse zu Anlagen, die mit einem CO_2-Speichernetz verbunden sind, transportiert werden, was die Kosten für bio-CCS erheblich steigern würde.

Summary

At the 21st Conference of the Parties of the United Nations Framework Convention on Climate in Paris in 2015, the heads of governments agreed to limit the increase of global average temperature to well below 2°C by 2100 compared to pre-industrial levels. It was agreed to pursue efforts to limit global temperature increase to 1.5°C. Following the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC), greenhouse gas (GHG) emissions need to be reduced by 40 to 70% compared to 2010 levels and by almost 100% until the end of the century (IPCC, 2014a) in order to limit global average temperature to less than 2°C.

To reach the necessary emission reductions, a portfolio of technologies is needed. The low mitigation actions that have been taken so far have increased the relevance of the debate over technologies that remove carbon dioxide (CO_2) from the atmosphere. Technologies that have net negative GHG emissions are called Carbon Dioxide Removal (CDR)-Technologies. Bio-CCS (Carbon Capture and Storage) is a CDR technology that has been associated with a major potential for attaining negative emissions. Bio-CCS is used for example to compensate non-CO_2 GHG emissions as an alternative to more costly mitigation technologies (IPCC, 2014b).

Many models used to run the scenarios are unable to achieve a likely warming of below 2°C (also referred to as "category 1" scenarios) if bioenergy, CCS and their combination bio-CCS are limited. In the scenarios considered in AR5, 104 out of 116 category 1 scenarios included bio-CCS to play a role in emission reduction (IPCC, 2014b).

The development and deployment of bio-CCS faces some critical issues, which raise questions regarding the feasibility of achieving the amount of negative emissions described in the scenarios:

- What is the potential supply of (sustainable) biomass?
- What is the potential to store CO_2 originating from both fossil and biomass feedstock?
- What is the timing of mitigation and the CO_2-injection rate?

To answer these questions, the 104 category 1 scenarios including bio-CCS were assessed. To create focus in the assessment, a selection of five models was made which cover almost 75% of the category 1 scenarios:

- Global Change Assessment Model (GCAM, including MiniCAM)
- Integrated Model to Assess the Global Environment (IMAGE)
- Model for Evaluating the Regional and Global Effects (MERGE)
- Model for Energy Supply Strategy Alternatives and their General Environmental Impact (MESSAGE)
- Regional Model of Investments and Development (REMIND)

To provide insights in the feasibility of bio-CCS scenarios, a three-stepped approach was taken: first, to identify and assess the underlying assumptions made in the selected models and scenarios and second, critically review the assumptions with regards to feasibility and sustainability based on literature and/or expert views. In the third step, the results of step 1 and step 2 were compared providing insights in the achievability of the individual scenarios and whether there is need for additional action.

In the first step, underlying assumptions and scenario outcomes of the selected models were identified and assessed, focusing on general indicators (population growth and economic growth), biomass development (biomass demand, types of biomass used and land use) and (bio-)CCS development (deployment of bio-CCS and development of CO_2 capture and storage). Based on the IPCC database, insights were provided in the development of primary energy from biomass, the deployment of CO_2 storage (both fossil and biogenic) and the CO_2-injection rate:

- All scenarios assume a growth in **biomass demand from primary energy** towards 100-350 EJ/yr in 2100. A small part of the scenarios assume a primary energy demand between 100-150 EJ/yr, the

majority of the scenarios assume primary energy demand between 175-275 EJ/yr. A small fraction assumes primary energy demand to exceed 300 EJ/yr;

- On the **development of bio-CCS** the selected scenarios show a large spread towards 2100: between 50-300 EJ/yr of bio-CCS. Some of the scenarios stay below 100 EJ/yr, while most of the scenarios show a growing trend towards 125-175 EJ/yr. A significant part of the scenarios show growth up to 205-300 EJ/yr. What is interesting is the share of bio-CCS of the total primary energy demand from biomass. In 2100 all selected scenarios show a bio-CCS share of 50% or more, of which about half is in the range of 75% or more. Some scenarios assume a bio-CCS share of 100%;
- The **development of CO_2 capture and storage** show large diversity between the selected scenarios towards 2100. Starting in 2010 with basically no CCS, the scenarios assume that in 2100 the CO_2 injection rate will be 10-60 Gt CO_2 per year (including biogenic and fossil CO_2). Over the period up to 2100 between 614,000 and 2,300,000 Gt CO_2 is assumed to be stored.

In the second step, literature and expert opinions are used to review the model outcomes. This led to the following insights:

- To ensure **sufficient biomass supply, sustainable cultivation and use of biomass is very important**. Governments and other stakeholders develop sustainability criteria and measures to enforce these. This includes formulation and implementation of measures to safeguard biodiversity, food security, water scarcity and soil degradation.
- A **global primary bioenergy production of up to 100 EJ/yr** can be realised from **waste and residues** and on abandoned agricultural land without improvements beyond autonomous trends. Realising a global sustainable primary bioenergy demand >100EJ/yr would require the implementation of additional sustainability measures: the higher the bioenergy potential, the more extensive and stricter additional measures should be. Realising **100-300 EJ/yr** is deemed possible with **additional measures and developments that can be supported on a project or feedstock procurement level**. Primary bioenergy production **>300 EJ/yr** can be realised, but would require **significant improvement of the global agri-food system**, amongst others by bridging yield gaps and improving supply chain logistics.
- The theoretical CO_2 storage potential is estimated between 8,000-15,000 Gt CO_2 (IEA, 2010b), the practical CO_2 storage capacity is estimated at 3,900 Gt CO_2 (Dooley, 2013). This assessment includes both onshore and offshore CO_2 storage capacity in deep saline formations, depleted gas fields, depleted oil fields, and unminable coal seams.
- The IEA Roadmaps on CCS (IEA, 2009; IEA, 2013) report on the expected amount of CO_2 that can be stored in 2050. Between the two roadmaps a declining trend was identified: **in 2009 the amount of CO_2 was estimated at 145 Gt CO_2**, while **in 2013 this estimation was lowered to 120 Gt CO_2**. The estimation was reduced because of the delays and difficulties in the development of CCS-industry to make this step towards fully integrated commercial-scale deployment.
- The current development rate of CCS-projects is lower than anticipated in most scenarios. The project pipeline shows that in the coming 15 years new CCS projects are expected to become operational online, however the capture capacity of these projects is less than estimated in the scenarios.
- The IEA Roadmaps on CCS (IEA, 2009; IEA, 2013) report on the expected injection rates of CO_2 in 2050. Similar to the amount of CO_2 stored, a declining trend was identified on injection rates between the two roadmaps: in **2009, the injection rate was estimated at 10 Gt CO_2**, while **in 2013 this estimation was lowered to 8 Gt CO_2 per year**.

The results of step 1 and step 2 were compared in the rough feasibility check, providing insights in the achievability of the individual scenarios on individual indicators. Depending on the differences between the model assumptions and outcomes and the literature review, there is a need for additional measures in order to realise the pathways described by the scenarios. There are three possible outcomes:

- Policies, measures and/or investments as described in literature are sufficient, no need for additional action;
- The scenarios assume increased development of the indicator, requiring additional policies, measures and/or investments;
- The scenarios require an extensive intensification of policies, measures and/or investments.

The results of the rough feasibility assessment are as follows:

- **None of the developments for bio-CCS in the scenarios would be possible without changes in policies, measures and/or investments in sustainable biomass <u>and/or</u> the realisation of sufficient CO_2 storage capacity.**
- **The majority of the scenarios (82) requires extensive intensification in policies, measures and/or investments in at least one of the three indicators.** Without such measures, the achievability of these scenarios seems unlikely.
- **A smaller part of the scenarios (17) the development of bio-CCS will require additional policies, measures and/or investments:**
  - All of these scenarios require additional measures to ensure sustainability of biomass.
  - Most of these scenarios require investments and concerted action to increase the development of CCS-infrastructure. Only a handful of the scenarios do not require additional measures.
- For the remaining 5 scenarios, there was not enough data available on primary energy use from biomass to be included in this overall result.

The results lead to the following main conclusions:

- **Carbon dioxide removal (negative emissions) appears to be one important measure in maintaining global warming below 2ºC, but its potential is expected to be limited.** Particularly regarding bio-CCS, due to lower realisation rates of CCS and requirements needed to cultivate and use biomass in a sustainable manner, the realisation of the required negative emissions will require additional policies, measures and/or investments. Following a path oriented towards these category 1 scenarios **without additional action**, can therefore significantly decrease the probability of limiting warming to below 2°C can.
- Following the lead of scenarios that largely depend on carbon dioxide removal **reduces the likelihood of limiting warming to less than 2ºC, as carbon dioxide removal may not be practically availably at the scales required, while misguided policies and investments could delay the required rapid emissions reductions and decarbonisation of the energy sector.**
- Comparing the current deployment of bioenergy and (bio-)CCS with the estimated deployment in the selected scenarios, shows that in some scenarios it was **assumed that deployment of (bio)-CCS would already have further advanced by now than is actually the case in reality**. Although at this moment it is plausible for current real-life deployment to catch up with pathways described by the scenarios, it is important to consider that **this delay can become critical for following a path described by scenarios that include a significant share of bio-CCS.** These scenarios rely (heavily) on the realisation negative emissions in the future to compensate their relatively high current CO_2 emissions. If the implementation of bio-CCS is delayed further or implemented at a smaller scale than originally planned, the feasibility of such a pathway in limiting global warming to below 2ºC becomes increasingly uncertain.
- The lack of matching between biomass sources and CO_2 storage resources could potentially limit capture and storage of biogenic CO_2 or require biomass to be transported to facilities connected to CO_2 storage network. The latter could then considerably increase the costs for bio-CCS.

1 Introduction

1.1 Background

At the 21st Conference of the Parties of the United Nations Framework Convention on Climate in Paris in 2015, the heads of governments agreed to limit the increase of global average temperature to well below 2°C by 2100 compared to pre-industrial levels. It was agreed to pursue efforts to limit global temperature increase to 1.5°C. Following the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC), greenhouse gas (GHG) emissions need to be reduced by 40 to 70% compared to 2010 levels and by almost 100% until the end of the century (IPCC, 2014a), in order to limit global average temperature to less than 2°C.

To reach the necessary emission reductions, a portfolio of technologies is needed. The relatively low ambition in mitigation actions taken so far have increased the relevance of the debate over technologies that remove carbon dioxide (CO_2) from the atmosphere. Technologies that have net negative GHG emissions are called Carbon Dioxide Removal (CDR)-Technologies. Bio-CCS (Carbon Capture and Storage) is a CDR technology that has been associated with a major potential for attaining negative emissions (for definition see chapter 2.1).

AR5 scenarios that are classified to likely stay within the temperature increase limit of 2°C, must stay within radiative forcing values of 2.3 to 2.9 Watt per m² in 2100. A clear majority of these AR5 scenarios include an overshoot of 0.4 Watt per m². In these scenarios, the relevance of bio-CCS technologies to compensate overshoot with negative emissions is high. Bio-CCS is used for example to compensate non-CO_2 GHG emissions as an alternative to more costly mitigation technologies (IPCC, 2014b). Moreover, many models used to run the scenarios are unable to achieve a likely warming of below 2°C (also referred to as "category 1" scenarios) if bioenergy, CCS and their combination, known as bio-CCS, are limited. In the scenarios considered in AR5, 104 out of 116 category 1 scenarios included bio-CCS to play a role in emission reduction (IPCC, 2014b).

Studies claim that negative emission technologies significantly enhance the possibility to meet low concentration targets. An earlier study of Azar showed that bio-CCS leads to a reduction of atmospheric concentrations of 50 to100 ppm at the same cost level as for abatement actions without bio-CCS (Azar, et al., 2010). The study also showed that for lower stabilization targets, i.e. low concentration levels, the cost reduction by bio-CCS becomes more significant. However, do these studies remain within the physical boundaries that may limit the assumed effectiveness of bio-CCS? And is the large-scale use of bio-CCS sustainable?

The application of bio-CCS has some critical issues, which raise questions regarding the feasibility of achieving the amount of negative emissions described in the scenarios. One such critical issue is the potential supply of (sustainable) biomass. The models which run the scenario use different assumptions with respect to availability of sustainable biomass. Another issue is the potential to store CO_2 originating from both fossil and biomass feedstock. A third critical issue concerns the timing of mitigation and the injection rate. Bio-CCS theoretically makes it possible to postpone emission reduction in the near term and compensate that by removing CO_2 in a later stage. This perception may cause delaying implementation of necessary timely measures. It may e.g. lead to higher overshoot leading to more climate impacts which might even be irreversible (O'Neill & Oppenheimer, 2004; Lenton, et al., 2008). In addition, development of technologies like (bio-)CCS may need a long lead time before large-scale deployment and creation of sufficient infrastructure.

1.2 Objective

The objective of the study is to understand and evaluate the main assumptions related to the role of bio-CCS in 2°C compatible IPCC scenarios assessed in the AR5. The study focusses on the analysis of general input assumptions, biomass assumptions and bio-CCS assumptions used in the models. The authors of this study have assessed the related impacts in a rough feasibility assessment of the scale to which bio-CCS is relied upon in the scenarios in line with sustainable limits.

The objective can be structured into the following interim goals:

- Identification and classification of 2°C compatible scenarios based on bio-CCS in AR5,
- Assessment of input variables and potentials of the scenarios with relevance for bio-CCS,
- Rough feasibility assessment and sustainability assessment of the scenarios and underlying models.

1.3 Structure

To provide insights in the feasibility of bio-CCS scenarios, a two-stepped approach was taken: first, to present the results and the underlying assumptions made in the selected models and scenarios and second, critically review the assumptions with regards to feasibility and sustainability based on literature and/or expert views. The first step results in an overview of the AR5 IPCC scenarios including bio-CCS, on the basis of which the most important scenarios were selected. The results are described in chapter 2. Based on IPCC data, model descriptions, literature and key climate-modelling expert input, the underlying assumptions related to general input (i.e. population and economic growth), biomass assumptions (including demand, type of biomass and land use) and bio-CCS assumptions (including storage potential) are identified and presented in chapter 3. In chapter 4, the results and assumptions as presented in chapters 2 and 3 are critically reviewed. The review is based on literature and modelling expert views. In order to provide a complete picture, chapter 6 gives an overview of non-bio-CCS scenarios. The report concludes in chapter 7 with a rough feasibility assessment of bio-CCS application in 2°C scenarios.

2 Methodology of the analysis

2.1 Definition of bio-CCS

In this study, bio-CCS is defined as processes in which CO_2 originating from biomass is captured and stored. These can be energy production processes or any other industrial processes with CO_2-rich process streams originating from biomass feedstocks. The CO_2 that is generated within these processes is separated with technologies generally associated with CCS for fossil fuels, e.g. post combustion, pre- combustion and oxy-fuel.

The underlying premise of bio-CCS is that it can be used to generate negative GHG emissions because biomass binds carbon from the atmosphere as it grows. With the conversion of the biomass, this carbon is usually released as CO_2. If, instead, the CO_2 coming from biomass is captured, transported to a storage site and permanently stored deep underground, the process is assumed to result in a net removal of CO_2 from the atmosphere. For most AR5 models (IMAGE, GCAM, REMIND) this includes emissions from land-use change related to bioenergy in addition to emissions from cultivation and processing (Van Vuuren D. , 2016).

The IPCC AR5 scenarios take into account CDR technologies which have net negative GHG emissions. The IPCC considers bio-CCS and afforestation as CDR technologies. Other technologies such as geoengineering are not included in the scenarios (IPCC, 2014a).

2.2 Definition of models and scenarios

There are several types of models. The two most common types and the role of scenarios in models are explained below.

Integrated assessment models (IAM) are tools that integrate multiple knowledge areas and systems. They combine climate, economic, environmental and energy systems and are used to evaluate the impacts of interventions across the studied systems. They integrate scientific and socio-economic aspects of climate change, energy and environment. Moreover, human activities and key aspects of the physical relationships driving climate change are included in these models. The primary aim of integrated assessment models is to assess policy options for climate change (Kolstad, 1998) (Kelly & Kolstad, 1998).

General Circulation Models (GCM) or climate models focus on the physical climate system only. They are used to assess the impacts of economic activities on the climate and the environment based on the amount of GHG emissions. The outcomes of climate models are for example atmospheric concentration, global average temperature, ocean water levels and the development of glacier melting.

IAMs can be classified into several model types. The most commonly used models are general equilibrium models. In this model type, the equilibrium of supply and demand determines the prices and volumes of production and consumption. Partial equilibrium models do only model the equilibrium of specific markets, like the energy markets, and do not model the complete equilibrium in an economy (Blok, 2007).

Models are used to analyse various scenarios. A scenario is a set of parameters that is based on historical data and assumptions and boundary conditions on pathways for future developments. Scenarios can be based on current political developments or show possible pathways of future changes. One could subdivide the scenarios in the baseline and mitigation scenarios. Baseline or business-as-usual scenarios show the development without additional mitigation actions. Mitigation scenarios include further mitigation actions and can be used to evaluate pathways to long-term climate goals.

The same scenario run in various models can result in multiple outcomes, as each model works under different assumption, simulates the studied systems on different levels of detail and simulates relationships between activities differently.

2.3 The IPCC AR5 scenarios

The IPCC scenario database is a transparent scientific database for the future development of global climate based on various pathways. It builds on multiple scientific models and shows a wide range of scenarios from business-as-usual scenarios to scenarios with stringent climate targets. The IPCC AR5 database comprises the outcomes of 1,184 scenarios that have been generated by 31 IAMs. All scenarios of the IPCC database have been published in peer-reviewed literature. They cover a minimum set of required variables, for which basic model and scenario documentation is available. The scenarios represent the full energy system and must include projections until at least 2030. All scenario results coming from different models were run through the same climate model MAGICC. Therefore, the effects on climate are based on the same climate model assumptions. This allows comparability of the outcomes like atmospheric CO_2 concentration, climate forcing and climate responses and a consistent view on the possible future effects of GHG emissions on climate.

The IPCC AR5 scenarios are assigned to different categories to differentiate between the scenarios along several dimensions. In terms of climate targets, the scenarios are classified by the radiative forcing in seven classes. Radiative forcing is expressed in W/m^2. The equivalence of the hypothetical CO_2 concentration of other GHG than CO_2 is based on the radiative forcing (IPCC, 2014c, S. 1312).

Table 1 summarises different parameters of the seven categories. Radiative forcing expressed in CO_2eq concentration levels and the change in CO_2eq emissions in 2050 and 2100 compared to 2010 is given. Moreover, the likelihood that the temperature increase stays within a specific limit is shown for each category.

Table 1: Key characteristics of the scenarios collected and assessed for WGIII AR5. For all parameters, the 10th to 90th percentile of scenarios is shown.

Category	CO_2eq concentrations in 2100 [ppm CO_2eq]	Subcategories	Change in CO_2eq emissions compared to 2010 [in %]		Likelihood of staying within a specific temperature level over the 21st century (relative to 1850-1900)			
			2050	2100	1.5°C	2°C	3°C	4°C
1	430-480	Total range	-72 to -41	-118 to -78	More unlikely than likely	Likely	Likely	Likely
2 (a)	480-530	No overshoot of 530 ppm CO_2eq	-57 to -42	-107 to -73	Unlikely	More likely than not	Likely	Likely
2 (b)	480-530	Overshoot of 530 ppm CO_2eq	-55 to -25	-114 to -90	Unlikely	About as likely as not	Likely	Likely
3 (a)	530-580	No overshoot of 580 ppm CO_2eq	-47 to -19	-81 to -59	Unlikely	More unlikely than likely	Likely	Likely
3 (b)	530-580	Overshoot of 580 ppm CO_2eq	-16 to 7	-183 to -86	Unlikely	More unlikely than likely	Likely	Likely
4	580-650	Total range	-38 to 24	-134 to -50	Unlikely	More unlikely than likely	Likely	Likely
5	650-720	Total range	-11 to 17	-54 to -21	Unlikely	Unlikely	More likely than not	Likely
6	720-1000	Total range	18 to 54	-7 to 72	Unlikely	Unlikely	More unlikely than likely	Likely
7	>1000	Total range	52 to 95	74 to 178	Unlikely	Unlikely	Unlikely	More unlikely than likely

Source: Ecofys based on (IPCC, 2014a), table SPM.1, p.22

The baseline scenarios fall into category 6 and 7 with CO_2eq concentrations of 720 to 1000 and more than 1000 respectively. These scenarios lead to a temperature increase of about 2.5 to 7.8°C (IPCC, 2014a, S. 22).

Besides the baseline scenario, the database includes about 900 mitigation scenarios that are listed in the categories 1 to 5 and some in category 6. In the category 1 scenarios, it is likely that the temperature increase stays within the 2°C limit reached besides others by limiting the CO_2 concentration in 2100 to 430 to 480 ppm CO_2eq. This requires substantial emission reductions until 2050 of about 40 to 70 percent compared to 2010 and almost no GHG emissions near 2100. In category 2, scenarios can be furthermore divided in two kinds of scenarios. All category 2 scenarios show a CO_2 concentration of 480 to 530 ppm CO_2eq in 2100 and are characterised by a 25 to 55 GHG emission reduction on 2050 compared to 2010 levels. The first group of scenarios is characterised by an overshoot of 530 ppm CO_2eq and it is about as likely as not that the temperature increase stays within 2°C. All other category 2 scenarios show no overshoot of 530 ppm CO_2eq and it is more likely than not that the temperature increase stays within 2°C. In all other categories, it is unlikely or more unlikely than likely that the temperature stays below 2°C (IPCC, 2014a, S. 22).

