



European Biofuels
TECHNOLOGY PLATFORM


Zero

Zero emissions platform

Biomass with CO₂ Capture and Storage (Bio-CCS)

The way forward for Europe





This document has been prepared on behalf of the Advisory Council of the European Technology Platform for Zero Emission Fossil Fuel Power Plants (ZEP) and the Steering Committee of the European Biofuels Technology Platform (EBTP). The information and views contained in this document are the collective view of the ZEP Advisory Council and EBTP Steering Committee and not of individual members, or of the European Commission. Neither the ZEP Advisory Council, the EBTP Steering Committee, the European Commission, nor any person acting on their behalf, is responsible for the use that might be made of the information contained in this publication.

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Key conclusions

- Recent research indicates that **more powerful technologies are now needed to keep global warming below 2°C¹** – and avoid irreversible climate change. This is echoed by warnings from both the United Nations Framework Convention on Climate Change (UNFCCC) and the International Energy Agency (IEA).
- There is therefore an urgent need for carbon-negative solutions such as **Bio-CCS – the only large-scale technology that can remove CO₂ from the atmosphere**. Bio-CCS combines sustainable biomass conversion with CO₂ Capture and Storage (CCS) – e.g. in biofuels and bioenergy production – and is already being deployed at industrial scale in the U.S.².
- Use of biofuels and bioenergy is steadily increasing in the European Union (EU) due to targets for renewable energy sources and **certain biofuels production routes could provide “low-hanging fruits” for early, low-cost CCS deployment**.
- A recent study indicated that, globally, Bio-CCS could remove 10 billion tonnes of CO₂ from the atmosphere every year by 2050³ using available sustainable biomass – equivalent to a third of all current global energy-related emissions. **In Europe, Bio-CCS could remove 800 million tonnes of CO₂ from the atmosphere every year by 2050³** using available sustainable biomass – equivalent to over 50% of current emissions from the EU power sector. This is *in addition* to any emissions reductions achieved by replacing fossil fuels with that biomass.
- **Bio-CCS could ultimately result in industry sectors whose overall emissions are below zero**, which could then offset emissions in other sectors where reductions are more difficult to attain.

The following actions are therefore urgently required at EU level:

- As for other low-carbon technologies, establish economic incentives to enable the large-scale deployment of Bio-CCS – in particular, **reward negative emissions via the capture and storage of biogenic CO₂ under the EU Emissions Trading Scheme**, in the same way as for fossil CCS.
- **Identify and incentivise the clustering of small-scale biogenic emission sources with other emission sources** in order to achieve economies of scale for CO₂ transport and storage.
- **Undertake R&D to determine the costs of the various Bio-CCS routes**, including additional costs induced by corrosion and other technology challenges when co-firing with high biomass percentages in existing boilers.
- **Establish dedicated funding for R&D and pilot projects** to further develop and prove advanced technologies.
- **Address issues specific to Bio-CCS deployment** (e.g. accelerate deployment of advanced biomass conversion processes) and establish an EU roadmap towards 2050.
- In addition, **establish additional non-ETS measures to enable EU CCS demonstration projects to take Final Investment Decision (FID)** and provide security for long-term investment.

¹ Above 1990 levels, as advised by the Intergovernmental Panel on Climate Change (IPCC)

² The ADM bioethanol-CCS project – see page 21

³ IEA Greenhouse Gas (GHG) Programme. Comprehensive life-cycle analyses (LCAs) for the carbon balance of biomass supply and conversion routes should be performed to verify these numbers.

1 Why Europe needs to go carbon-negative

1.1 More powerful technologies are now needed to keep global warming below 2°C

In its Fourth Assessment Report, the IPCC stated that in order to keep global warming below 2°C and avoid the most dangerous consequences of climate change, GHG emissions must be reduced by 50-85% by 2050 – and peak no later than 2015⁴.

More recent research, however, indicates that even these findings were too optimistic⁵ and the UNFCCC now warns that “we are putting ourselves in a scenario where we will have to develop more powerful technologies to capture emissions out of the atmosphere”⁶. This was echoed by the IEA in its World Energy Outlook 2011: “The door to 2°C is closing”⁷.

1.2 Bio-CCS: the only large-scale technology that can remove CO₂ from the atmosphere

In short, there is now an urgent need for carbon-negative solutions, i.e. systems that *remove* CO₂ from the atmosphere. Indeed, Bio-CCS – the combination of CO₂ Capture and Storage (CCS) with sustainable biomass conversion – is the only large-scale technology that can achieve net negative emissions (in addition to any emissions reductions achieved by replacing fossil fuels with that biomass).

This has already been recognised at an international level, e.g. in the IPCC’s Special Report on Renewable Energy Sources and Climate Change Mitigation⁸ and in the Technology Roadmap Carbon Capture and Storage in Industrial Applications jointly published by the IEA and the United Nations Industrial Development Organization (UNIDO)⁹.

Bio-CCS: a definition

Bio-CCS may be defined as processes in which CO₂ originating from biomass is captured and stored. These can be energy production processes or any other industrial processes with CO₂-rich process streams originating from biomass feedstocks. The CO₂ is separated from these processes with technologies generally associated with CCS for fossil fuels.

Biomass binds carbon from the atmosphere as it grows; but with the conversion of the biomass, this carbon is again released as CO₂. If, instead, it is captured, transported to a storage site and permanently stored deep underground, this would result in a *net removal of CO₂* from the atmosphere.

Bio-CCS has already entered the European policy debate: the EU Energy Roadmap 2050¹⁰ not