2.4 Selection of scenarios and models

This study aims at analysing relevant bio-CCS related issues of 2°C compatible scenarios and are thus focussed on category 1 scenarios and the respective models.

The AR5 database contains 116 category 1 scenarios. The same scenarios (assumptions and boundary conditions) can lead to (substantial) different outcomes in different models. Thus, the selection of a limited set of scenarios bears the risk of 'unbalanced' choices, which do not reflect the range of outcomes under different modelling approaches.

As indicated above, each of the selected models consists of multiple scenarios. At both the level of models and scenarios assumptions are made on a set of indicators. Typically, the model assumptions on these indicators are more high-level, reflecting a range of pathways possible within the model. These pathways are made specific within the scenarios, by making detailed and clear-cut assumptions on the indicators. For the analysis of bio-CCS, the scenario-level is most interesting. To create focus in the assessment, the choice was made not to analyse all models and scenarios in detail, but to select the five main models which cover almost 75% of the category 1 scenarios:

- Global Change Assessment Model (GCAM, including MiniCAM)
- Integrated Model to Assess the Global Environment (IMAGE)
- Model for Evaluating the Regional and Global Effects (MERGE)
- Model for Energy Supply Strategy Alternatives and their General Environmental Impact (MESSAGE)
- Regional Model of Investments and Development (REMIND)

The GCAM model was formerly known as MiniCAM. In the following analysis, MiniCAM scenarios are discussed separately from GCAM scenarios.

Table 2 summarises the key characteristics of these five models.

Table 2: Key characteristics of main models

	GCAM	IMAGE	MERGE	MESSAGE	REMIND
Economic coverage and feedback	Partial Equilibrium -	Partial equilibrium	General equilibrium	General equilibrium	General equilibrium
Type of model	Integrated assessment model	Integrated assessment model	Integrated assessment model	Energy engineering model for medium- to long-term energy system planning and policy analysis	Integrated assessment model, couples a top down macroeconomic growth model with a detailed bottom-up energy system model and a simple climate mode

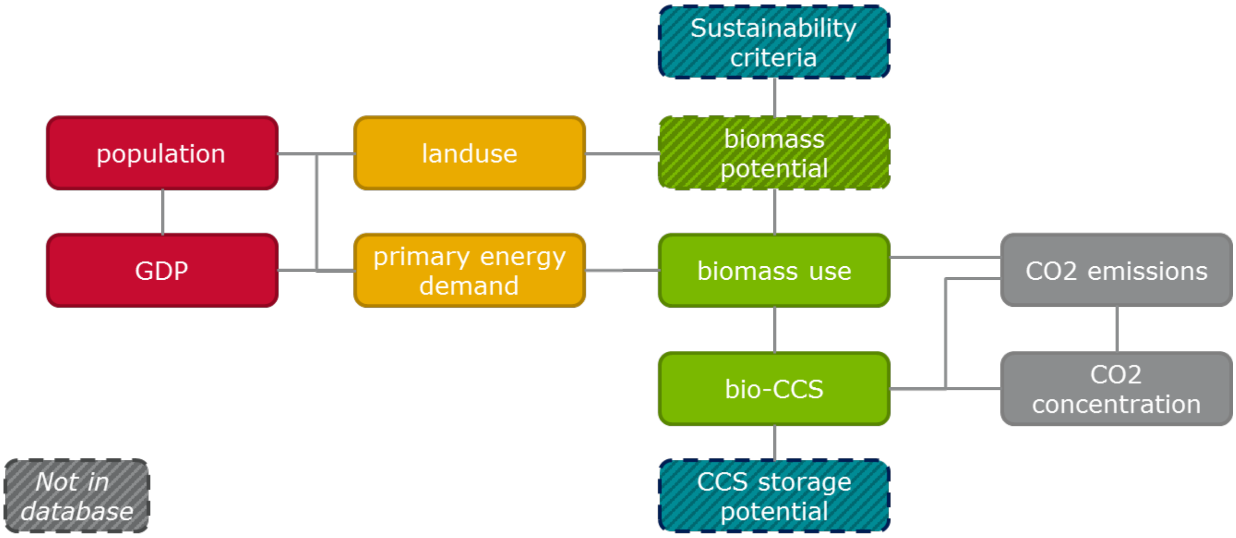
	GCAM	IMAGE	MERGE	MESSAGE	REMIND
Focus	Representation of human earth systems including interactions between the global economic, energy, agricultural, land use and technology systems	Long-term dynamics of global environmental change, such as air pollution, climate change, and land-use change	Alternative assumptions about the rate of energy efficiency (EE) improvements, the future of nuclear and CCS generation, and the availability of sustainable biomass.	Minimising total discounted energy system costs	Technological development and change, and long-term investments in energy technologies
Number of scenarios in database (with bio-CCS)	139 (99)	79 (51)	92 (36)	140 (100)	158 (111)
Number of category 1 scenarios (with bio-CCS)	18 (15)	16 (16)	23 (21)	8 (7)	15 (13)
End year of model	2100	2100 (4 scenarios until 2050)	2100	2100	2100
Representation of land-use	Land use by land type for bioenergy and food consumption	Land use by land type for bioenergy and food consumption	No land use included	Land use by land type for bioenergy	Land use emissions via marginal abatement cost curves and from a land use model
Bioenergy	Bioenergy is treated as an explicit product of the agriculture-land-use portion of the model. For projections on agriculture and land use, the Agriculture and Land Use model (AgLU) is used.	IMAGE makes use of projections from other models, such as MAGNET for changes in food production and trade for a broad set of crops and animal products and TES to compute land use changes based on regional production	Various options for biomass use mostly used for electricity production	MESSAGE is in addition coupled to agricultural model GLOBIOM for consistent projections of land-use	No specifics on bioenergy

Source: Ecofys based on (IPCC, 2014c), table A.II.14, p.1309f. and (IIASA, 2015; Brenkert, Smith, Kim, & Pitcher, 2003; Edenhofer & et.al., 2010)

3 Analysis of bio-CCS in selected IPCC models and scenarios

In this chapter, the focus is on the assumptions made for input variables that influence the development of biomass and bio-CCS. In Figure 1 an overview is provided of the indicators included in this study and their relation to biomass and bio-CCS and the resulting CO_2 emissions and concentration and finally the possibility of limiting global warming to under 2ºC.

Figure 1: Overview of indicators included in this study



Source: Ecofys

The indicators that are included in this study are population growth and GDP (in red), land use and primary energy demand (in orange), biomass potential (in shaded green) and sustainability criteria and CCS storage potential (in shaded blue).

The figure shows that each of the indicators have an influence on biomass and/or bio-CCS either directly or indirectly. Population growth, GDP and sustainability criteria have an indirect influence, the other indicators have a direct influence. CCS storage potential only has an influence on the development of bio-CCS.

These indicators will be assessed based on available IPCC data, model and scenario descriptions found in literature. Specific attention will be paid to the underlying assumptions that are used as a basis for the development of the indicators and thus the development of biomass use and bio-CCS. In this section, the focus is on identifying the underlying assumptions and describing the development of biomass use and bio-CCS from the models.

This chapter is structured as follows: in section 3.1 the general input indicators population growth and GDP are analysed, followed by section 3.2 in which the indicators are analysed that influence biomass assumptions (including biomass demand, type of biomass used and land use). In section 3.3 the focus is on bio-CCS assumptions (including bio-CCS development and storage potential).

3.1 Analysis of general input assumptions

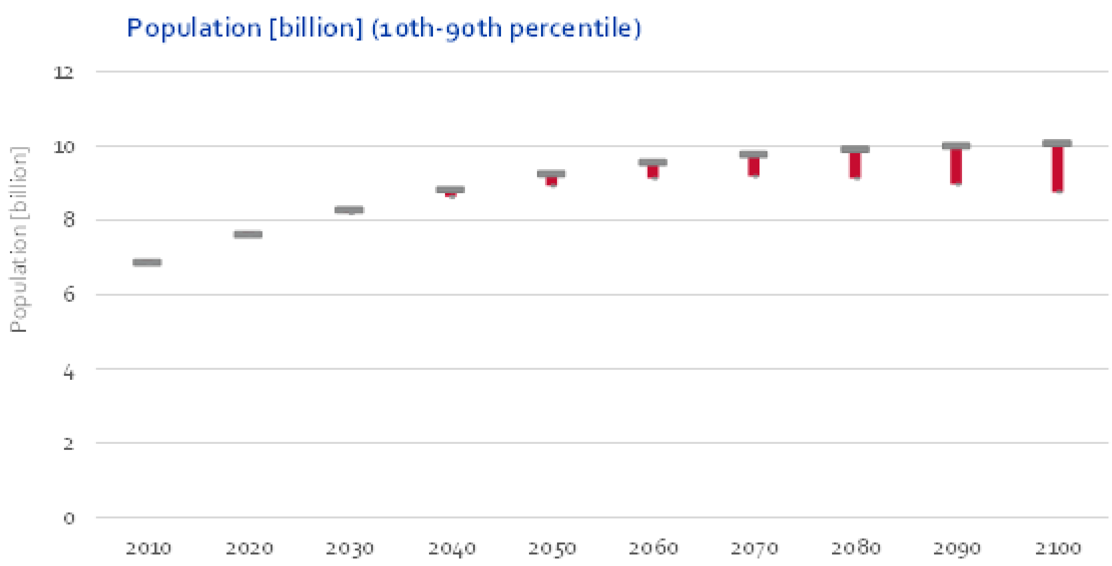
In this section, the focus is on the assumptions made for input variables that indirectly influence the development of biomass and bio-CCS.

Population growth influences the share of land-cover available for biomass, as a growing population will increase the need for land for infrastructure and food. GDP in its turn can influence the development of energy demand, the need for energy supply from renewable energies and the availability of financial resources to invest in the development of renewable energy.

3.1.1 Population growth

Figure 2 shows the development of population in the scenarios represented by the 10th to 90th percentile and the median value.

Figure 2: Development of population in scenarios



Source: Ecofys based on IPCC (2014c)

The graph shows that all scenarios show a similar growing trend towards 2070 whereas after 2070 the population development of the scenarios diverges. Some scenarios assume that the growth will continue, albeit on a slower pace, while other models expect a decline in population. For 2100 the graph shows a range of population between 8.8 (10th percentile) to 10.1 billion people (90th percentile).

For the selected models, the assumed development in population for 2050 and 2100 is presented in Table 3 below. The table shows that there are basically two clusters of models in population development. GCAM and MiniCAM show a similar development and IMAGE, MESSAGE and REMIND are based on similar assumptions on population development. Specifically, in the **IMAGE** scenarios it is assumed that population development will probably stabilise or decrease in the second half of this century. It is therefore likely that after 2050 biomass demand for food will decline (considering further yield increases) and therefore the potential for energy will grow (Van Vuuren D. , 2016).

The table shows that for GCAM and MiniCAM scenarios the population is expected to slightly decline between 2050 and 2100 and stays below 9 billion people in both scenario years. The scenarios of IMAGE, MESSAGE and REMIND reach a population of over 9 billion people already in 2050 and show a growth up to over 10 billion people in 2100.

Table 3: Assumed population development selected models in 2050 and 2100

Model	Min. Population 2050 [billion]	Max. Population 2050 [billion]	Min. Population 2100 [billion]	Max. Population 2100 [billion]
GCAM	8.9	8.9	8.8	8.8
MiniCAM	8.8	8.8	8.7	8.7
IMAGE	9.2	9.4	9.6	10.2
MERGE	9.3	9.3	10.1	10.1
MESSAGE	9.2	9.4	9.5	10.4
REMIND	9.2	9.3	9.1	10.1

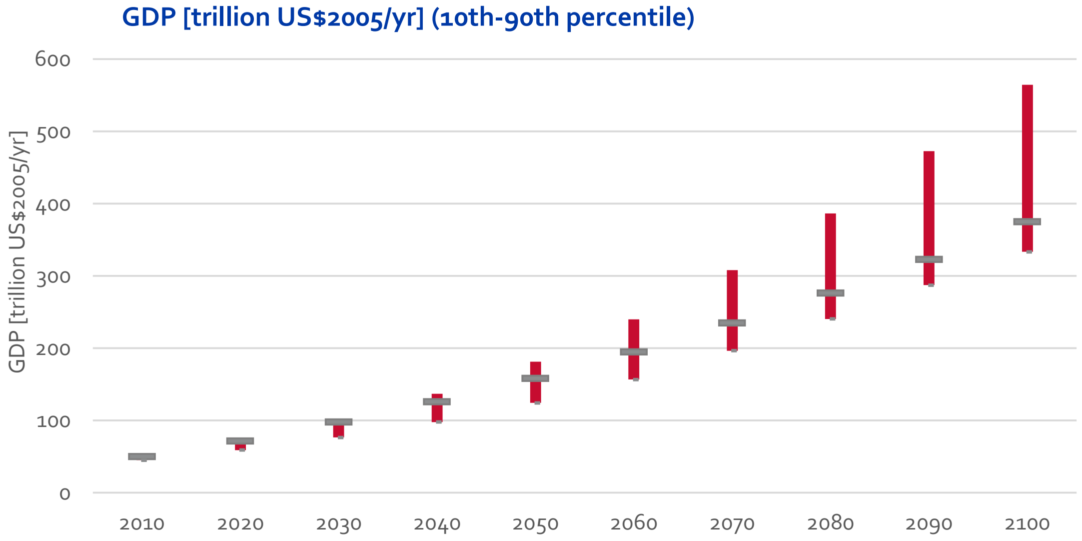
Source: Ecofys based on IPCC (2014c)

A closer look into the data shows that GCAM, MiniCAM and MERGE scenarios assume an (almost) uniform development in population, showing no differences between the scenarios of one model. IMAGE, MESSAGE and REMIND do show variations in their scenarios.

3.1.2 Economic growth

Economic growth by means of global GDP is the second input variable that is assessed in this section. Figure 3 shows the development of GDP between 2010 and 2100 in US$, displayed as real values based on 2005. All scenarios assume a growing trend towards 2100, but the growth rate differs between the models. This results in a wide range in 2100 of between 330 (10th percentile) up to 560 trillion US$(2005) (90th percentile). However, most scenarios assume a GDP growth to the lower end of the range in 2100 leading to a median value of 380 trillion US$(2005).

Figure 3: Development of global GDP in scenarios



Source: Ecofys based on IPCC (2014c)

To provide better insights in the different assumptions used in the models, the assumed development of global GDP for 2050 and 2100 per model is presented in Table 4.

Table 4: Assumed GDP development of selected models in 2050 and 2100

Model	Min. GDP 2050 [trillion US$ (2005)]	Max. GDP 2050 [trillion US$ (2005)]	Min. GDP 2100 [trillion US$ (2005)]	Max. GDP 2100 [trillion US$ (2005)]
GCAM	124	124	367	367
MiniCAM	119	122	305	365
IMAGE	119	212	246	600
MERGE	152	172	308	444
MESSAGE	151	154	324	361
REMIND	140	170	284	418

Source: Ecofys based on IPCC (2014c)

The table shows that the scenarios of some of the models GCAM, MiniCAM and MESSAGE have assumed a narrow range for GDP developments, while the scenarios of IMAGE, MERGE and REMIND show large variety. In fact, all GCAM scenarios are based on the same GDP growth path which are close to the 10^{th} percentile of all scenarios in 2050 and slightly below the median in 2100. The MiniCAM and MESSAGE scenarios show also only small deviations in the assumed GDP development and only from 2050 on. GDP development in all MiniCAM scenarios remains below that of the GCAM scenarios. The MESSAGE scenarios are mainly based on one growth path which is close to the upper values for MESSAGE in the table.

IMAGE, MERGE and REMIND scenarios show the highest estimations for GDP. IMAGE scenarios show basically three different development paths with the majority of the scenarios being at the upper limit of the range indicated in the table and of all scenarios. MERGE only includes one scenario that assumes a GDP of 308 trillion US$, while all other MERGE scenarios show values of 350 trillion US$ or higher.

3.2 Analysis of biomass assumptions

In this section, an overview is provided of input assumptions made for biomass variables in the selected models. These are underlying assumptions influencing the model results on the development of bioenergy and bio-CCS. The following input variables are included in the assessment:

- Biomass potential (see chapter 4.1)
- Biomass demand
- Type of biomass used
- Land use for biomass

In the following sub-sections, each of the variables will be described.

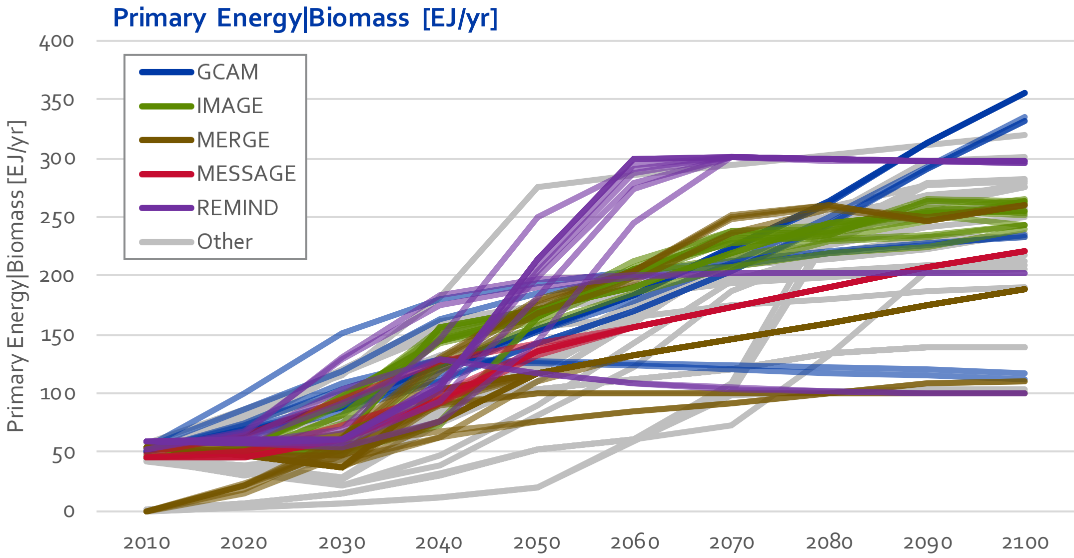
3.2.1 Biomass demand

Figure 4 shows the development of primary energy from biomass of the scenarios up to 2100. The graph shows that all scenarios in the assessed four models assume a growth in biomass usage between 2010 and 2100, albeit in different pathways. Roughly four trends can be identified:

- **Linear growth:** A stable, linear growth is assumed between 2010 and 2100.
- **Early steep growth:** A steep growth is assumed between 2030 and 2060. After 2060 the volume of primary energy from biomass stabilises and slightly decreases towards 2100.
- **Delayed steep growth:** A moderate growth up to 2040 and a steep growth between 2040 and 2070 is assumed. From 2070 to 2100 most scenarios of this growth path stagnate.
- **Stabilising:** Primary energy demand from biomass grows moderately up to 2050. For the second half of the century, a declining trend has been assumed.

The different trends result in large ranges: in 2050, the primary energy from biomass is between 20-280 EJ per year, for 2100 the range is expected between 100 and 360 EJ per year.

Figure 4: Development of primary energy from biomass



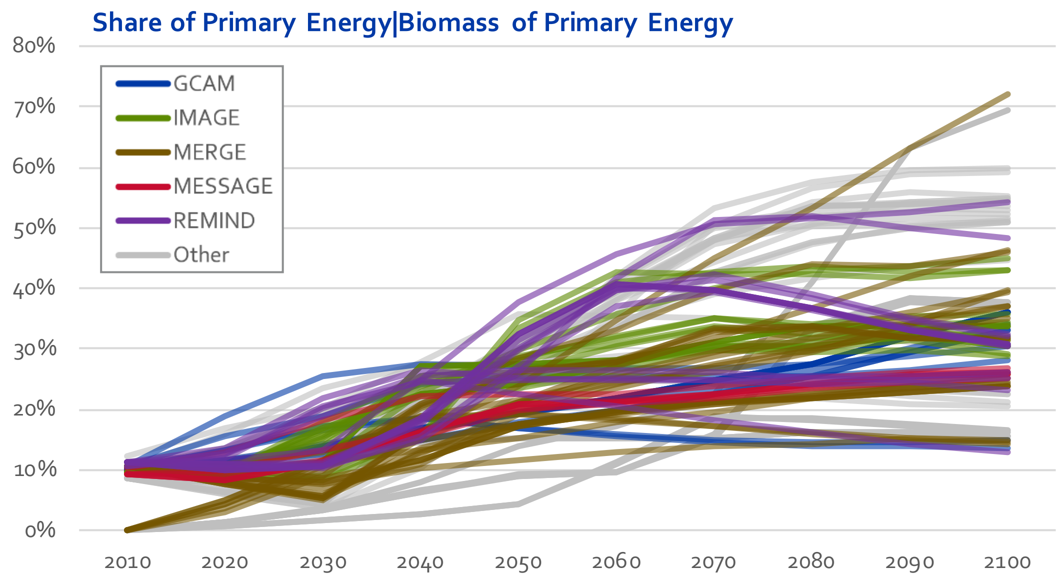
Source: Ecofys based on IPCC (2014c)

The figure highlights the following results for the models in focus:

- The **GCAM** scenarios show a steady, almost linear growth of primary energy from biomass up to 2050. Between 2050 and 2100, some scenarios assume a steeper growth up to 2100, while other scenarios show a slight decrease in primary energy from biomass.
- All **IMAGE** scenarios show a continuous growth in primary energy from biomass between 2010 and 2100. Between 2030 and 2080 a large range is shown between the maximum and minimum values in scenarios.
- **MERGE** scenarios show quite a spread in the scenarios. Some scenarios show a steep almost linear growth towards 2060-2070, others show a steep growth between 2030-2040 and then a linear growth towards 2100. In 2100 the MERGE scenarios converge to three values.
- The **MESSAGE** scenarios show a stable growth of primary energy from biomass up to 2100. After 2050, all scenarios show a similar growth.
- The **REMIND** scenarios show either an early steep growth or a delayed steep growth in primary energy from biomass. In most scenarios, the energy demand from biomass stagnates or slightly declines from 2060 on. The REMIND scenarios shows a large range between scenarios and the highest values in 2060.
- For the **MiniCAM** scenarios the database does not contain data on primary energy from biomass.

To create insights in the development of biomass as compared to total primary energy demand, Figure 5 illustrates the share of biomass of total primary energy demand for the scenarios from 2010 to 2100.

Figure 5: Share of biomass of total primary energy demand



Source: Ecofys based on IPCC (2014c)

The graph shows that the share of primary energy from biomass increases over the years in all scenarios. The shares increase from about 10% in 2010 up to 40% in 2050 and up to 70% in 2100. Other scenarios start at ~0% in 2010 and either take of slow in the beginning and then steeply growing after 2050 (one IMAGE scenario even grows towards 70% in 2100) or growing almost linearly to about 40% in 2100. Again, the range of results is quite significant already in 2050 and even stronger in 2100. However, some scenarios show only a slight increase of the share of biomass resulting in a share only slightly above the 2010 limit.

Most the **GCAM** scenarios show a continuous increase up to 30 to 40% in 2100. All **MESSAGE** scenarios assume a low increase from 10% in 2010 to about 25% in 2100. The **IMAGE** scenarios all show a medium strong increase up to 30 to 45% in 2100 comparable to the majority of the GCAM scenarios. **MERGE** scenarios all start at 0% or 10% in 2010, but show a wide variety in 2100, ranging from 15% and 20% on the low end, up to 45% and even over 70% on the high end. The **REMIND** scenarios also show a wide range for 2100 between slightly above 10% and 55%. In contrast to the other models, the biomass-share of total primary energy demand peaks in most the REMIND scenarios in 2060 to 2070 and slightly declines afterwards.

3.2.2 Type of biomass use

The availability of biomass depends to a large extent on the types of biomass that are included in the scenarios. In this section, an overview is provided of these assumptions for each of the selected models. For the MESSAGE scenarios, no specific information could be retrieved on the types of biomass used in the scenarios.

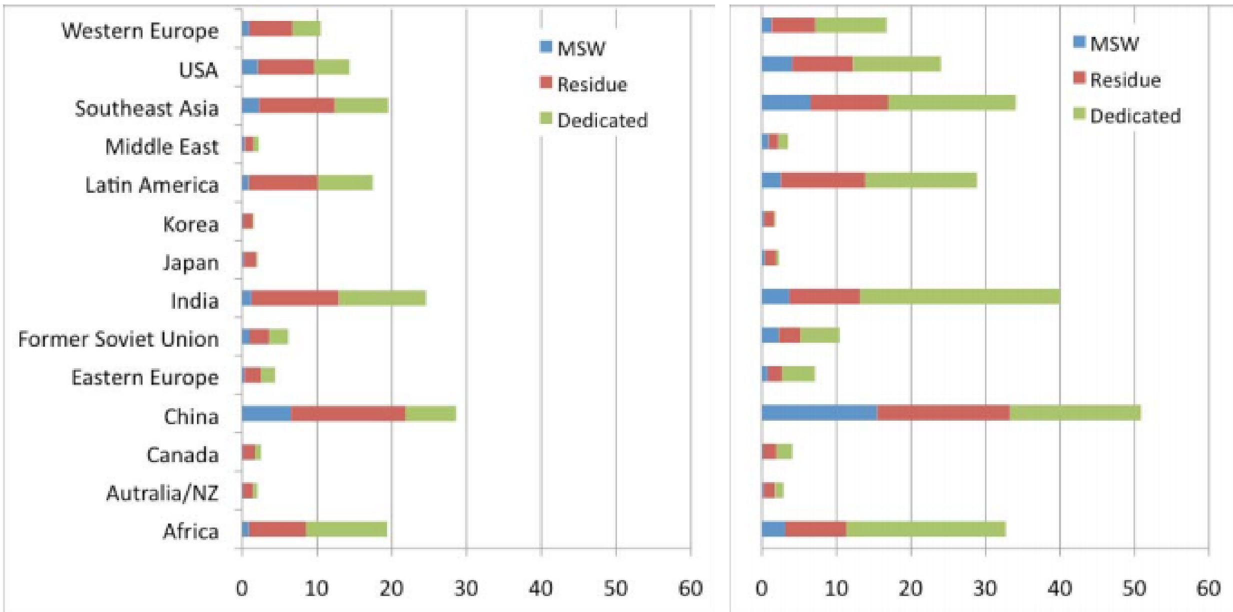
GCAM

In the GCAM model, the following biomass types are included (Wise, et al., 2014):

- **Bioenergy Crops:** Lignocellulosic sources such as perennial grasses and woody crops
- **Biomass residues:** Agricultural and Forestry residues
- **MSW:** Organic Municipal Solid Waste
- **Conventional biofuels:** Conventional or first-generation biofuel sources such as corn, sugars, oil crops that are also grown as part of food production (only for biofuels)

The mix of biomass in the GCAM model is influenced by different variables, such as the types of policies assumed and geographical region (Wise & Luckow, 2011). Figure 6shows for the GCAM model how the biomass mix changes over regions for organic municipal solid waste (MSW), biomass residues (Residue) and bioenergy crops (Dedicated).

Figure 6: Biomass production in 400ppm GCAM scenarios for 2050 (left) and 2095 (right) in EJ per year



Source: (Luckow, Wise, Dooley, & Kim, 2010)

The figure shows that biomass residues are the dominant biomass type used for bio-CCS in all regions in 2050. Towards 2100 the role of dedicated bioenergy crops will become more important. Between 2050 and 2100 biomass production is expected to grow in all regions. Overall, most of the growth in biomass production will come from a growth in bioenergy crops and to a lesser extent from growth in the use of MSW. The share of biomass residues slightly increases.

IMAGE

In the IMAGE scenarios, the focus is solely on woody bioenergy crops (Van Vuuren, Bellevrat, Kitous, & Isaac, 2010). Based on various studies and literature sources[1], woody or grass-type biomass (e.g. miscanthus, switch grass, and agricultural residues) are expected to become the most dominant source of bioenergy in the long-term. These sources can be directly used in power plants and industry.

In the AR5 IMAGE scenarios is estimated that the availability of biomass residues for bioenergy production is ~70 EJ/year. Recent calculations based on best estimations of the IMAGE modellers come to ~50 EJ/year which is used in current scenarios (Van Vuuren D. , 2016).

MERGE

The MERGE scenarios include the following biomass feedstocks: wood residues, soybean, corn grains, sugar cane, stover and domestic wastes (Magné, Kypreos, & Turton, 2010; Marcucci, 2014). The availability of the

[1] Based on: Van Vuuren, D.P., et al. (2008), Outlook on agricultural change and its drivers. In: Watson, B. (Ed.), International Assessment of Agricultural Science and Technology Development. Island Press, Washington D.C. and Hoogwijk, M. (2004), On the Global and Regional Potential of Renewable Energy Sources. Utrecht University.

feedstocks is derived from multiple sources and vary from between 50 EJ in 2000 up to 200 EJ in 2100 (Magné, Kypreos, & Turton, 2010; Marcucci, 2014).

MiniCAM

In the MiniCAM scenarios, two types of biomass are included (Brenkert, Smith, Kim, & Pitcher, 2003):

- Biomass from waste, including landfills, agricultural residues, wood wastes, etc. For most of the regions this type of biomass is enough to supply all the present biomass demands.
- Biomass from dedicated biomass farms, such as switchgrass or hybrid poplar (Smith, Brenkert, & Edmonds, 2006).

REMIND

In the REMIND scenarios, the following types of biomass use are included (Luderer, et al., 2015):

- Conventional biomass produced from sugar, starch, and oil crops (typically small in quantity, based on an exogenous scenario)
- Biomass residues, including residues from agriculture and forest
- Second-generation purpose-grown biomass from specialized lignocellulosic grassy and woody bioenergy crops, such as miscanthus, poplar, and eucalyptus

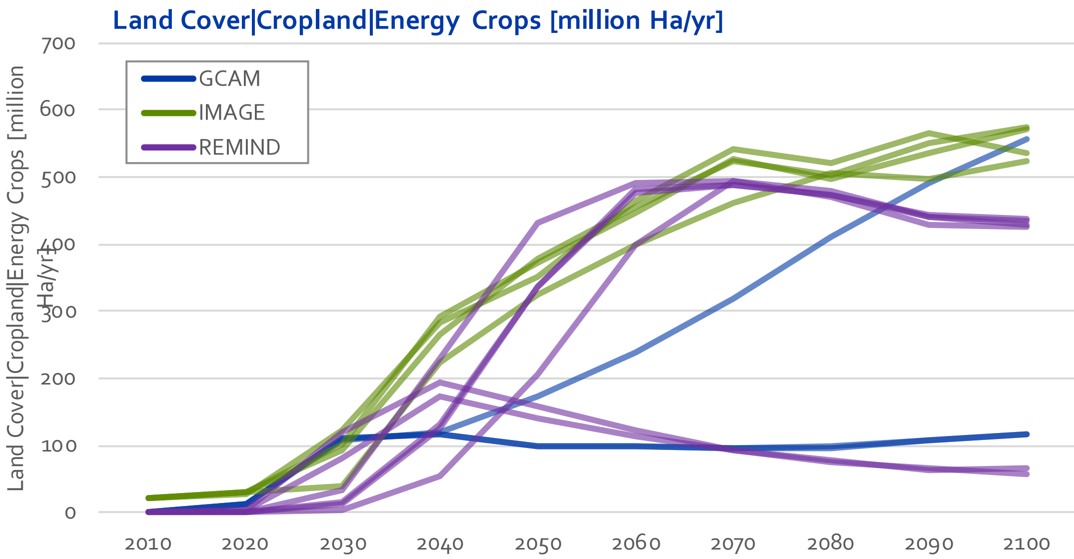
It is assumed that first generation modern biofuels are phased out, because of high costs, impact on land-use change and competition with food production. Therefore, the main sources of bioenergy in REMIND scenarios are second-generation purpose-grown biomass and lignocellulosic agricultural and forestry residues. In contrast of first generation biomass feedstock, second generation biomass refers to non-edible feedstocks. Second-generation biomass does not compete with food production if cultivated on less fertile land that is not suitable for food crops. An example are grasslands, where mowed grass offers an enormous potential for additional biomass. Ecofys estimated this potential at over 30 million tonnes per year in the EU, Belarus, Russia and Ukraine, already excluding 75% of the grass as used for other purposes. There is also a huge potential of agricultural and forestry residues (Ecofys, 2016).

3.2.3 Land use for biomass

As discussed in section 3.2.1, the potential and development of biomass for energy generation depends on the availability of biomass. An important source is biomass from energy crops. In this section, the assumptions for land use for biomass in the scenarios is discussed.

Figure 7 shows the development of energy crops between 2010 and 2100. Information on energy crops are only available for some models and scenarios as not all indicators need to be reported. The IPCC database does not contain information on energy crops for MiniCAM and MESSAGE scenarios.

Figure 7: Land covered by energy crops



Source: Ecofys based on IPCC (2014c)

The figure shows the different development paths of land cover for energy crops between 2010 and 2100. Most scenarios assume a stronger uptake of land use for energy crops between 2020 and 2030. The majority of the scenarios assumes a continuous growth until 2100. Especially between 2030 and 2060 some scenarios show a steep growth. After 2060 the growth flattens and in some scenarios the availability of land for energy crops declines after 2060. A few scenarios show a decline in land use for energy crops already in 2030 or 2040[2] .

The following results can be retrieved from the figure for the models in focus:

- The **GCAM** scenarios show a steep growth between 2020 and 2030. After 2040, the scenarios diverge in the development of land cover for energy crops. Most scenarios assume a small decline in land use for energy crops, while other scenarios assume a stable growth up to 2100. This results in a large range.
- The assumed development of land use for energy crops in the **IMAGE** model seem quite uniform between scenarios. A steep growth is expected after 2030 lasting until 2070. In 2080 a small decrease is expected, but between 2080 and 2100 a slight increase in land use for energy crops is expected. The IMAGE scenarios assume the highest land cover values for energy crops for 2100. Although this will have implications for the amount of land available for food, it does not necessarily mean that food production will decline. In the IMAGE scenario, it is assumed that 80% of increasing food demand will be met by increasing yield and only 20% by new land-use (Van Vuuren D. , 2016). In section 0 the concept of yield increase is elaborated in more depth.
- In most of the **REMIND** scenarios the land use for energy crops is expected to grow significantly between 2030 and 2050. In some scenarios, the land cover for energy crops declines after 2050, while it rises in others until 2060. After 2070 all scenarios show a decline in the availability of land use for energy crops.

[2] The other scenarios in the graph of the models not in focus are all from the POLES model. These are not displayed in the figure as data from the IPCC database seems to be wrong.

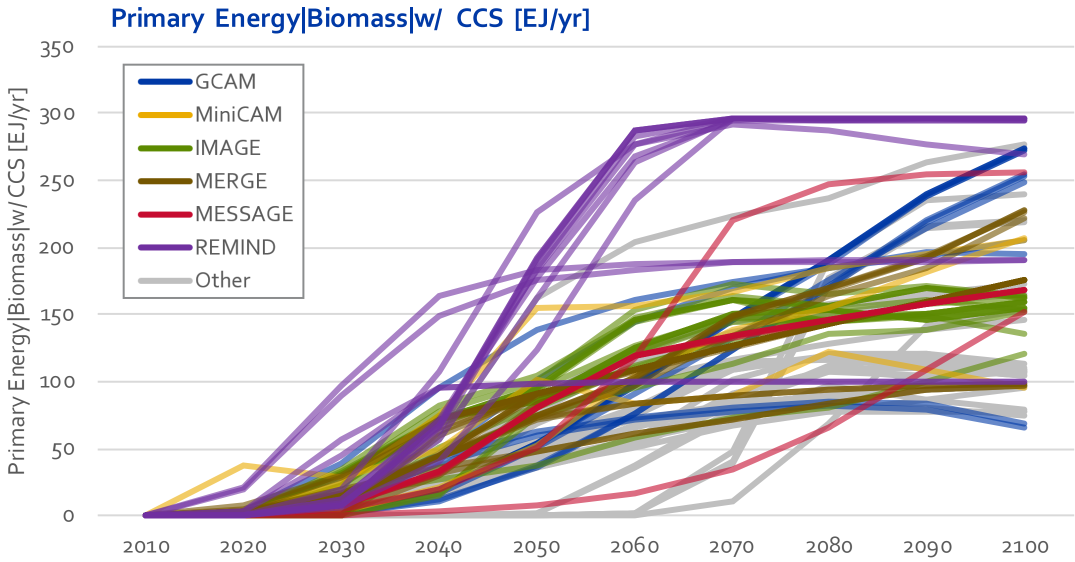
3.3 Analysis of bio-CCS assumptions

3.3.1 Bio-CCS development

To create insights in the development of bio-CCS Figure 8 shows the different development paths for primary energy from biomass with CCS between 2010 and 2100. Similar to the development of primary energy from biomass, different trends are identified:

- **Linear growth:** The first uptake of bio-CCS is assumed to take place between 2020 and 2040.For the second half of the century a stable, linear growth is assumed. Depending on the growth rate, the amount of primary energy from biomass with CCS in 2100 shows a wide range.
- **Early uptake, steep growth:** An early uptake of bio-CCS between 2015 and 2030 followed by a steep growth towards 2060-2070 is assumed. After 2070 the growth stabilises or slightly declines.
- **Delayed uptake, steep growth:** A delayed uptake of bio-CCS takes place between 2050 and 2060 followed by a steep growing trend towards 2090. Between 2090 and 2100 the growth stabilises.
- **Moderate growth:** A moderate growth of bio-CCS up to 2090-2100 is assumed leading to values of about 100 EJ per year in 2100.

Figure 8: Development of primary energy from biomass with CCS



Source: Ecofys based on IPCC (2014c)

The majority of the scenarios show a continuous growth up to 2100. In total, the primary energy from biomass combined with CCS ranges between 70 EJ and 300 EJ per year in 2100.

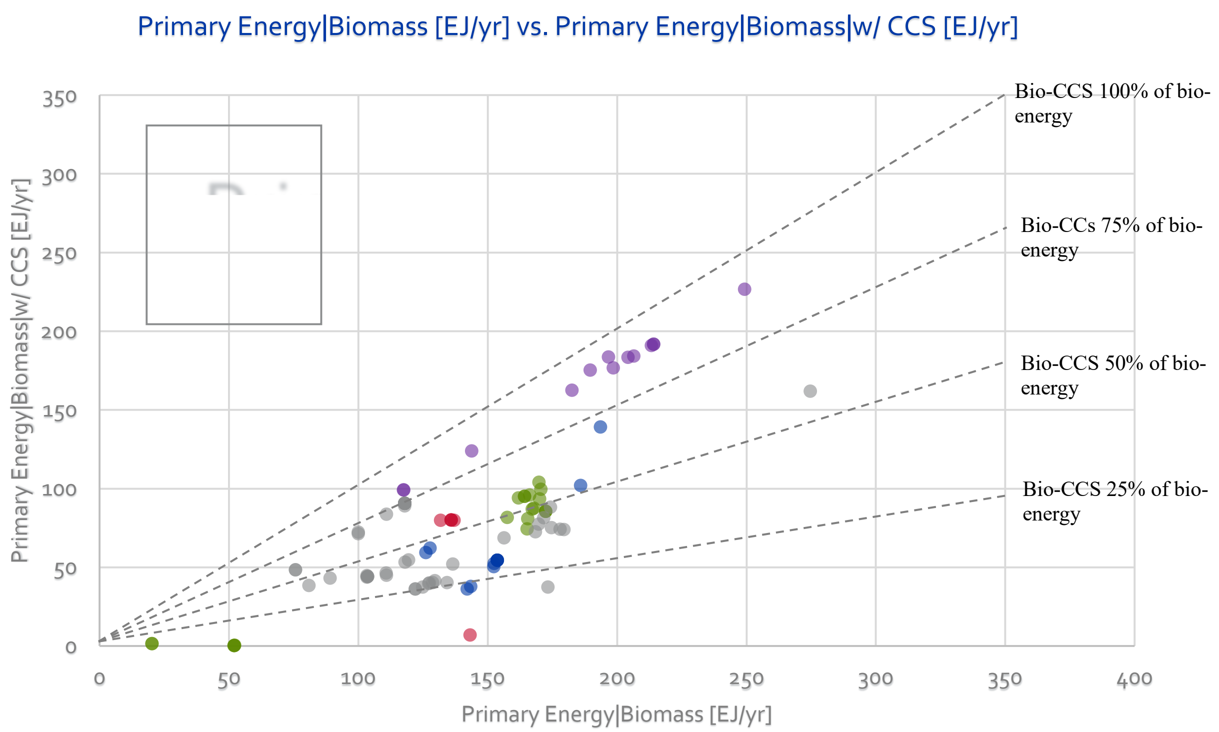
The following results for the individual models can be retrieved from the figure:

- **GCAM** scenarios show a growth in bio-CCS from 2030 onwards. The scenarios show differences in growth pace: the scenarios that assume large growth will continue to grow fast up to 2100, while other scenarios assume a moderate growth between 2060 and 2090 and even a decrease in 2100.
- For the **IMAGE** scenarios, the starting point for the implementation and uptake of bio-CCS differs widely between the scenarios. Some scenarios assume bio-CCS to start in 2030, while other scenarios do not expect any implementation before 2060. In total, the scenarios show a wide range of primary energy from biomass with CCS for 2100 of between 70 EJ to 240 EJ per year.

- **MERGE** scenarios show three types of development paths: a steep, almost linear growth from 2020 towards 2100, a steep growth between 2030 and 2050, which flattens towards 2100 and moderate growth towards 2100;
- Most of the **MESSAGE** scenarios assume a similar growth path as the MiniCAM scenarios with an increase between 2030 and 2060 and a continuous but reduced growth rate up to 2100.
- Scenarios of the **MiniCAM** show mixed pictures. Market uptake is expected around 2020-2030 and a steep growth is expected between 2030 and 2050. After 2070, the scenarios show a slight increase or decrease.
- The majority of the **REMIND** scenarios show the strongest increase between 2030 and 2060 and stagnate afterwards. The REMIND scenarios do reach the highest bio-CCS level of all scenarios of up to 300 EJ per year.

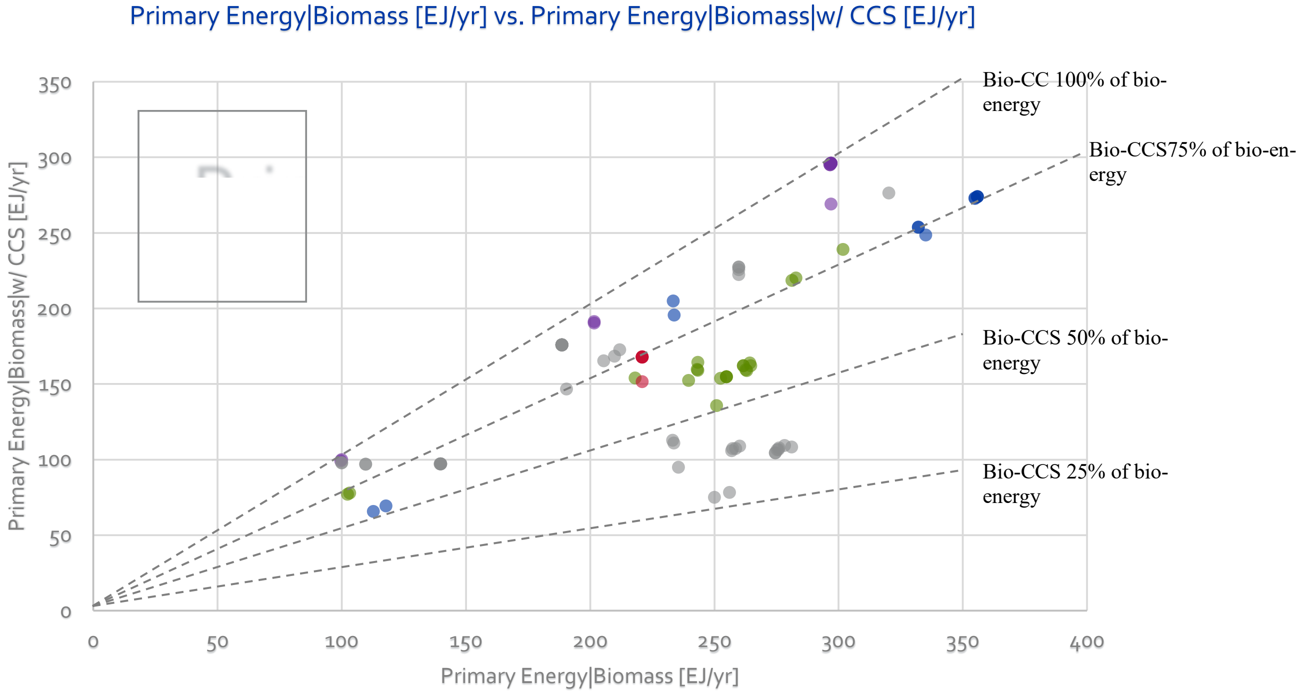
Figure 9 and Figure 10 show the relation between bio-CCS and primary energy from biomass for the years 2050 and 2100. Figure 9 illustrates that almost all scenarios assume a significant increase of bio-CCS until 2050. Some scenarios assume primary energy from biomass to reach about 200 EJ per year in 2050 and a share of bio-CCS of almost 100% of the biomass. However, most scenarios assume a primary energy production from biomass of 80-170 EJ per year of which 25-75% is covered by from bio-CCS. The scenarios show a correlation between biomass demand and bio-CCS. Bio-CCS is limited by nature to the biomass demand, however, scenarios with a high biomass demand show also a relatively high use of bio-CCS.

Figure 9: Primary energy from biomass (total vs. with CCS) in 2050



Source: Ecofys based on IPCC (2014c)

Figure 10: Primary energy from biomass (total vs. with CCS) in 2100



Source: Ecofys based on IPCC (2014c)

Figure 9 and Figure 10 show for most scenarios a growth in the primary energy demand from biomass and bio-CCS increases until 2100. In general, the correlation between increasing biomass and bio-CCS demand still holds, especially for the scenarios of the models in focus. In 2100, the scenarios assume bio-CCS values up to 300 EJ per year and show a minimum use of 60 EJ per year. The share of bio-CCS as part of the total primary energy demand from biomass is also increasing towards 2100. In 2050, the majority of the models in focus shows a bio-CCS share of 25-75%. In 2100, all models show a share of at least 25% up to 100%. Most models seem to assume a share between 75%-100%, while only slightly smaller shares are assuming 50-75% or even 25-50% bio-CCS.

The following conclusions can be drawn for the models in focus:

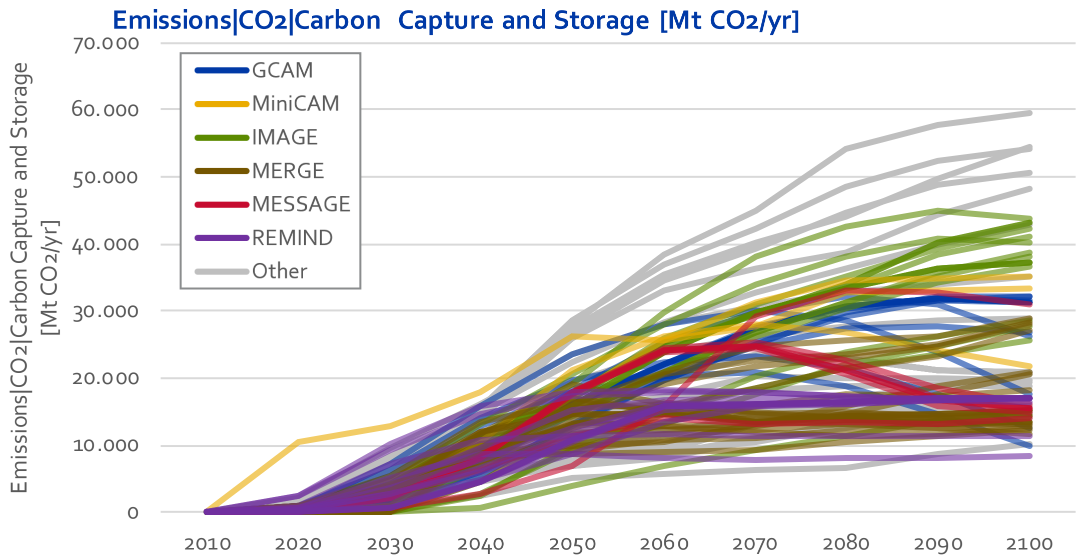
- **GCAM** scenarios show a wide range of biomass demand and bio-CCS usage for 2050 and in particular for 2100. In 2100, the low biomass demand scenarios show a low share of bio-CCS of about 50% whereas the high biomass demand scenarios show also high shares of bio-CCS of about 70 to 80%. No data was available for **MiniCAM** scenarios.
- The majority of the **IMAGE** scenarios shows a bio-CCS use rate of 50% in 2050 with a biomass demand of about 170 EJ per year and a bio-CCS usage of about 90 EJ per year. For 2100, an increase in biomass demand and bio-CCS is assumed in most scenarios, leading to a bio-CCS share of about 60%.
- **MERGE** scenarios show two different trends in 2050: the first in which about 75% of biomass energy is equipped with CCS and second where less than 50% is equipped with CCS. In 2100, MERGE scenarios show variation in the primary energy from biomass, but in all scenarios roughly between 85%-100% of the biomass plants is equipped with CCS.
- The **MESSAGE** scenarios show a relatively low biomass demand in 2050 and 2100. However, the majority of the MESSAGE scenarios show a high share of bio-CCS of more than 50% in 2050 and of about 70% in 2100.

- The **REMIND** scenarios show the highest increase of bio-CCS with up to 230 EJ per year in 2050 and 300 EJ per year in 2100. The majority of the scenarios are also at the upper limit of the assumed biomass demand of all scenarios. The REMIND scenarios assume that bio-CCS will be applied to almost all biomass-plants in 2100.

3.3.2 Development of CO_2 capture and storage

Information on the storage potential assumed in the scenarios can be derived by analysing their use of CCS. Figure 11 shows the development of CO_2 emissions stored with CCS, both fossil emissions and emissions from biomass.

Figure 11: Total captured CO_2 emissions per year



Source: Ecofys based on IPCC (2014c)

The figure shows that a wide range of development paths for CCS has been assumed in the scenarios. Starting in 2010 with basically no CCS, the scenarios assume that in 2100 between 10,000 and 60,000 Mt of CO_2 emissions will be stored each year with CCS.

Table 5 gives a detailed view on the range of the stored CO_2 emissions in the scenarios per model. Moreover, the table shows the aggregated stored emissions of the scenarios from 2010 to 2100. Based on the aggregated stored emissions conclusions on the storage capacities can be made. The aggregated stored emissions represent the minimum storage capacities assumed in the scenarios.

Table 5: Stored CO_2 emissions in Mt CO_2 per year

Model	Min. *2050*	Max. *2050*	Min. *2100*	Max. *2100*	Lower Aggregated *2010-2100*	Upper aggregated *2010-2100*
GCAM	12,809	23,695	9,820	32,330	1,212,557	1,755,144
MiniCAM	17,463	26,144	21,657	35,296	1,627,365	2,197,337
IMAGE	3,993	20,515	15,283	43,728	614,420	2,330,965
MERGE	8,659	19,090	11,550	28,935	695,818	1,567,334
MESSAGE	6,930	17,894	14,173	30,980	890,840	1,523,100

REMIND	8,641	17,898	8,346	16,994	636,928	1,329,528

Source: Ecofys based on IPCC (2014c)

The scenarios of the models in focus, assume a minimum available CO_2 storage potential between 614,000 Mt CO_2 ($1.0*10^{12}$ m^3)[3] and 2,331,000 Mt CO_2 ($3.9*10^{12}$ m^3). Considering all AR5 category 1 scenarios, the CO_2 storage potential is estimated between 462,000 Mt CO_2 ($0.8*10^{12}$ m^3) and 3,000,000 ($5.0*10^{12}$ m^3). The average storage capacity reported in all models and scenarios is 1,349,000 Mt CO_2 ($2.2*10^{12}$ m^3), which includes also models and scenarios that see no or only limited potential for CCS.

[3] The density of pure CO_2 in reservoirs varies between 53-100 kg/m^3 in the reservoir initial state and 500-765 kg/m^3 in the reservoir end state (DHV & TNO, 2008). To estimate the volume of CO_2 in reservoirs, the average density of the end state is used: 632.5 kg/m^3.

4 Review of the application of biomass in IPCC scenarios

In this section, the assumptions made in the IPCC scenarios are now critically reviewed. Based on existing literature and modelling expert views, the assumptions as described in the previous chapter, are challenged. The focus will be on primary energy demand for biomass and injection rates of CCS. Other factors that are included are storage potential and the growth rate of bio-CCS. Additionally, also more qualitative factors are used, such as the risks and limitations of CCS.

In a first step, the biomass assumptions made in the selected models and scenarios are reviewed. The focus of this review is on the following aspects: general input assumptions (population and economic growth), sustainability criteria (including land-use availability, land use change emissions and productivity assumptions) and the assumed deployment and growth rates.

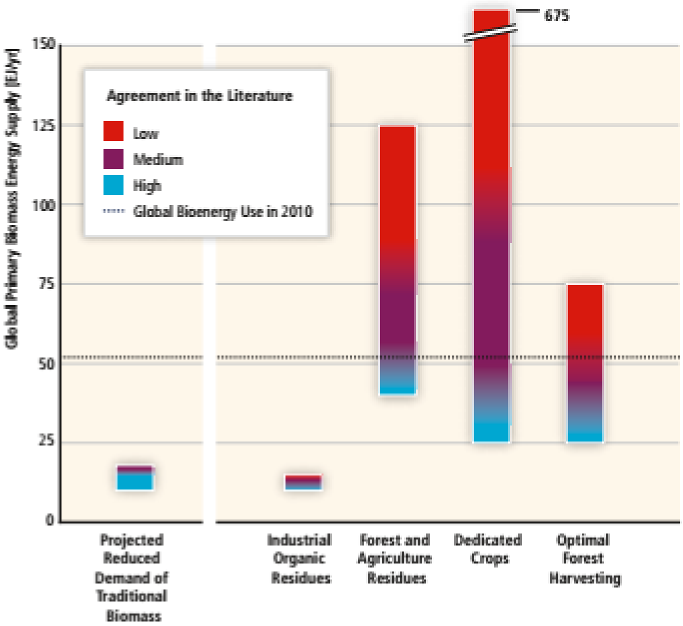
4.1 Biomass potential in literature

Biomass potential refers to the annual available biomass as an input feedstock for any end-use (feed, food, energy). The potential for biomass can be determined in different ways and is thus highly dependent on its definition. One needs to distinguish at least between theoretical, technological, economic and sustainable potential. The theoretical potential describes the physical upper limit of a specific crop under ideal conditions (soil, weather, crop management) without any constraints. The technological potential describes the amount of biomass that can be explored with existing technologies, the economic potential limits to the amount that can economically be used and the sustainable potential includes limiting factors like water scarcity, land degradation and protection of biodiversity (see section 0 for more details)

Projections on biomass potential for energy vary widely in the literature. In IPCC AR5, the authors indicate that it is difficult to make accurate estimations as these are based on different assumptions about sustainability and socio-ecological constraints. The IPCC report estimates the worldwide biomass potential to be in a wide range of less than 50 EJ to more than 1,000 EJ per year in 2050, which is presented in the following Figure 12 (IPCC, 2014c). The figure includes five categories:

- Projected reduced demand of traditional biomass - It is assumed that the demand for household use of biomass (e.g. cooking, water, space heating, etc.) or small-industries (e.g. brick and pottery kilns, bakeries, etc.) will be reduced as a result of improving technologies.
- Industrial organic residues – This refers organic waste streams from households, restaurants and other industrial sectors, including resources such as wooden products and waste waters suitable for anaerobic biogas production.
- Forest and agricultural residues – Forest residues include residues from thinning and logging, as well as dead wood from natural disturbances. Agricultural residues include harvest residues, manure, etc.
- Dedicated crops – Include all crops that are cultivated for bioenergy purposes (e.g. sugar crops, switchgrass and Miscanthus).
- Optimal forest harvesting – This refers to the fraction that is available for bioenergy after taking into account the demand for other uses (e.g. pulp and paper, construction, etc.). Forest management is required to optimise the harvest and maintain the condition of the forest.

Figure 12: Global Technical Bioenergy Potential by main resource category for the year 2050



Source: (IPCC, 2014c)

The colour indicates the degree of agreement in the estimates, from blue (high agreement in the literature) to purple (medium agreement) to red (low agreement). It is notable that among literature, there is high agreement for a total primary energy demand from biomass of about 100 EJ per year, medium agreement on demand up to 250 EJ per year and low agreement on demand exceeding 250 EJ per year.

The figures of the International Energy Agency are slightly higher. According to the International Energy Agency, global primary energy supply from biomass will increase from about 50 EJ today to 100 EJ in 2030 and 160 EJ in 2050 (IEA, 2012; IEA, 2016). In order to reach this potential, the IEA states that the "key priority should be to improve the efficiency of existing biomass to energy production" and to mobilise further biomass with a focus on residues and wastes, but also including energy crops (IEA, 2012).

It is important to note that the sustainable potential for biomass is a matter of choice. The potential can be large or small. If no measures are taken to support the sustainable development of biomass feedstock, then the potential will be rather small as one can only take the leftovers from other sectors. If more focus is given to sustainable development of agriculture and forestry, the potential could be much larger. Quantifying the amount of primary energy from biomass that can be supplied sustainably is a very complex assessment, as it includes assumptions on population growth, availability of land, strictness sustainability criteria and the extent to which these criteria are being implemented globally. There is no consensus in literature on an upper limit for the amount of primary bioenergy that can be used sustainably. However, literature and experts seem to agree that a global primary bioenergy production of up to 100EJ/yr (approximately twice the current consumption) can be realised from waste and residues and on abandoned agricultural land without improvements beyond autonomous trends (National Research Council, 2015; Slade, Bauen, & Gross, 2014; Azar, et al., 2010; Creutzig, et al., 2015). Exceeding 100 EJ/yr would require the implementation of additional sustainability measures: the higher the bioenergy potential, the more extensive and stricter additional measures should be. Literature is not very explicit about quantifying this relationship. Based on Ecofys expertise primary supply of up to 300 EJ/yr is deemed possible with additional measures and developments that can be supported on a project or feedstock procurement level. Also, primary bioenergy production >300 EJ/yr is found to be possible, but this would require significant improvement of the global agri-food system, amongst others by bridging yield gaps and improving supply chain logistics.

4.2 General input assumptions

In section 3.1 an overview is provided of the assumed developments in population and economic growth. Population and economic growth indirectly influence biomass and (bio-)CCS potential, mostly through land-use (trade-off between food and energy). Due to various, direct and indirect relationships between different factors, assessing the potential amount of biomass available for energy use is rather complicated. Therefore, we provide a brief description of how some of these factors influence biomass potential.

Both population and economic growth influence land-use. Additionally, economic growth influences food diets: increasing wealth leads to growing meat consumption and subsequently to higher CO_2-emissions from land use, particularly since more agricultural land is required for livestock-based as opposed to plant-based food production (Van Vuuren D. , 2016; IPCC, 2014). Food demand and biomass potential influence each other due to the limited availability of cropland, while a growing energy demand requires greater energy resources (including biomass), thus potentially causing higher CO_2 emissions. Therefore, renewable energy and options that enable negative emissions become increasingly important to limiting global warming to less than 2°C. At the same time, however, the potential for bioenergy is limited by increasing food demand, making it more difficult to achieve larger amounts of negative emissions from bio-CCS.

This trend is identified in other models as well: in most scenarios, the growth rate of population slows down significantly after 2050 or even shows a small population decrease. However, economic growth increases after 2050 in basically all scenarios, meaning that the pressure on energy demand and food production continues to increase after 2050.

4.3 Legal sustainability criteria for biomass

Although biomass is not a finite resource (though partially dependent on finite resources) its annual availability is limited and varies over time. In an attempt to reflect the sustainable limits of biomass availability, some governments are currently developing sustainability criteria, to reduce negative impacts on e.g. biodiversity, food security, water scarcity and soil degradation. These criteria should limit biomass use in the short term to a level that ensures its availability in the long term. For the biomass models (as used for instance in the AR5 models), the internalisation of these sustainability criteria is interpreted as a constraint or limitation of biomass potential. As mentioned above, sustainability of biomass and their potential are related to each other: greater focus on sustainable development of agriculture and forestry could ensure biomass potential does not decrease over time.

Below, factors are listed that are important in the sustainability criteria debate according to (Winning, 2013). For each of these factors a short description is provided of how they could influence the availability of biomass for energy production:

- **Future land use and crop yields:** Most scenarios assume that increasing food demand will be met by increasing yields. However, they also envisage a further expansion of land used for agriculture (typical values are around 5 - 45%). In scenarios with higher yield gains and lower demand for food production, the bioenergy potential is higher.
- Ecofys assessed the potential for yield increase of agricultural crops in the EU in a project for the EC. Best practice strategies to increase actual yield for a specific crop cover ideal management practices for: Crop variety, Fertilisation, Crop protection, Cultivation practices, Crop rotation. Land expansion was not considered as a valid option for yield increase. Even in high yielding countries like Germany or France we estimated a technical-sustainable potential for yield increase of 2-5% depending on crop type. For low yielding countries like Romania a technical-sustainable yield increase of 8-10% was estimated. The technical-sustainable potential includes constraints such as optimised use of agro-chemicals, exclusion of measures like irrigation and Clearfield technology and has implications on transport, storage and handling (Ecofys, 2016).

- **Land use planning:** Competition between bioenergy and food production can occur if both food and energy are produced from the same crop or if, due to scarce land availability, one of the options is economically preferred. The competition can be reduced if bioenergy production can be concentrated on previously unused land without biodiversity loss, carbon emissions, land-use conflicts or if production is limited to agricultural and forestry residues (Ecofys, 2014). A further aspect, which most models do not consider, is how climate change effects bioenergy supply and the competition for food (Calvin, et al., 2013).
- **Land-use change emissions:** Most AR5 models in our database include land-use change emissions, but not all include these related to bioenergy: only IMAGE, GCAM and REMIND do so (Van Vuuren D. , 2016). Typically assumed bioenergy related emissions covering land-use change, cultivation and processing are 5 kgCO_2/GJ biomass. The emissions of solid biomass fuels used for power production are determined at 91 kg CO_2/GJ (Caldecott, Lomax, & Workman, 2015), which means that the negative emissions of bio-CCS are estimated at 86 kgCO_2/GJ. This number is taken as a global average (Van Vuuren D. , 2016).
- **Type of crops:** The type of crops used for bioenergy influences the efficiency of land use. The second-generation bioenergy (cellulosic, waste and residues) are expected to increase performance compared to first generation (food crops) bioenergy. However, some conversion technologies are still in their infancies (e.g. cellulosic from straw) as are reliable figures on sustainable yields in real world plantations, including the medium- to long-term impacts of their cultivation on limiting factors such as soil fertility and water availability. Therefore, empirical data is limited regarding what yield can be sustained over the long periods of time assumed in the scenarios.
- **Agricultural and forestry residues:** The use of agricultural residues for bioenergy increases the potential for bioenergy without leading to additional land use. Several literature reviews have gathered insight on global biomass residue potentials, with estimates primarily ranging from 20 -100 EJ annually (Caldecott, Lomax, & Workman, 2015; Slade, Bauen, & Gross, 2014; Azar, et al., 2010). Some studies have made higher estimates reaching up to 120 EJ ((Caldecott, Lomax, & Workman, 2015) and one review study has even suggested a range of biomass residue potential up to 325 EJ (Kappas, 2013). The wide range of estimates is caused by diverse assumptions regarding what constitutes as residue, how much of it is available, how using residues impacts carbon and nutrient cycles and what existing and potential alternative uses there are (Brack, 2017; Creutzig, et al., 2015; Smith P. , et al., 2015 a.).

Sustainability of biomass covers environmental, social and economic aspects. However, the focus of mandatory sustainability criteria currently puts more emphasis on the emissions footprint and is limited in regard to e.g. biodiversity and environmental protection. There is a legal framework for sustainable biomass laid down in the Renewable Energy Directive (RED) by the European Commission (EC), which however is limited to biofuels and bioliquids. So far, no mandatory sustainable criteria have been developed for solid biomass for power and heat, but are discussed in the negotiation of the RED II draft proposal by the EC from November 2016.

For biomass feedstock produced in the EU, the cross-compliance rules of the Common Agricultural Policy (CAP) also apply[4]. These lack a GHG focus, yet cover good agricultural and environmental conditions, related to soil protection, maintenance of soil organic matter and structure, avoiding the deterioration of habitats and water management, and legislative standards covering, inter alia, the environment. Member States are also required to monitor and report every two years to the EC on the estimated impact of biofuels on biodiversity, water resources, water quality and soil quality with the Member State, as well as the changes in

[4] Member States progress report, see: http://ec.europa.eu/agriculture/direct-support/cross-compliance/index_en.htm

commodity prices and land use within the Member State associated with its increased use of biomass[5]. The EC is also required to report every two years to the European Parliament on any social impacts resulting from biofuel policy on the availability of food and affordable prices and wider development issues (including land rights and ratification and implementation of the conventions of the ILO (International Labour Organisation) in countries which are significant source of feedstock used for biofuels)[6].

Under the RED, compliance can be demonstrated through the use of voluntary schemes recognised by the EC or national systems implemented by Member States[7]. Voluntary schemes have become the preferred approach in most Member States and in some Member States (e.g. Germany and the Netherlands) the only option allowed in the national system is to adhere to one of the recognised voluntary schemes[8]. As of today, 19 voluntary schemes have been recognised by the EC.[9]

The voluntary schemes differ with regard to their mandatory sustainability criteria. Whereas some schemes simply reflect the legal mandatory criteria in the RED, other like the Roundtable for Sustainable Biomass (RSB) also demand social and economic criteria and have criteria for food security and promotion of rural development when cultivating in specific regions.

The abovementioned criteria are all related to direct sustainability risks. In addition, there are also sustainability risks due to indirect land use change (ILUC). ILUC is the effect that when existing cropland is used for biofuel feedstock production, the previous land use is displaced and as a result there is an increased risk that non-agricultural land is converted into cropland elsewhere. ILUC can therefore lead to higher GHG-emissions and loss of biodiversity. The RED was recently amended by the "ILUC directive", which must be transposed into national legislation by September 2017.

The Renewable Fuel Standard (RFS2) in the USA covers broadly similar mandatory sustainability criteria to the RED. These requirements relate to restrictions on land conversion after December 2007 and also minimum GHG saving targets for biofuels. For a pathway to be accepted in the RFS2, the US Environmental Protection Agency (EPA) calculates the typical GHG-emissions associated with that pathway. The minimum GHG-saving that has to be achieved for the pathway to be eligible depends on the fuel type; this ranges from 20% for renewable fuel, to 50% for biomass based diesel and advanced biofuel and up to 60% for cellulosic ethanol. These two are the most developed legal sustainability regimes for biomass globally.

Whereas a theoretical potential only has a physical upper limit in the cultivation of a feedstock, a sustainable potential also takes into account biosphere limits represented by protection of biodiversity and carbon stocks, GHG emissions and wider environmental criteria like soil, water and air quality. According to (Calvin, et al., 2013) models are diverse in this regard, taking into account some of these aspects to varying degrees (e.g. availability of land for food and timber and the impact of land use change). Furthermore, there is currently no agreement on what sustainability criteria should look like with regards to biomass for power and heat, therefore it is unclear how this could best be incorporated in models and what its quantitative effect on biomass availability is.

In order to account the emission reduction effect from CCS in biomass use, it is important to understand the carbon emissions resulting from the production of bioenergy, which differ from feedstock to feedstock. A

[5] EU Commission renewable energy progress report, see: https://ec.europa.eu/energy/en/topics/renewable-energy/progress-reports

[6] EU Commission renewable energy progress reports. See: http://ec.europa.eu/energy/node/70

[7] According to the legislation bilateral agreements between the EU and third countries are also foreseen, although none have been agreed to date.

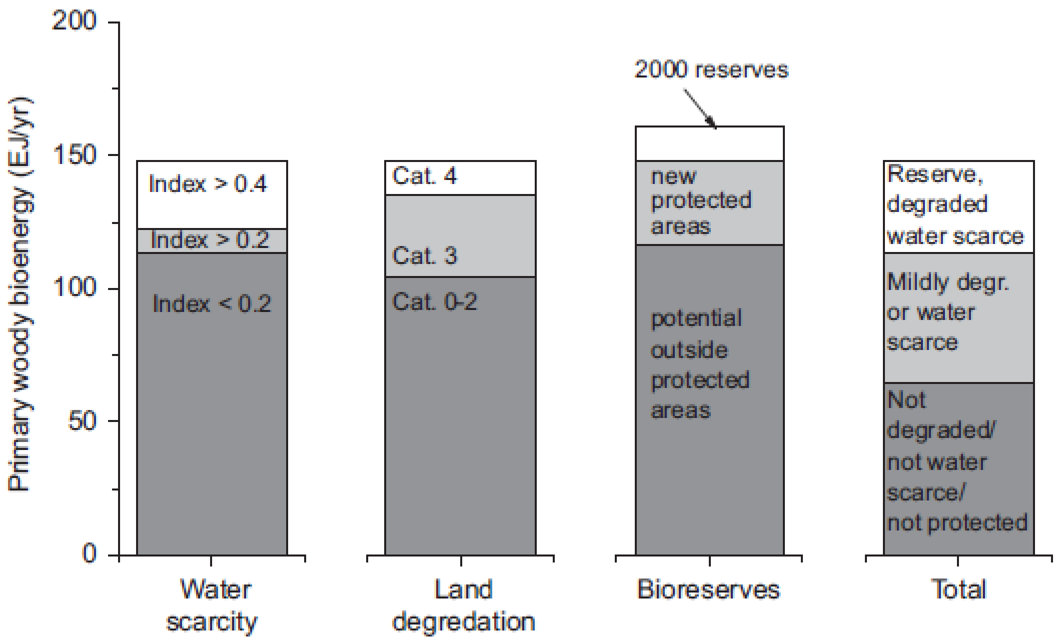
[8] The term "voluntary schemes" defines sustainability standards for biofuels which have been developed by the private sector and can be used to demonstrate compliance with the RED or a national scheme. Even if the use of one of the voluntary schemes is mandatory, the term "voluntary" remains. Some schemes also go beyond mandatory requirements.

[9] EU Commission, DG Energy: http://ec.europa.eu/energy/en/topics/renewable-energy/biofuels/voluntary-schemes

life-cycle analysis of bioenergy production considers emissions from cultivation, transportation and processing. Waste and residues have low or no emissions in the cultivation phase, as either the emissions are mostly attributed to the main crop or the material is a post-use from another process (e.g. used cooking oil). The emissions that occur during the bioenergy production are deducted from the carbon absorbed and stored in the specific biomass resources. The remaining carbon balance minus the emission resulting from the CCS energy penalty[10] can be claimed as carbon dioxide removals, or negative emissions.

In anticipation of the implementation of sustainability criteria, a sensitivity analysis was performed for the IMAGE scenarios, providing insights in the possible effects of sustainability criteria for the availability of woody biomass in scenarios (Van Vuuren, Van Vliet, & Stehfest, 2009). The sustainability criteria used in this sensitivity analysis, focus on biodiversity protection, but also refer to constraints due to water scarcity and land degradation. The results of the effects of these sustainability constraints on the sustainable primary wood bioenergy potential are shown in Figure 13.

Figure 13: Impacts of sensitivity analysis on 2050 potential for woody biomass in IMAGE model.



Source: (Van Vuuren, Van Vliet, & Stehfest, 2009)

The three constraints influence the sustainable biomass potential as follows:

- For **water scarcity** three levels of water scarcity are included in the analysis: the allowance of minor water scarcity[11] (index <0.2), the allowance of modest water scarcity (0.2 - 0.4) and the allowance of severe water scarcity (>0.4). The graph shows that based on the level of water scarcity, the availability of woody biomass ranges between 120 EJ and 150 EJ per year. Typically, water scarcity is largely overlooked in estimating biomass availability due to large aggregations, whereas this has been shown to be an important limiting factor in regional-scale studies (Van Vuuren, Van Vliet, & Stehfest, 2009). Following sensitivity analyses with water scarcity maps, 17% of the bioenergy potential may be excluded as this potential was located in severe water-scarce areas (Van Vuuren, Van

[10] CCS energy penalty refers to an efficiency reduction caused by CCS technology as compared to an energy source without CCS, described for example in the IPCC Special Report on Carbon Dioxide Capture and Storage (IPCC, 2005)

[11] Based on the results obtained with the Water Gap model for development of water stress under the baseline scenario of the OECD Environmental Outlook (Van Vuuren, Van Vliet, & Stehfest, 2009)

Vliet, & Stehfest, 2009). However, a better approach would be calculating water demand on the watershed level, which is currently not done in the assessed models. Some models that were not included in this study do include watershed models, such as CMIP5 (Kato & Yamagat, 2014).

- For **land degradation**, an overview was provided based on data from the GLASOD database[12]. Three levels of degradation were included: none to minor degradation (Category 0-2), serious degradation (Category 3) and severe degradation (Category 4). The severe degradation category might not be interesting for bioenergy at all, because of the high production costs.
- The results show that depending on the amount of land degradation that is accepted, the availability of woody biomass ranges between 110 and 150 EJ per year.
- These results include the broad assumption, that cultivation on degraded lands would be prioritised over non-degraded lands, despite considerably higher investments necessary to achieve viable yields there. In general, using degraded lands would be counterproductive as it reduces the amount of production available in the long run, not to mention other implications for environmental, social and economic sustainability linked to difficulties in correctly identifying and delineating such areas.
- For **biodiversity/bioreserves** three levels of land availability are included: no land-use of protected areas, including the very ambitious expansion of reserves by 2050 and the inclusion of the 2000 bioreserves. The results show that based on this criterion the availability of woody biomass ranges between 125 EJ and 160 EJ per year.

The combination of the three constraints results in the total effect and is shown in the farthest column to the right in Figure 13. The graph shows that, depending on how strict sustainability criteria are, availability of woody biomass ranges between 60 EJ and 150 EJ per year. It is difficult to determine the direction of the sustainability debate, as the opinions on this topic vary greatly. According to Van Vuuren (2016), the current debate does not give any reason to change the conclusions of the sensitivity analysis as performed in 2009. According to his findings, up to 100 EJ/year of primary energy from biomass is *probably* within a sustainable limit, while between 100-300 EJ/year *might* be within a sustainable limit. Primary energy from biomass exceeding 300 EJ/year will definitely not be possible within a sustainable limit (Van Vuuren D. , 2016).

For the **MESSAGE model**, a similar assessment has been undertaken that shows similar findings. The bioenergy potential applied in the MESSAGE model is estimated at around 160 EJ per year for 2050, implying the use of all abandoned agricultural land and half the natural grassland. When strict sustainability criteria are applied, the bioenergy potential is limited to below 100 EJ in 2050, and possibly considerably lower (Winning, 2013). For the development towards 2100, MESSAGE expects that the bioenergy potential is considerably higher through further expected improvements in yields and a decreasing growth of global population (as compared to 2010-2050). As a result, the technical potential in 2100 is expected to be in the range of 200-400 EJ per year. Strict sustainability criteria suggest a more realistic potential would be below 200 EJ in 2100 (Winning, 2013).

Based on the results of the sensitivity analyses, it can be concluded that if sustainability criteria are considered, the availability of biomass for power and heat is significantly limited in both the IMAGE and MESSAGE scenarios. For the other models and scenarios no comparable analyses were available.

4.4 Deployment and growth rates

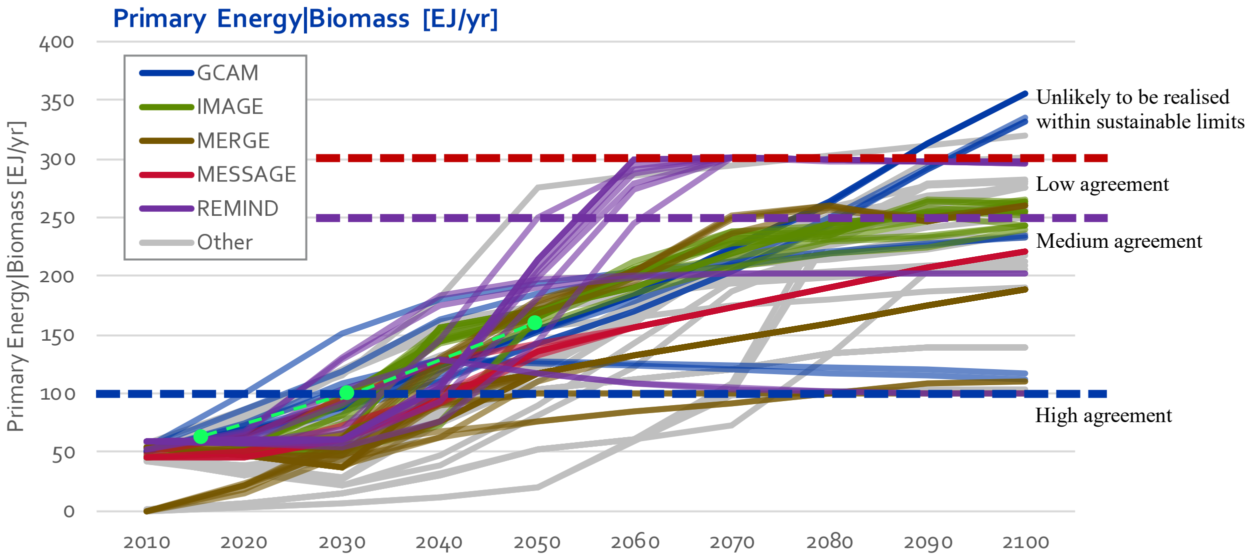
In Figure 14 the primary energy supply from biomass as described in literature is compared to the results from the selected models (see also Figure 12). In this figure, the primary bioenergy supply for 2016, 2020

[12] The GLASOD database is based on information on soil degradation available in the late 1980s, using a high level of aggregation and does not provide information on possible development of land degradation in the future. However, it does provide an initial insight into the overlay with bioenergy potential and land degradation (Van Vuuren, Van Vliet, & Stehfest, 2009).

and 2030 from IEA (2012, 2016) are indicated with the green dots. The coloured lines show the ranges based on IPCC (2014c) (see also section 4.1) within which literature agrees highly (blue: 0-100 EJ), medium (purple: 100-250 EJ) and low (red: >250 EJ).

The different trends result in large ranges: in 2050, the primary energy from biomass is between 20-280 EJ per year, for 2100 the range is expected between 100 and 360 EJ per year.

Figure 14: Development of primary energy from biomass in the selected models compared to the current developments and estimations from literature



Source: Ecofys based on (IEA, 2012; IEA, 2016; IPCC, 2014c)

Currently, primary energy from biomass accounts for about 50 EJ (IEA, 2016). Scenarios from IMAGE and MESSAGE show comparable values lying within a 10% range of the current value, while GCAM and REMIND scenarios show values around 60 EJ or more (>20% higher than current levels). This means that realisation of GCAM and REMIND scenarios is already lagging behind. However, considering the target that these scenarios aim for in 2050/2100 it is expected that these scenarios can still be realised, albeit following a different growth path.

The REMIND scenarios show steep growth rates between 2040 and 2060, which are amongst the steepest in the overview. Although no evidence is found that such growth rates can or cannot be realised, achieving such growth rates while also assuming a population growth of almost 1 billion people in that same period, seems very challenging.

5 Review of the application of (bio-)CCS in IPCC scenarios

In this section assumptions made in the selected models and scenarios on CCS and bio-CCS are reviewed. The focus of this review is on the following aspects: the availability of CO_2 storage capacity, the assumed deployment and growth rates, risk factors of bio-CCS (including environmental impacts and human health) and the role of biogenic CO_2. Based on the reviews of these aspects, conclusions are drawn on the plausibility of the selected scenarios.

5.1 The availability of CO_2 storage capacity

5.1.1 CO_2 storage capacity in literature

Geological CO_2 storage sites may be developed in suitable geology media in many regions of the world. It is expected that a very large theoretical CO_2 storage capacity resource is available. However, the level of detail and resolution required in the data make reliable and accurate estimation of CO_2 storage capacity in deep saline aquifers practical only at the local and site-specific scales (Bachu, Bonijoly, Bradshaw, & Mathiassen, 2007). The potential for real world effective CO_2 storage capacity will be constrained by physical, technical, regulatory, environmental and economic limitations. Some assessments of global practical CO_2 storage capacity are available and include methodologies that attempt to quantify the social, technical and economic factors that restrain real world CO_2 storage capacity development.

We review CO_2 storage capacity estimates from IPCC (IPCC, 2005) and IEA (IEA, 2010b) for theoretical CO_2 storage and Dooley (Dooley, 2013) for practical CO_2 storage. The IEA estimates the global theoretical geological CO_2 storage potential very large, between 8,000 $GtCO_2$ to 15,000 $GtCO_2$ (IEA, 2010b). The IPCC Special Report Carbon Dioxide Capture and Storage estimates that with a likeliness of at least 66% there is at least 2,000 $GtCO_2$ of global storage capacity, with a much larger potential possible. Known oil and gas fields alone have a global CO_2 storage capacity of approximately 675–900 $GtCO_2$ and that they occupy only a small fraction of the pore volume in sedimentary basins.

Both sources provide high level estimates of theoretical capacity, based on known oil and gas fields and geological basin level mapping deep saline formations. The IPCC 2005 regards the upper limit estimates of CO_2 storage to be uncertain due to lack of information and an agreed methodology. Global capacity estimates have been calculated by simplifying assumptions and using very simplistic methods and hence are not reliable. Dooley (2013) provides global estimates of effective CO_2 storage of 13,500 Gt CO_2 and practical CO_2 storage capacity of 3,900 Gt CO_2 (Dooley, 2013). Dooley compiles local and regional CO_2 storage capacity estimates providing an updated assessment of global CO_2 storage capacity. This assessment includes both onshore and offshore CO_2 storage capacity in deep saline formations, depleted gas fields, depleted oil fields, and un-minable coal seams. Dooley concludes that estimated cumulative demand for storage is modest when compared to global estimates of the potential effective or practical capacity of deep geologic CO_2 storage reservoirs. It is not possible to exactly determine the viability of storage capacity; individual sites need to be mapped, characterized and tested. This can result in the exclusion of storage capacity if a storage site does not meet geological, performance or environmental requirements, decreasing the storage capacity even further.

5.1.2 CO_2 storage requirements

Total estimates of CO_2 to be stored to 2100 including fossil, industrial and biogenic CO_2 (Table 5) provide a total upper estimate of ~2,330 Gt CO_2 and a lower estimate of 614GtCO_2. Thus, all CO_2 storage estimates are within the practical CO_2 storage estimates provided by Dooley (Dooley, 2013). The assessment (Figure 18) of the scale of biogenic CO_2 to be stored cumulatively provides a range of 290-1,100 Gt CO_2 of biogenic CO_2 to be stored by 2100. This is equivalent to ~2%-8% of effective storage capacity provided by Dooley (Dooley, 2013) and ~8%-26% of current practical storage capacity.

These results indicate that **global CO_2 storage capacity potential is not likely to be a key limiting factor for CO_2 storage**. However, depending on the stringency of defining criteria for practical CO_2 storage capacity, the upper estimates of very large fossil, industrial and biogenic CO_2 storage to 2100 may begin to reduce plausibility. Furthermore, the existence of a practical CO_2 storage resource does not directly lead to accessible CO_2 storage capacity, as the resource must be mapped and characterised to be available for permanent CO_2 storage. This means that the **location of CO_2 storage, timely access to qualified CO_2 storage sites and the rate at which CO_2 storage sites can be developed could limit deployment**.

5.1.3 Location of CO_2 storage

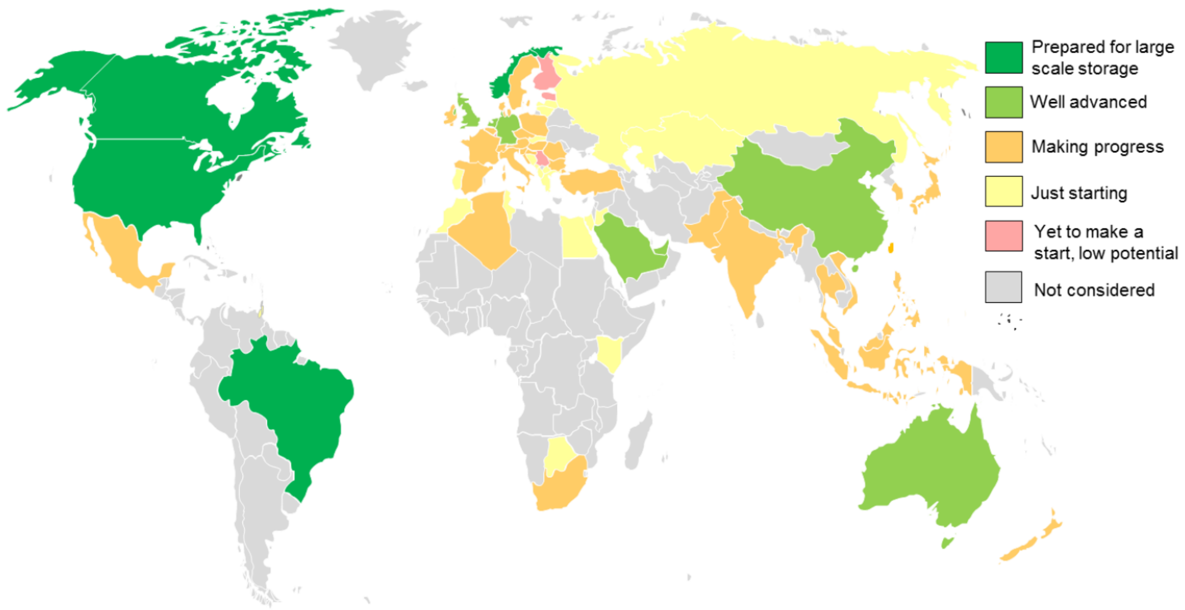
Dooley estimates that ~60% of the global practical storage capacity is in the United States. The National Energy Technology Laboratory (NETL) of the U.S. Department of Energy, 4th edition of U.S. carbon utilization and storage atlas (Atlas IV) range from total storage capacity in the United States between about **1,800 Gt CO_2** and **13,700 Gt CO_2**, (Anderson, 2016). In order to realise the global bio-CCS potential and its negative CO_2-emssions, this means that a significant share of the bio-CCS plants would then have to be located in North-America and should be connected to CO_2 infrastructure. From the model perspective, we know that at least in the IMAGE model it is assumed that all available storage potential on a continent-level can be accessed and used by all CO_2 supply available in the individual countries (Van Vuuren D. , 2016). This assumption implies that the decision-making process on the required CO_2 transport infrastructure is included in the decision-making on developing bio-CCS plants and developing CO_2 storage sites. Although this would most likely increase the complexity of the decision-making process, it would not be possible to deploy bio-CCS without the existence of a CO_2 infrastructure, linking biogenic CO_2 capture to CO_2 storage sites. This implies that CO_2 networks should be developed continent-wide, so that every bio-CCS plant could access the (nearest) geological sink and/or that bio-CCS plants should be built close to geological sinks. It is unclear whether these assumptions also hold for the other models based on what information has so far been published.

This geographical matching, or lack thereof, means that biomass availability and proximity to CO_2 storage potential could also be a limiting factor on biogenic CO_2 capture and storage. Chen & Tavoni (Chen & Tavoni, 2013) explore differential regional endowments of geological storage capacity affecting biogenic CO_2 capture. They expect bio-CCS to be implemented primarily in Latin America and assign Direct air capture and storage especially to the transition economies and the MENA region (Middle East and North Africa).

An investment case must exist for CO_2 storage sites to be developed in advance of widespread CO_2 capture development. Commercial CO_2 storage operators will require security of income or a secure CO_2 supply, especially in the early phases of the sectors development (Deloitte, 2016). Globally there is currently no commercial case for private investment in the characterisation, provision and operation of dedicated CO_2 storage sites.

In their global storage readiness assessment GCCSI (2015) provides an overview of the current development status of individual countries concerning storage readiness. The scoring was performed on three key elements (GCCSI, 2015): History of research and development programs focused on CCS; Open, innovative and advanced oil and gas industry; and Incentives for CCS — e.g. public funding, CO_2 tax, or utilisation of CO_2.

Figure 15: Overview of global storage readiness

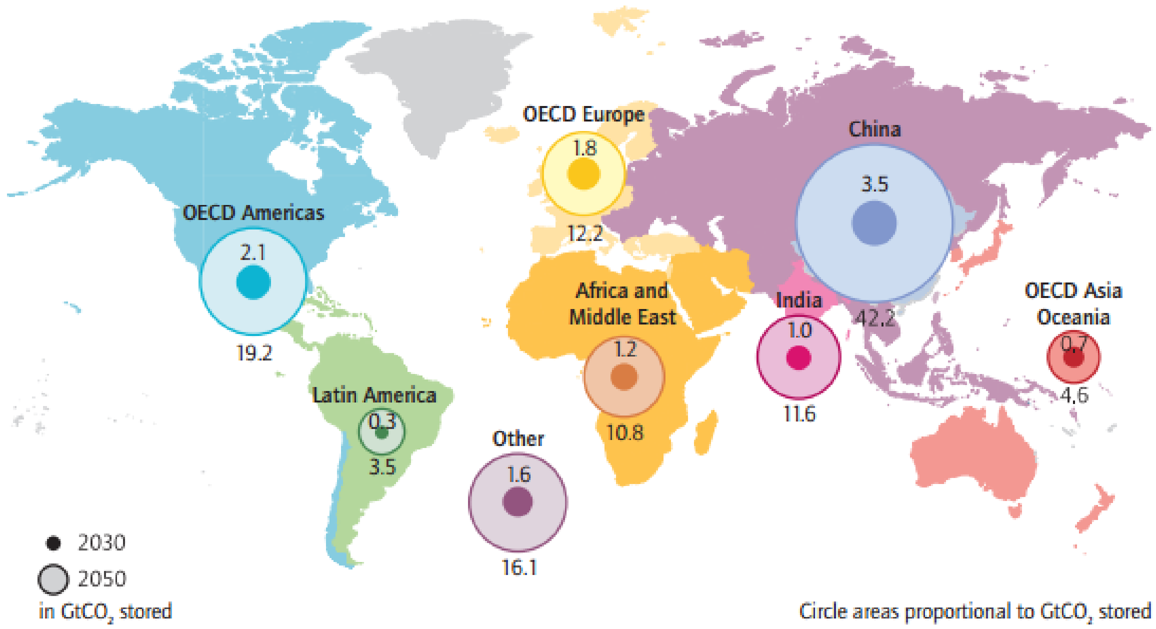


Source: (GCCSI, 2015)

The colour-codes indicate the level of storage readiness of the countries. Figure 15 shows that only a few countries are storage ready (Brazil, Canada, Norway, USA) and seven other countries are well advanced (Australia, China, Germany, Netherlands, Saudi Arabia, UAE, and the United Kingdom). The overall assessment concluded that significant work is required to ensure more countries are 'CO_2 storage ready'. Chen & Tavoni observe that regional storage constraints do arise and give regions with large storage potential a competitive advantage in conducting CDR (Chen & Tavoni, 2013).

These results can be compared to the assessment of IEA (2013) on the amount of CO_2 captured from the different regions (IEA, 2013):

Figure 16: Cumulative CO_2 captured between 2015-2030 and to 2050, by region to meet 2 degrees scenarios



Source: (IEA, 2013)

Figure 16 shows that between 2015 and 2030 most CO_2 will likely be captured in China, North America and Europe and that near 2050 India and Africa are also likely to play an important role. Comparing the graphs leads to the observation that quite some work is needed in Europe, India and Africa to ensure CO_2 storage up to 2030 and that also in China progress is required for storage readiness.

The institutional capacity of governments to permit, oversee and retire large numbers of CO_2 storage sites, and the permitting and oversight of CO_2 transport infrastructure has not been demonstrated. CO_2 transport and storage requires legal and regulatory frameworks to be developed and enforced by jurisdictions hosting CO_2 storage sites (IEA, 2010). The potential for thousands of CO_2 storage sites to be commissioned, operated and decommissioned by 2100 may require extensive national oversight depending on the regulatory environment (CO2Europipe, 2011).

Although it will not be possible to draw solid conclusions based on the data above, it raises some concerns. For instance, only a small number of countries is currently ready for CCS.

5.1.4 Timely access to qualified CO_2 storage

The development of permanent CO_2 storage sites takes time, sites must be mapped, environmental impact assessments and government approval processes of individual sites must be conducted, CO_2 and brine flow modelled, appraisal drilling where necessary and finally developed with injection wells and other infrastructure. Depending on the location and geology, work must begin on developing a CO_2 storage site 5 to 15 years prior to CO_2 is capture and injection (IEAGHG, 2011). CO_2 storage characterisation may not always be successful as results may deem the site unsuitable (Scott, Gilfillan, Markusson, Chalmers, & Haszeldine, 2013). The IPCC models do not currently reflect on development time of CO_2 storage as a limiting factor. This could potentially lead to overvalued storage capacities availability and reduce the short-term application of the technology if development efforts are not undertaken.

An additional consideration to gross CO_2 storage capacity availability is the rate at which CO_2 can be injected. The global CO_2 injection rate is a function of the number of CO_2 storage sites in operation. An individual storage site has a limited CO_2 injection rate, so increasing the CO_2 injection rate for a CO_2 network will require additional CO_2 storage sites to be added. The scale of availability of accessible CO_2 injection and total storage capacity is dependent on the human and capital resources devoted to the investigation, characterisation and development of CO_2 storage sites. These are all important factors when moving from theoretical CO_2 storage potential to practical CO_2 storage capacity. As the process of geological CO_2 storage characterisation to full development takes many years, practical measures to provide CO_2 storage must begin long in advance of CO_2 injection and storage (IEAGHG, 2011).

5.2 Deployment and growth rates

Regarding the growth rate of CCS, three indicators were assessed: the number of wells that can be drilled; the maximum feasible injection rate; and CO_2 infrastructure.

In 2015, 15 CCS projects were operational, representing an installed capacity of 28 Mt CO_2/yr (GCCSI, 2016). This installed capacity matches with 32 scenarios (ca. one third) that indicated an installed capacity of 28 Mt CO_2/yr or lower in 2015. If the current trend is extrapolated, the installed capacity of CCS projects in 2020 would be about 60 Mt CO_2/yr in 2020. Again, 32 scenarios indicate a similar result. However, averaging the installed capacity of all scenarios in 2020 will result in 550 Mt CO_2, which is nine times higher. This means that for most of the scenarios a significant gap between the real deployment and the IPCC scenario deployment of CCS is growing quite fast. Between 2020 and 2030 the installed capacity of CO_2 capture in the modelled scenarios increases quickly, with an average growth rate of about 500 Mt CO_2/yr. Literature describes a development time for CCS-projects of about 5-15 years (IEAGHG, 2011), which means that a share of the infrastructure which occurs in the modelled scenarios between 2020 and 2030 would already have to be under development now. For the period between 2020 and 2030 currently about 11 projects are known that are under development. **It is therefore expected that the uptake of CCS will most likely not go as fast as estimated in the majority of the scenarios**.

5.2.1 Number of wells that can be drilled

The median rate of CO_2 storage from all sources, biogenic, fossil, industrial in 2050 of all scenarios requires ~14,000 CO_2 injection wells to be in operation in that year if each well can inject 1 Mt CO_2 per annum. CO_2 storage on this scale may be plausible when compared to existing activities of the oil and gas industry, where in 2013 alone, ~3,000 offshore development wells and ~70,000 onshore development wells were completed (Cook, 2014).

In section 5.4 an estimation is made on the number of wells that must be drilled in order to realise the storage potential. In the maximum scenario (REMIND) almost 40,000 wells must be drilled up to 2100. Comparatively, the oil and gas industry has in 2013 alone drilled about 70,000 onshore wells (Cook, 2014). This means that **drilling capacity alone is not a limiting factor for biogenic CO_2 storage**. However, it would require that at least a share of the drilling capacity (in terms of equipment and human resources) would be used for drilling CO_2 wells instead of oil and gas wells. Revenues from oil and gas are high, whereas in most regions no revenue for CO_2 storage or CCS exists. If this continues, drilling capacity will be prioritised for the oil and gas industry. As long as the business case for oil and gas production remains more favourable than the business case for CCS, it can be expected that deployment of CCS storage capacity will become more difficult.

However, no dedicated CO_2 storage industry currently exists (ZEP, 2014). A rapid scale up may not be industrially practical due to limited industrial and human capacity. Professionals and expertise required to develop CO_2 storage overlap with activities of the hydrocarbon extraction sector, potentially creating a market conflict for limited personnel and equipment (Whiriskey, 2015).

5.2.2 Feasible injection rate

The majority of models exhibit biogenic CO_2 injection and storage at the rate of hundreds or thousands of millions of tonnes a year by 2040 (see chapter 5.4 for details on the biogenic CO_2). The **GCAM-scenario** and **REMIND-scenario** exhibit approximately ~2,000 Mt CO_2 to ~4,000 Mt CO_2 of biogenic CO_2 to be injected for storage in 2040. Taking CO_2 storage conditions to be 10 MPa and 40°C CO_2 density is approximately 600 kg m^3 a simple comparison with current global oil production can be made (Mac Dowell, Fennell, Shah, & Maitland, 2017). The CO_2 injection **GCAM-scenario** and **REMIND-scenario** respectively is equivalent to 58 – 115 million barrels (MMbbl) of CO_2 per day. **These suggest that biogenic CO_2 injection in 2040 would be roughly comparable to current global oil production at 87 million barrels of oil per day** (CIA, 2014). Meeting this need in 2040 would require, at a minimum, a concerted effort to develop and characterise CO_2 storage sites from the 2020s due to the development lead times for transport infrastructure and development of permanent CO_2 storage sites. However, many of the scenarios exhibit large scale biogenic CO_2 storage as of 2020, which is not consistent with present real-world actions to make CO_2 storage available. For large scale CO_2 storage activities to take place from 2020, investments in exploration, characterisation and site development would need to be currently ongoing, reducing the plausibility of these scenarios.

5.2.3 CO_2 transport infrastructure

CO_2 storage requires suitable geological strata, but these do not exist in every region therefore CO_2 transport would be required. Full deployment of (bio-)CCS will require a well-developed CO_2 transport network, consisting of pipelines, trucks, barges and ships.

It is not possible to assess the means (pipeline, ship, barge) or distance of CO_2 transport until 2100 based on current available data. Large emissions sources tend to be clustered, such as the industrial conurbation of the Ruhr. CO_2 transport would be required to connect these emissions clusters to existing CO_2 storage sites, or those under development. Shipping and inland barges would be an option to offer more flexible CO_2 transport in the initial phase of development, requiring less time to plan and construct (Fimbres Weihs, Kumar, & Wiley, 2014). As more sectors and sites are equipped for capture and storage, pipeline transport becomes economically preferable.

The rate of CO_2 transport (pipeline, ship, barge) development envisioned to transport the large volumes of biogenic CO_2 may be challenging. Currently, no incentive for the development of widespread CO_2 collection and transport networks for fossil, industrial or biogenic CO_2 exists.

All AR5 models distinguish CO_2 storage potential and biomass potential on a regional or continental basis (IIASA, 2015b). Deployment of biogenic CO_2 capture and storage thus rely on CO_2 transport networks. IMAGE includes no specific assumptions on time needed to build the transportation network; it also assumes that this will not be a limiting factor in the deployment of CCS (Van Vuuren D. , 2016). However, the development of a large CO_2 collection and transport networks (pipeline, barge, ship) takes time and would have to expand in a step wise process (i.e. from Rotterdam to Ruhr and then deeper into Germany). Delayed or lacking development of CO_2 transport networks would limit the matching between biomass sources and CO_2 storage resources. This could limit capture and storage of biogenic CO_2 or require biomass to be transported to facilities connected to CO_2 storage network. The cost of infrastructure to transport CO_2 from bio-CCS production areas to storage locations needs to be further evaluated (Smith, et al., 2015). Biogenic CO_2 capture scenarios requiring large amounts of CO_2 to be stored will only be possible with much further development of CO_2 infrastructure and experience with CO_2 storage (Tavoni & Socolow, 2012). This will thus depend on the development and deployment of CCS in the coming years.

5.3 Risk factors in the deployment of (bio-)CCS

The European Academies Science Advisory Council (EASAC) regard the main concerns that need to be addressed to secure and demonstrate the safe performance of any specific CO_2 storage site include the following (EASAC, 2013):

- Risks of **CO_2 leakage** and its consequences in terms of environmental effects and safety
- Effects of **CO_2 pressure build-up** in storage formations caused by the injection of CO_2
- The possibility of **induced seismicity**, which could result in damage to buildings and infrastructure, and may threaten seal integrity
- **Long-range impacts** on other facilities and activities, including the effects of the pressure plume and far field brine migration

5.3.1 CO_2 leakage

CO_2 leakage may be focused or diffuse. Focused leakage may occur through existing and/or abandoned wells, or through fractures and fracture zones intersecting the cap rock (sealing rock in CO_2 storage site). In diffuse leakage, CO_2 migrates through the cap rock itself. CO_2 leakage from wells has been identified as the primary avenue should leakage occur. It is essential for the integrity of a CO_2 store to understand the prior history of each basin proposed for CO_2 storage (Goebel,, Hoffman, & Nicholson,, 2015). The risk of leakage through wells needs to be remediated and thorough, analytical and baseline mapping is required to identify abandoned legacy wells and their quality (Celia & Nordbotten, 2009). The potential for leakage through the cap rock itself, or through fractures and fracture zones, requires assessment of geological, hydrodynamic, geomechanical and geochemical with modelling at basin and reservoir scales.

If CO_2 leakage were to occur, one of the primary concerns for human health is the possibility of asphyxiation and/or contamination of potable water via the mobilization of toxic metals resulting in increased cancer risk (Siirila-Woodburn, Sitchler, Maxwell, & Mccray, 2010). Assessment of human health impacts from historical records of 286 natural CO_2 seep locations in Italy show the risk that gas seeps present to the population is orders of magnitude lower than many other natural or socially accepted hazards. (Roberts, Wood, & Haszeldine, 2011).

Detection of leakage from the CO_2 storage site and brine migration to surrounding geological formations or the terrestrial environment requires monitoring, measurement and verification (MMV) of CO_2 storage. Monitoring of a CO_2 storage site must continue after CO_2 injection has stopped, known as the post-closure phase (Rütters, 2013).

5.3.2 CO_2 pressure build-up and induced seismicity

Large-scale pressure build-up may become a limiting factor for storage capacity, as the over-pressurisation may cause fractures in the cap rock, may drive CO_2 or brine leakage through localised pathways, and may even cause induced seismicity. The total storage capacity of a CO_2 storage site is limited by pressure. Follow on CO_2 storage sites in the vicinity of existing CO_2 storage sites may have effective storage capacity reduced by increased pore fluid pressure resulting from existing CO_2 storage activities. CO_2 storage site planning, permitting and operation require well-designed injection schemes and monitoring protocols. Basin level planning of CO_2 storage development can aid maximising CO_2 storage resource (Pearce, Bentham, Kirk, Pegler, & Remmelts, 2014). Good operating practices and reporting and monitoring mitigate the risks related to pressure build-up (Chadwick, et al., 2008; DNV, 2012).

CO_2-storage can cause pressure waves through the ground which are referred to as induced seismicity, typically, such events are small. CO_2 storage site management and performance guidelines will need to define the acceptable levels and impacts of induced seismicity, and should establish optimised monitoring and control measures (IEAGHG, 2013). Yet standards do not exist and it must be taken into account that monitoring requirements as well as mitigation measures limit the usable storage potential and raise storage costs.

5.3.3 Public acceptance

There is a potential for public acceptance to prevent or delay the development of CO_2 storage sites and CO_2 transport infrastructure (Schumann, Duetschke, & Pietzner, 2014). Induced seismicity, like other environmental impacts, negatively affects public acceptance of CO_2 storage development and results in a reduced rate of deployment in many areas. Therefore, the deployable CO_2 storage potential can be further limited when population density is considered. It is unclear whether public acceptance is included in the models. Based on Van Vuuren, it is known that public acceptance is not included as a factor in IMAGE (Van Vuuren D. , 2016).

5.4 Implications for CO_2 storage of only biogenic CO_2

As indicated in the previous sections of this chapter, the CCS-industry is developing more slowly than described in the majority of the scenarios. It is therefore uncertain whether the industry would be able to scale-up fast enough to store all CO_2 from fossil power production, industrial activities and bio-CCS described in the scenarios. Possibly clear choices will have to be made, for instance to find alternatives for fossil power and to focus CCS-activities entirely on biogenic CO_2 only.

Assessing the feasibility of the rate of biogenic CO_2 transport, injection and storage capacity development to 2100 requires the conversion of primary biomass energy utilised with CCS to biogenic CO_2 captured and stored[13]. By using the assumptions in Table 6, it was estimated that the conversion of 50 EJ of biomass results in around 4,500 Mt of CO_2. Including an encompassing carbon conversion, capture, transport and storage efficiency of 70%[14] would result in around 3,100 Mt of CO_2 to be transported and stored for 50 EJ of biomass use combined with CCS. Table 6 is used to calculate the CO_2 emissions stored from bio-CCS, using the AR5 database. The result is presented in Figure 17 and Figure 18.

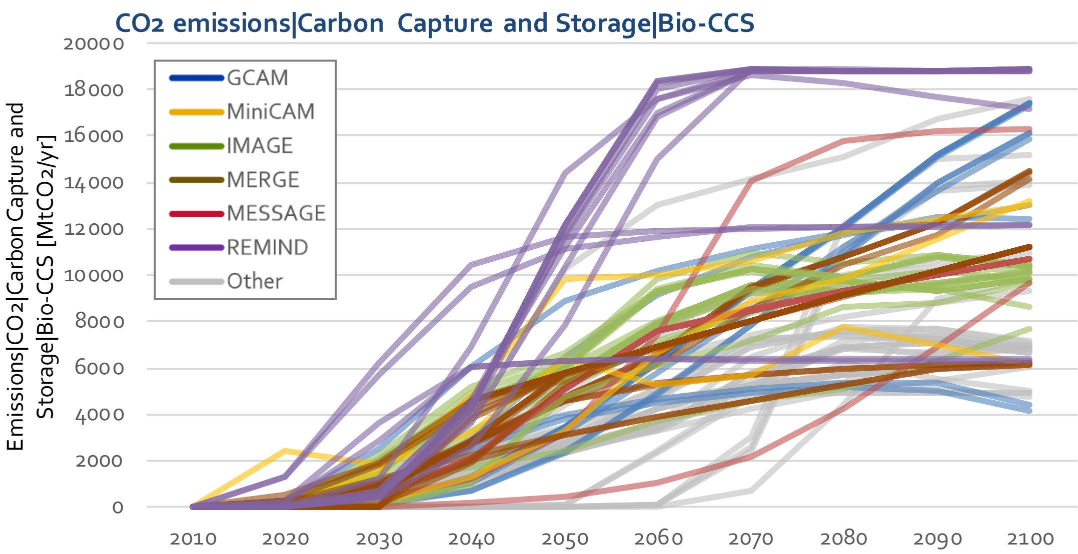
[13] The methodology is an expansion of an analysis found in "Planetary limits to BECCS negative emissions, 2015, Andrew Wiltshire and T. Davies-Barnard, AVOID 2 programme."

[14] The assumed different figures for the net storage 'efficiency' of bio-CCS, the percentage of total biomass carbon removed from the atmosphere on a life-cycle basis. Methodology from "Stranded Carbon Assets and Negative Emissions Technologies, 2015, Ben Caldecott, Guy Lomax & Mark Workman, stranded assets programme, University of Oxford

Table 6: Assumptions used for representative CO_2 storage sites and primary biomass energy to illustrated CO_2 storage development

Parameter	Unit	Source
CO_2 content biomass	91 kg CO_2/GJ	(Caldecott, Lomax, & Workman, 2015)
Energy Density of Biomass	20 J/g	(Field, Campbell, & Lobell, 2008)
CO_2 storage site capacity	100 Mt CO_2	(IEAGHG, 2011)
CO_2 storage site injection rate	4 Mt CO_2/yr	(IEAGHG, 2011)
CO_2 injection rate per injection well	1 Mt CO_2/yr	
CO_2 storage site operational life	25 years	(ZEP, 2011)
Length of time to develop CO_2 storage site	7 years	(IEAGHG, 2011)
Conversion, capture, transport and storage efficiency of carbon content of biomass	70%	(Caldecott, Lomax, & Workman, 2015)

Figure 17: Illustrative development of CO_2 to be injected in CO_2 storage from biomass with CCS



Source: Ecofys based on IPCC (2014c)

The majority of the scenarios show a continuous growth of CO_2 injection to 2100. In total, the CO_2 to be stored from biomass combined with CCS ranges between 4,400 Mt CO_2 and 19,000 Mt CO_2 per year in 2100, with a median of 4,000 Mt CO_2 to be stored annually in 2050.

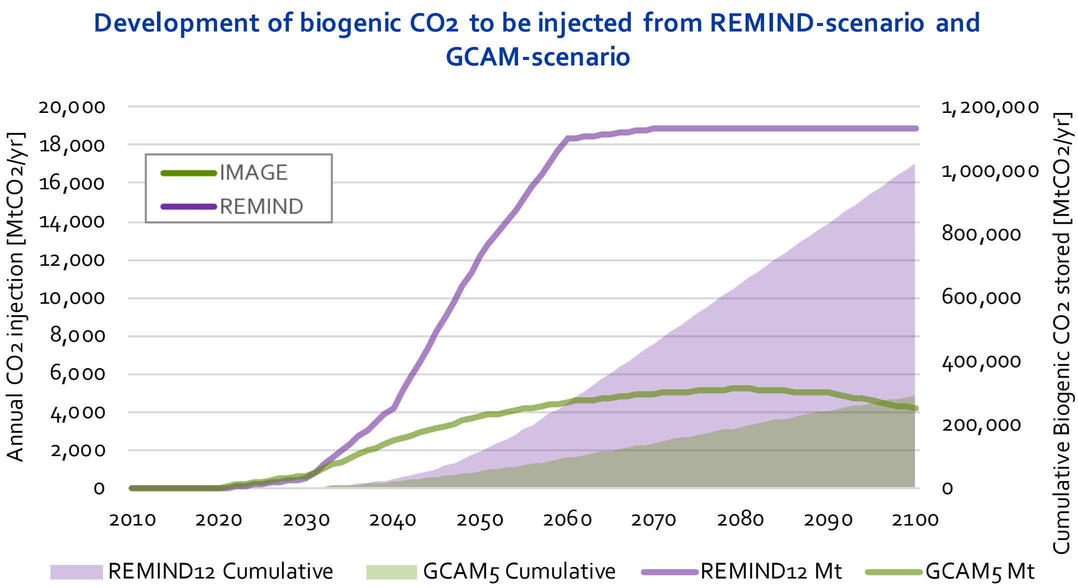
The following information on the individual models can be drawn from the figure:

- **GCAM** scenarios show a growth in biogenic CO_2 storage from 2030 onwards. The scenarios show differences in growth pace: the scenarios that assume large growth will continue to grow fast up to 2100, while other scenarios assume a moderate growth between 2060 and 2090 and even a decrease in 2100.
- Scenarios of the **MiniCAM** show a more varied picture. Biogenic CO_2 storage is expected around 2020-2030 with a steep growth expected between 2030 and 2050. After 2070, the scenarios plateau with only small increases or decreases.

- In **IMAGE** scenarios, the starting point for the requirement of bio-CO_2 injection and storage differs widely between the scenarios. Some scenarios assume biogenic CO_2 storage to begin in 2030, others implement bio-CO_2 storage only after 2060.
- **MESSAGE** scenarios in general assume a similar growth path as the MiniCAM scenarios with use of biogenic CO_2 storage between 2030 and 2060 and a continuous but reduced growth rate up to 2100.
- The majority of the **REMIND** scenarios show the strongest use of bio-CO_2 injection and storage between 2030 and 2060, plateauing to 2100. The REMIND scenarios reach the highest bio-CCS level of all scenarios of up to 19,000 Mt of CO_2 injected per year.

An assessment of the practical, political and environmental considerations of the scale of CO_2 injection and storage envisioned by the models requires an analysis of the number of individual CO_2 storage sites to be constructed, operated and retired. Two scenarios exhibiting the maximum and minimum use of bio-CCS in 2100 were chosen, the REMIND 1.5LIMITS-RefPol-450-PC scenario (hereafter named the REMIND-scenario) and the GCAM 3.0EMF27-450-LimBio scenario (hereafter named GCAM-scenario). These two scenarios are plotted in Figure 18. The aggregated biogenic CO_2 to be stored from now to 2100 is approximately 1,000,000 Mt CO_2 and 290,000 Mt CO_2 for REMIND-scenario and GCAM-scenario respectively.

Figure 18: Illustrative development of biogenic CO_2 to be injected in CO_2 stores from REMIND-scenario (max injection in 2100) and GCAM-scenario (min injection in). Cumulative biogenic CO_2 stored to 2100 for REMIND-scenario and GCAM-scenario



Source: Ecofys based on IPCC (2014c)

The storage of biogenic CO_2 begins simultaneously for both scenarios in 2020. With a CO_2 storage mapping, characterisation, permitting and development time of approximately 7 years, CO_2 stores to be in use by 2020 would already have to be under development now. As CO_2 storage sites have a limited capacity, they must be retired once available capacity is used. The retirement of existing storage sites necessitates their replacement with the development of new CO_2 storage sites to maintain or expand CO_2 injection and storage capacity in line with biogenic CO_2 injection.

The illustrative results for the **REMIND-scenario**

- **REMIND-scenario** exhibits the maximum amount of biomass use with CCS in 2100, with ~300 EJ of bioenergy and ~18,000 Mt CO_2 stored in 2100 alone. This requires a large number and extensive global network of CO_2 storage and CO_2 transport to be developed, with a total of ~9,500 CO_2 storage sites being developed until 2100 (Table 7).
- Development begins early in the modelling period with the first storage sites required from 2020. Approximately 13 storage sites (assuming a storage site of 100 Mt) would need to be commissioned every year in the 2020s for biogenic CO_2. Few dedicated CO_2 storage sites of the scale described have been developed and permitted to date. Drawing the industrial and human capacity required to reach the rate of CO_2 storage development in this period may be a challenge. No commercial rationale for CO_2 storage exists at present. In addition, national bodies would be required to assess and permit CO_2 storage sites at a rate far beyond what is currently undertaken.
- By 2050, some 3,000 storage sites would be required to be in operation globally, requiring the drilling of some 12,000 CO_2 injection wells. In this period, the first CO_2 storage sites reach the end of their operational lives, with approximately 80 storage sites and ~300 injection wells being retired in the years directly preceding 2050.
- Very rapid growth rates in CO_2 storage deployment are observed from 2030 to 2060 with ~10% per annum growth over the period and a ~22% annual growth from 2030 to 2040. The growth in development of storage sites is accelerated by the replacement of retiring sites. Again, the industrial, legal and political feasibility of such a rapid expansion must be questioned. Such rapid expansion of CO_2 storage over long periods could potentially negatively affect public acceptance of CO_2 storage and retard deployment.
- By 2100 some 4,700 CO_2 storage sites are retired globally. Retired CO_2 storage sites enter a period of monitoring and verification of CO_2 storage security prior to handover to the state authority (a period of 20 years under the current EU CO_2 storage directive). The large number of decommissioned storage sites that would have to be administered by state bodies could put a strain on capacity.
- Especially between 2030 and 2060 the REMIND-scenario requires very large and rapid capacity building by national subsurface administrative bodies to plan, permit and oversee the operation and decommissioning of CO_2 storage sites.

Table 7: Annual rate of development and retirement of CO_2 sites to meet REMIND-scenario biogenic CO_2 injection and storage from 2010 to 2100

REMIND-scenario	2010 - 2019	2020 - 2029	2030 - 2039	2040 - 2049	2050 - 2059	2060 - 2069	2070 - 2079	2080 - 2089	Aggregated 2010-2100
Sites Developed	0	118	850	1950	2124	1741	1775	853	~ 9,500
Sites Decommissioned	0	0	0	-66	-530	-1460	-1770	-845	~ 4,700
Sites Developed per year	0	1	13	93	212	248	213	154	
Sites Decommissioned per year	0	0	0	0	-13	-93	-199	-155	

Source: Ecofys based on IPCC (2014c)

The illustrative results for the **GCAM-scenario** scenario:

- The **GCAM-scenario** exhibits the minimum amount of biomass use in 2100 with CCS in the models reviewed, with an annual use of ~65 EJ of bioenergy and the injection of 4,000 Mt CO_2 in 2100, with a total of ~2,500 storage sites being developed (Table 8).
- Development begins early in the modelling period with the first storage sites required from 2020. Under the illustrative storage capacity and injection rate 12 storage sites are commissioned every year in the 2020s for biogenic CO_2. Few dedicated CO_2 storage sites of the scale described have been developed and permitted to date. The industrial and human capacity required to reach the rate of CO_2 storage development in this period may be a challenge. In addition, national bodies would be required to assess and permit CO_2 storage sites at a rate far beyond what is currently undertaken.
- By 2050, some 1,000 storage sites would be in operation globally to enable the biogenic CO_2 injection rate of the **GCAM-scenario** (~4,000 Mt CO_2/year), with ~4,000 CO_2 injection wells being completed. As with the **REMIND-scenario** the years preceding 2050 see the first CO_2 storage to be decommissioned, with ~100 CO_2 storage sites retired.
- The **GCAM-scenario** exhibits modest growth rates in annual CO_2 storage deployment from 2030 to 2060 with a decline thereafter in number of new CO_2 storage sites commissioned annually. 2060 sees the peak in CO_2 storage site development with some ~65 storage sites developed in that year.
- From 2030 to 2060 global annual expansion of the number of CO_2 storage sites is ~5%. Expansion is rapid for the period from 2030 to 2040 at ~10% per year, but then plateaus with near zero growth by 2070.
- Starting in 2080 the **GCAM-scenario** sees a decline in CO_2 injection with the number of CO_2 storage sites commissioned declining from a peak in 2060.
- In the 2050's, the illustrative assessment indicates ~200 CO_2 injection wells must be completed each year to meet injection capacity for biogenic CO_2.
- By 2100 some 1,400 CO_2 storage site will have been retired globally under **GCAM-scenario.** These end of operational life CO_2 storage sites require a period of monitoring and verification of CO_2 storage security prior. After this process is completed the relevant state authority take stewardship of the storage site. The majority of sites decommissioning is post 2050 with the annual rate of decommissioning not exceeding 50 sites per annum globally.

Table 8: Annual rate of development and retirement of CO_2 sites to meet GCAM-scenario biogenic CO_2 injection and storage from 2010 to 2100

GCAM-scenario	2010 - 2019	2020 - 2029	2030 - 2039	2040 - 2049	2050 - 2059	2060 - 2069	2070 - 2079	2080 - 2089	Aggregated 2010-2100
Sites Developed	0	156	430	426	513	517	330	108	~ 2,500
Sites Decommissioned	0	0	0	-92	-310	-390	-255	-155	~ 1,400
Sites Developed per year	0	12	16	46	48	65	44	26	
Sites Decommissioned per year	0	0	0	0	-16	-46	-32	-19	

Source: Ecofys based on IPCC (2014c)

6 Rough feasibility assessment

In this chapter, the feasibility of the selected 2ºC scenarios is broadly assessed, based on the analysis of the background information of these scenarios (chapter 3) and the literature and expert reviews (chapter 4 and 5). The general feasibility of the scenarios will be assessed on three indicators:

- Sustainability of biomass (by the amount of biomass included in the scenarios)
- Development of CCS-industry (by the amount of CO_2 stored in 2050)
- Development of CCS-industry (by the CO_2 injection rate in 2050)

Based on the literature reviews of chapters 4 and 5 a scoring table was established for each indicator on which the scenarios are scored. This scoring table consist of two threshold values: a lower limit and a higher limit value. Comparing the scenarios to these threshold values provide insights whether the scenarios are feasible within the framework of policies, measures and/or investments as described in literature. The results of the feasibility check can therefore be as follows:

- In case the scenario shows a value lower or equal to the lower limit value, policies, measures and/or investments as described in the scenario are sufficient, and it seems the level of bio-CCS implementation could generally be feasible without additional action;
-
- In case the scenario exceeds the lower limit value, but is lower or equal to the higher limit value the scenarios could be feasible if there are, additional policies, measures and/or investments;
- In case the scenarios exceed the higher limit value, the scenarios require a global scale intensification of policies, measures and/or investments.

The first pathway represents the situation that can be achieved by implementing policies and measures as defined in literature, including the required investments. This pathway does not require additional action compared to literature. The second pathway describes the situation in which additional policies, measures and investments are required, but on a level that additional effort of individual countries and/or regions can be sufficient to achieve this. The third pathway describes the situation that extensive additional action is required. Additional efforts by a selection of countries will probably not be enough, it will most likely require coordinated and concerted action, increasing the complexity of achieving the pathway.

It will not be possible to use the results of the rough feasibility assessment for conclusions on the achievability of individual scenarios, as there is not enough data and information available to make such assessments.

6.1 Sustainability of biomass

This first indicator focuses on the feasibility that the level of primary energy from biomass as assumed in the scenarios will be realised in a sustainable way.

The review on biomass potential in chapter 4 lead to the following results:

- There is no consensus in literature on an upper limit for the amount of primary bioenergy that can be used sustainably;
- Literature and experts seem to agree highly that a global primary bioenergy production of up to 100EJ/yr (approximately twice the current consumption) can be realised from waste and residues and on abandoned agricultural land without improvements beyond autonomous trends;
- Primary energy from biomass 100-300 EJ/yr would require the implementation of additional sustainability measures: the higher the bioenergy potential, the more extensive and stricter additional measures should be. Up to 300 EJ/yr generally seems feasible if there are additional measures and developments that can be supported on a project or feedstock procurement level;

- Primary bioenergy production >300 EJ/yr may be possible, but this would require significant improvement of the global agri-food system, amongst others by bridging yield gaps and improving supply chain logistics.
- This aligns quite well with the literature assessment of the IPCC (IPCC, 2014c) in which there is high agreement for a total primary energy demand from biomass of about 100 EJ per year, medium agreement on demand up to 250 EJ per year and low agreement on demand exceeding 250 EJ per year.

Based on the review, the following categorisation is made for the rough feasibility assessment on sustainability of biomass:

Table 9: Scoring table for sustainability of biomass

Primary energy from biomass	Feasibility assessment
0-100 EJ/yr	Current policies, measures and/or investments are sufficient
100-300 EJ/yr	The scenarios require additional policies, measures and/or investments
>300 EJ/yr	The scenarios require a global scale intensification of policies, measures and/or investments

Scoring the scenarios on these indicators lead to the following result:

Table 10: Results of rough feasibility assessment on sustainability of biomass

Model	Number of scenarios	No changes needed	Additional action required	Global scale intensification required	No information available
GCAM	12	0	4	8	0
IMAGE	16	0	15	0	1
MERGE	21	2	19	0	0
MESSAGE	7	0	6	0	1
MiniCAM	3	0	0	0	3
REMIND	13	0	4	9	0
OTHER	32	0	30	2	0
TOTAL	**104**	**2**	**78**	**19**	**5**

The table shows that only two scenarios can be realised without the need for additional policies, measures and/or investments. The other scenarios will require additional action, of which 19 would require global scale intensification of policies, measures and/or investments to realise the primary energy demand from biomass in a sustainable manner. The majority of scenarios in this latter category are GCAM and REMIND.

A full overview of the plausibility check for biomass and (bio-)CCS criteria can be found in Annex 1.

6.2 CO_2 storage up to 2050

The second indicator focuses on the amount of CO_2 that can be stored in 2050. This will largely depend on the availability of storage locations and partly on the development the CCS-industry, for instance on the availability of CO_2 infrastructure. In chapter 5 the availability of storage locations and the expected amount CO_2 to be stored in 2050 has been reviewed:

- Theoretical CO_2 storage potential is estimated between 8,000 and 15,000 Gt CO_2 (IEA, 2010b);

- The practical CO_2 storage capacity is estimated at 3,900 Gt CO_2 (Dooley, 2013). This assessment includes both onshore and offshore CO_2 storage capacity in deep saline formations, depleted gas fields, depleted oil fields, and unminable coal seams;
- According to IEA, safe and effective storage of CO_2 has been demonstrated and this needs to be scaled-up towards large-scale commercial projects;
- More effort should be put in identifying viable storage sites;
- The largest challenge for deployment of CCS is however the full integration of the individual components into large-scale commercial demonstration projects;
- The IEA Roadmaps on CCS (IEA, 2009; IEA, 2013) report on the expected amount of CO_2 that can be stored in 2050. Between the two roadmaps a declining trend was identified: in 2009 the amount of CO_2 was estimated at 145 Gt CO_2, while in 2013 this estimation was lowered to 120 Gt CO_2;
- The estimation was reduced because of the delays and difficulties in the development of CCS-industry to make this step towards fully integrated commercial-scale deployment;

Based on the review, the following categorisation is made for the rough feasibility assessment of CO_2 storage up to 2050:

Table 11: Scoring table for CO_2 storage up to 2050

CO_2 stored up to 2050	Feasibility assessment
0-120 Gt CO_2	Current policies, measures and/or investments are sufficient
120-145 Gt CO_2	The scenarios require additional policies, measures and/or investments
>145 Gt CO_2	The scenarios require a global scale intensification of policies, measures and/or investments

The most recent estimation of IEA of 120 Gt CO_2 (IEA, 2013) is used as the threshold to what should be possible under current policies, measures and investments. The estimation made in the previous CCS Technology Roadmap of 145 Gt CO_2 (IEA, 2009) is used as the threshold to what should be possible with additional action. Above 145 Gt CO_2 is possible, but it will require global scale action in the form of intensification of policies, measures and/or investments in CCS.

Scoring the scenarios on these indicators lead to the following result:

Table 12: Results of rough feasibility assessment on sustainability of biomass

Model	Number of scenarios	No changes needed	Additional action required	Global scale intensification required	No information available
GCAM	12	0	0	12	0
IMAGE	16	3	1	12	0
MERGE	21	0	3	18	0
MESSAGE	7	1	0	6	0
MiniCAM	3	0	0	3	0
REMIND	13	0	5	8	0
OTHER	32	5	9	18	0
TOTAL	**104**	**9**	**18**	**77**	**0**

The results show that only nine scenarios will not need additional actions to realise the amount of CO_2-stored in 2050. The other scenarios will require additional policies, measures and/or investments. The majority (77 scenarios, almost 75% of the included scenarios) will require global scale intensification of policies, measures and/or investments.

6.3 CO_2 injection rate in 2050

The third indicator focuses on the injection rate of CO_2 that can be realised in 2050. This will largely depend on the development the CCS-industry and the availability of CO_2 infrastructure. In chapter 5 the development of CCS-industry towards 2050 has been reviewed:

- As of this moment, there is no dedicated CO_2 storage industry. A rapid scale up may not be industrially practical due to limited industrial and human capacity. Professionals and expertise required to develop CO_2 storage overlap with activities of the hydrocarbon extraction sector, potentially creating market conflict for limited personnel and equipment;
- The current development rate of CCS-projects is lower than anticipated in most scenarios. The project pipeline shows that in the coming 15 years new CCS projects are expected to become operational online, however the capture capacity of these projects is less than estimated in the scenarios;
- Operation of (bio-)CCS comes with certain risks. For each specific location and situation, individual risk assessments will be made in order to decide whether or not safe operation of (bio-)CCS can be ensured. Considering the availability of geological storage potential, it is expected that there will be sufficient storage capacity available to ensure safe operation and storage of biogenic CO_2. According to IEA, lack of understanding and public acceptance of the technology by the public contributes to delays and difficulties in deployment (IEA, 2013);
- The IEA Roadmaps on CCS (IEA, 2009; IEA, 2013) report on the expected injection rates of CO_2 in 2050. Similar to the amount of CO_2 stored in 2050, a declining was identified on injection rates between the two roadmaps: in 2009, the injection rate was estimated at 10 Gt CO_2, while in 2013 this estimation was lowered to 8 Gt CO_2 per year.

Based on the review, the following categorisation is made for the rough feasibility assessment of CO_2 storage up to 2050:

Table 13: Scoring table for CO_2 injection rate in 2050

CO_2 stored up to 2050	Feasibility assessment
0-8 Gt CO_2 per year	Current policies, measures and/or investments are sufficient
8-10 Gt CO_2 per year	The scenarios require additional policies, measures and/or investments
>10 Gt CO_2 per year	The scenarios require a global scale intensification of policies, measures and/or investments

Similar to the scoring for the amount of CO_2 stored in 2050, IEA Technology Roadmaps were used to determine the threshold values: the lower limit is based on the most recent estimation of IEA (8 Gt CO_2 per year) (IEA, 2013), the higher limit is based on the previous CCS Technology Roadmap (10 Gt CO_2 per year) (IEA, 2009). Meeting this value would require additional action. Exceeding the injection rate of 10 Gt CO_2 per year could be possible, but will require global scale action in the form of intensification of policies, measures and/or investments in CCS.

Scoring the scenarios on these indicators lead to the following result:

Table 14: Results of rough feasibility assessment on CO_2 injection rate in 2050

Model	Number of scenarios	No changes needed	Additional action required	Global scale intensification required	No information available
GCAM	12	0	0	12	0
IMAGE	16	1	2	13	0
MERGE	21	0	2	19	0
MESSAGE	7	1	0	6	0
MiniCAM	3	0	0	3	0
REMIND	13	0	2	11	0
OTHER	32	12	3	17	0
TOTAL	**104**	**14**	**9**	**81**	**0**

The results show that fourteen scenarios can be realised without additional actions. The other scenarios will require additional policies, measures and/or investments. Over three-quarters of the scenarios (81 in total) will require global scale intensification of policies, measures and/or investments.

6.4 Overall results rough feasibility assessment

To conclude the rough feasibility assessment, the results of the individual assessments are combined. Table 15 provides an overview of the integrated result, showing for each model the number of scenarios that:

- Does not need additional action
- Will need additional action on at least one indicator
- Will need global scale intensification of action on at least one indicator

Table 15: Overall results of rough feasibility assessment

Model	Number of scenarios	No changes needed	Additional action required	Global scale intensification required	No information available
GCAM	12	0	0	12	0
IMAGE	16	0	2	13	1
MERGE	21	0	2	19	0
MESSAGE	7	0	0	6	1
MiniCAM	3	0	0	0	3
REMIND	13	0	0	13	0
OTHER	32	0	13	19	0
TOTAL	**104**	**0**	**17**	**82**	**5**

The table shows that all scenarios will require additional measures. The majority of the scenarios will require extensive attention on at least one indicator.

7 Conclusions, discussion and recommendations for further research

In this chapter, the main conclusions from the study will be provided, as well as a short paragraph on discussion and recommendations for further research.

7.1 Conclusions

At the 21st Conference of the Parties of the United Nations Framework Convention on Climate in Paris in 2015, the heads of governments agreed to limit the increase of global average temperature to well below 2°C by 2100 compared to pre-industrial levels. To reach the necessary emission reductions, a portfolio of technologies is needed, including those that generate negative emissions. IPCC AR5 scenarios in line with this global target rely heavily on bio-CCS.

The objective of this study was to identify the underlying assumptions of bio-CCS within the mitigation scenarios covered in IPCC AR5, regarding general input assumptions (population and economic growth), biomass assumptions (including biomass demand, type of biomass used and land-use) and CCS assumptions (including bio-CCS development and storage potential). These assumptions were evaluated through a rough analysis of the feasibility of all scenarios in realising their assumed bio-CCS potential and, hence, in presenting a realistic pathway in limiting global temperature rise below 2°C (also referred to as "category 1 scenarios"). In this study 116 category 1 scenarios were assessed, of which 104 include the use of bio-CCS.

Bio-CCS is a technology selected by the climate models because it **generates energy while at the same time reducing the amount of CO_2 in the atmosphere**. This makes it an ideal energy technology as in **most scenarios CO_2 needs to be removed from the atmosphere to stay below 2ºC due to a late or insufficient uptake of renewable energies and energy efficiency**. The extent to which bio-CCS is included as well as the overall dependency on negative emissions varies between the scenarios.

The analysis of the scenarios showed a wide range of application of bioenergy and CO_2 storage:

- **The amount of primary bioenergy in the scenarios up to 2100 varies between 100-350 EJ/yr.**
- **There is no consensus in literature on an upper limit for the amount of primary bioenergy that can be used sustainably.**
  - A global primary bioenergy production of up to 100 EJ/yr (approximately twice the current consumption) seems feasible and may be realised from waste and residues and on abandoned agricultural land without improvements beyond autonomous trends.
  - A supply of up to 300 EJ/yr seems possible if additional policies, measures and/or investments are taken.
  - Primary bioenergy production >300 EJ/yr is theoretically possible, but would require that the wider global agri-food system is significantly changed, amongst others by bridging yield gaps, reducing live-stock and improving supply chain logistics.
- **In order to preserve the availability of bioenergy in the future, cultivation and usage will require strict rules and regulations. Increasing the amount of bioenergy in the future would require even stricter rules and a global approach on sustainability criteria;**
- The **amount of stored CO_2 in the scenarios up to 2100 varies between 600 and 2,300 Gt CO_2**. Of this, between 290-1,100 Gt CO_2, or about 50%, results from bio-CCS;
- In the scenarios, different **growth rates for the development of CCS and bio-CCS are assumed, but it is unclear on what these rates are based.** It is unclear how the development of CO_2 infrastructure is included in the scenarios and there is no data available to show how and if (biogenic) CO_2 sources and potential CO_2 sinks are matched;

The selected scenarios underwent a rough feasibility assessment, with a specific focus on the development of bio-CCS. The objective of the analysis is to create a perspective on the achievability of the assumed amount of bio-CCS in these scenarios. For the assessment, the following indicators were used:

- Sustainability of biomass
- The amount CO_2 stored up to 2050
- The maximum injection rate of CO_2 in 2050

Based on literature and expert opinions three pathways were described for each of the indicators: 1) potential policies, measures and/or investments as described in literature are sufficient, no need for additional action, 2) the scenarios assume increased development of the indicator, requiring additional policies, measures and/or investments, and 3) the scenarios require global scale intensification of policies, measures and/or investments.

Based on the rough feasibility assessment the achievability of the amount of bio-CCS assumed in the selected scenarios shows the following picture:

- The results of the feasibility assessments of the individual indicators showed that:
    - On **sustainability of biomass,** 2 scenarios do not require additional action, 78 scenarios require additional action and 19 scenarios require global scale intensification of policies, measures and/or investments to realise the primary energy demand from biomass in a sustainable manner. For 5 scenarios, no information was available to perform the assessment.
    - For the **amount CO_2 stored up to 2050**, 9 scenarios can be achieved without additional action, 18 scenarios require additional action and 77 scenarios require further global scale action.
    - For the **maximum injection rate of CO_2 in 2050**, 14 scenarios can be achieved without additional action. The remaining 90 scenarios require additional action, of which 81 scenarios require further global scale action.
- **None of the developments for bio-CCS in the scenarios would be possible without changes in policies, measures and/or investments in sustainable biomass and/or the realisation of sufficient CO_2 storage capacity.**
- **The majority of the scenarios (82) requires extensive intensification in policies, measures and/or investments in at least one of the three indicators.** Without such measures, the achievability of these scenarios seems unlikely.
- **A smaller part of the scenarios (17) the development of bio-CCS will require additional policies, measures and/or investments:**
    - All of these scenarios require additional measures to ensure sustainability of biomass.
    - Most of these scenarios require investments and concerted action to increase the development of CCS-infrastructure. Only a handful of the scenarios do not require additional measures.
- For the remaining 5 scenarios, there was not enough data available on primary energy use from biomass to be included in this overall result.
- The rough feasibility assessment is by no means a perfect assessment of bio-CCS potential. It is merely indicative to give a rough idea of how realistic the implementation of many scenarios would be on the abovementioned indicators. Further criteria must be analysed to determine how much bioenergy potential is really available, whether higher injection rates are possible and if an increased storage capacity is available before 2050. This is difficult to properly analyse based on current available data and unforeseen energy/infrastructural developments.

The results lead to the following conclusions:

- **Carbon dioxide removal (negative emissions) appears to be one important measure in maintaining global warming below 2°C, but its potential is expected to be limited.** Particularly regarding bio-CCS, due to lower realisation rates of CCS and requirements needed to cultivate and use biomass in a sustainable manner, the realisation of net-negative emissions will require additional policies, measures and/or investments. Without additional action, the probability of these category 1 scenarios staying below the 2°C level can decrease significantly.
- Bio-CCS is the most well-known carbon dioxide removal technology. Others, although not regarded in this study, such as direct air capture and afforestation may also have a potential, but these are likely to be just as or more limited than bio-CCS. Direct air capture, for example, requires enormous amounts of energy. Afforestation has similar limitations to bio-CCS regarding land area requirements and competition with food, with the further limitation of not providing energy.
- **This means rapid decarbonisation of the energy sector and rapid reductions in overall emissions are of utmost priority, to ensure that the limited amount of carbon dioxide removal potential that will likely be available can still provide net zero emissions.**
- At the same time, there is a thin balance between the energy demand from biomass, food security and biodiversity conservation. It is therefore essential that with an increasing demand for primary energy from biomass, its cultivation and usage should be closely monitored and coordinated efficiently. For usage, it could be more effective to limit use biomass for industrial use and/or specifically to create negative emissions, as opposed to e.g. co-firing coal plants.
- Following the lead of scenarios that largely depend on carbon dioxide removal **reduces the likelihood of limiting warming to less than 2°C, as carbon dioxide removal may not be practically available at the scales required, while misguided policies and investments could delay the required rapid emissions reductions and decarbonisation of the energy sector.**
- Comparing the current deployment of bioenergy and (bio-)CCS with the estimated deployment in the selected scenarios, shows that in some scenarios it was **assumed that deployment of (bio)-CCS would already have further advanced by now than is actually the case in reality**. Although at this moment it seems plausible that current real-life deployment could catch up to pathways described in scenarios, it should be realised that **this delay can become critical if real world development orients towards scenarios describing a significant share of bio-CCS.** These scenarios rely (heavily) on the realisation of negative emissions in the future to compensate their relatively high current CO_2 emissions. If the realisation of bio-CCS would be delayed further or only implemented on a smaller scale, the feasibility of such a pathway for maintaining a below 2°C target becomes increasingly uncertain.
- The lack of matching between biomass sources and CO_2 storage resources could potentially limit capture and storage of biogenic CO_2 or require biomass to be transported to facilities connected to CO_2 storage network. The latter could then considerably increase the costs for bio-CCS.

7.2 Discussion

- In general, there was a lack of detailed data needed to obtain solid information on model and scenario assumptions. Without this data, it was not possible to provide detailed backgrounds on assumptions and rationales, insights between individual scenarios or to create a deeper understanding in the scenario results. It was therefore mostly unclear what assumptions were made in the models and scenarios on biomass and CO_2 storage related topics, such as:
  - Land-use change emissions
  - Sustainability criteria
  - Water scarcity for biomass
  - CO_2 storage availability
  - CO_2 infrastructure development

- It is unclear to what extent models consider the effects of a changing climate on bioenergy supply and the competition for food. Some models show a steep increase use of biomass energy while also assuming large growth of the world's population. With the limited amount of data available, it was not possible to create better insights in how this could be achieved and under what assumptions.
- In several scenarios assumptions were made about the future increase in crop yields. An increase in crop yields would validate an increase in bio-energy while also assuming a growing world population. Although current research looks promising, there is however no proof whether it will lead to the desired results.
- In the assessment, the development of the CCS-industry is included as the overall CCS-industry, including fossil-power, industries and bio-CCS. It could be argued that CO_2 storage should only be used to store CO_2-emissions of sources that can generate negative emissions (all CDR, including bio-CCS) or for which no renewable options are available (yet), such as certain industries. On the other hand, development of CCS is expected to first occur with the lowest cost applications which would include fossil-power. Secondly, application with fossil-power could be needed to reduce the cost for CO_2 capture and storage as well as to drive the development of a large CO_2 infrastructure.
- To our knowledge, the models do not take into account public perception towards CCS. From literature and experience we know that "lack of understanding and acceptance of the technology by the public, as well as some energy and climate stakeholders, also contributes to delays and difficulties in deployment" (IEA, 2013).

7.3 Recommendations for further research

- Reducing future dependence on carbon dioxide removal through more immediate cuts in CO_2 emissions will not completely avoid the requirement for carbon dioxide removal at a significant scale. There is thus a need for the development of technologies enabling the deployment of bio-CCS and other carbon dioxide removal technologies at scale in parallel to accelerating deep emissions cuts.
- To better understand the implications of a more effective use of limited bio-CCS resources, it would be useful to develop scenarios in which CCS is only applied to sources that can create negative emissions or to sources for which there are no renewable alternatives (e.g. industrial sources). Currently, all scenarios utilise CO_2 storage for the decarbonisation for a range of significant CO_2 point sources including, fossil thermal electricity generation (e.g. coal, natural gas), industrial CO_2 sources (e.g. cement, steel) and biogenic CO_2 storage for carbon dioxide removal. Based on IEA CCS roadmap, over one-third of the CCS capacity will be dedicated to capture and store CO_2 from fossil power plants. As the current pace of CCS development is limited, the focus for CCS should be on creating negative emissions (bio-CCS) or on sectors for which there are no alternatives (industry). The alternative for fossil power should be renewable energy.
- To assist the development of additional policies and measures addressing these issues, pathways from the research community are needed that describe a more rapid decarbonisation and reduction of overall emissions. These pathways should rely less on negative emissions/CDR-technologies, yet describe options for the most efficient use of the limited CDR potential.
- **Sustainability criteria** are an important factor as they ensure the long-term potential of biomass and thus bio-CCS. **None of the assessed scenarios stays below the threshold of 100 EJ/yr for which it is most likely that biomass can be used in a sustainable way.** Almost 20% of the scenarios exceed the 300 EJ/yr, for which it is not very likely that it can be realised within sustainable limits. Among them are several GCAM and REMIND scenarios.
- The **current development rate of CCS-projects is lower than in most scenarios**. The project pipeline shows that in the coming 15 years new CCS projects are expected to become online, however the **capture capacity** of these projects is **significantly lower** than estimated in the scenarios.
- As of this moment, there is **no dedicated CO_2 storage industry**. A rapid scale up may not be industrially practical due to limited industrial and human capacity. Professionals and expertise required to

develop CO_2 storage overlap with activities of the hydrocarbon extraction sector, potentially creating market conflict for limited personnel and equipment.

- **Operation of (bio-)CCS comes with certain risks**. For each specific location and situation, individual risk assessments will have to be made in order to decide whether or not safe operation of (bio-)CCS can be ensured. It is unknown to what extent this will impact the deployment of (bio-)CCS.

8 References

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Annex 1 Results of rough feasibility assessment

The following table shows the results of the rough feasibility check for every scenario. The scenarios are characterised using the following colours:

- Policies, measures and/or investments as described in literature are sufficient
- Need for additional policies, measures and/or investments
- Need for extensive intensification of policies, measures and/or investments
- Not enough data available

Scenarios	Primary energy from bio-mass	CCS storage All CCS	CO_2 stored All CCS	Overall result
	Max value	CO_2 in-jection rate 2050	CO_2 stored in 2050	
GCAM 2.0AME CO2 price $30 (5% p.a.)				
GCAM 2.0AME CO2 price $50 (5% p.a.)				
GCAM 3.0EMF27-450-Conv				
GCAM 3.0EMF27-450-FullTech				
GCAM 3.0EMF27-450-LimBio				
GCAM 3.1LIMITS-450				
GCAM 3.1LIMITS-500				
GCAM 3.1LIMITS-RefPol-450				
GCAM 3.1LIMITS-RefPol-450-EE				
GCAM 3.1LIMITS-RefPol-450-PC				
GCAM 3.1LIMITS-StrPol-450				
GCAM 3.1LIMITS-StrPol-500				
IMACLIM v1.1EMF27-450-Conv				
IMACLIM v1.1EMF27-450-FullTech				
IMACLIM v1.1EMF27-450-LimBio				
IMACLIM v1.1EMF27-450-LimSW				
IMACLIM v1.1EMF27-450-LowEI				
IMACLIM v1.1EMF27-450-NucOff				
IMAGE 2.4 EMF22EMF22 2.6 OS BECCS				
IMAGE 2.4AME 2.6 W/m2 OS				
IMAGE 2.4AMPERE2-450-FullTech-OPT				
IMAGE 2.4AMPERE2-450-LimSW-OPT				
IMAGE 2.4AMPERE2-450-LowEI-HST				
IMAGE 2.4AMPERE2-450-LowEI-LST				
IMAGE 2.4AMPERE3-450				
IMAGE 2.4AMPERE3-CF450				
IMAGE 2.4EMF27-450-FullTech				
IMAGE 2.4EMF27-450-LimSW				
IMAGE 2.4EMF27-450-LowEI				
IMAGE 2.4EMF27-450-NucOff				

Scenarios	Primary energy from bio-mass	CCS storage All CCS	CO_2 stored All CCS	Overall result
IMAGE 2.4LIMITS-450				
IMAGE 2.4LIMITS-RefPol-450				
IMAGE 2.4LIMITS-RefPol-450-EE				
IMAGE 2.4LIMITS-RefPol-450-PC				
MERGE_EMF27EMF27-450-Conv				
MERGE_EMF27EMF27-450-FullTech				
MERGE_EMF27EMF27-450-LimBio				
MERGE_EMF27EMF27-450-LimSW				
MERGE_EMF27EMF27-450-LowEI				
MERGE_EMF27EMF27-450-NucOff				
MERGE-ETL_2011AMPERE2-450-Conv-OPT				
MERGE-ETL_2011AMPERE2-450-FullTech-HST				
MERGE-ETL_2011AMPERE2-450-FullTech-LST				
MERGE-ETL_2011AMPERE2-450-FullTech-OPT				
MERGE-ETL_2011AMPERE2-450-LimBio-OPT				
MERGE-ETL_2011AMPERE2-450-LimSW-HST				
MERGE-ETL_2011AMPERE2-450-LimSW-LST				
MERGE-ETL_2011AMPERE2-450-LimSW-OPT				
MERGE-ETL_2011AMPERE2-450-LowEI-HST				
MERGE-ETL_2011AMPERE2-450-LowEI-LST				
MERGE-ETL_2011AMPERE2-450-LowEI-OPT				
MERGE-ETL_2011AMPERE2-450-NucOff-LST				
MERGE-ETL_2011AMPERE2-450-NucOff-OPT				
MERGE-ETL_2011AMPERE3-450				
MERGE-ETL_2011AMPERE3-CF450				
MESSAGE V.1EMF22 2.6 OS				
MESSAGE V.3AME CO2 price $50 (5% p.a.)				
MESSAGE V.4LIMITS-450				
MESSAGE V.4LIMITS-RefPol-450				
MESSAGE V.4LIMITS-RefPol-450-EE				
MESSAGE V.4LIMITS-RefPol-450-PC				
MESSAGE V.4LIMITS-StrPol-450				
MiniCAM_EMF22EMF22 2.6 NTE				
MiniCAM_EMF22EMF22 2.6 OS				
MiniCAM_EMF22EMF22 2.6 OS w Delay				
POLES EMF27EMF27-450-FullTech				
POLES EMF27EMF27-450-LimSW				
POLES EMF27EMF27-450-LowEI				
POLES EMF27EMF27-450-NucOff				
REMIND 1.3AME 2.6 W/m2 OS				
REMIND 1.3AME CO2 price $50 (5% p.a.)				
REMIND 1.5EMF27-450-Conv				
REMIND 1.5EMF27-450-FullTech				

Scenarios	Primary energy from bio-mass	CCS storage All CCS	CO_2 stored All CCS	Overall result
REMIND 1.5EMF27-450-LimBio				
REMIND 1.5EMF27-450-LimSW				
REMIND 1.5EMF27-450-LowEI				
REMIND 1.5EMF27-450-NucOff				
REMIND 1.5LIMITS-450				
REMIND 1.5LIMITS-RefPol-450				
REMIND 1.5LIMITS-RefPol-450-EE				
REMIND 1.5LIMITS-RefPol-450-PC				
REMIND 1.5LIMITS-StrPol-450				
TIAM-ECNLIMITS-450				
TIAM-ECNLIMITS-RefPol-450				
TIAM-ECNLIMITS-RefPol-450-EE				
TIAM-ECNLIMITS-RefPol-450-PC				
TIAM-ECNLIMITS-StrPol-450				
TIAM-World_Mar2012AME CO2 price $50 (5% p.a.)				
TIMES-VTT-2011AME CO2 price $50 (5% p.a.)				
WITCH_AMPEREAMPERE2-450-FullTech-HST				
WITCH_AMPEREAMPERE2-450-FullTech-LST				
WITCH_AMPEREAMPERE2-450-FullTech-OPT				
WITCH_AMPEREAMPERE2-450-LowEI-HST				
WITCH_AMPEREAMPERE2-450-LowEI-LST				
WITCH_AMPEREAMPERE2-450-NucOff-HST				
WITCH_AMPEREAMPERE2-450-NucOff-LST				
WITCH_AMPEREAMPERE2-450-NucOff-OPT				
WITCH_AMPEREAMPERE3-450				
WITCH_AMPEREAMPERE3-CF450				
WITCH_LIMITSLIMITS-450				
WITCH_LIMITSLIMITS-RefPol-450				
WITCH_LIMITSLIMITS-RefPol-450-EE				
WITCH_LIMITSLIMITS-RefPol-450-PC				
WITCH_LIMITSLIMITS-StrPol-450				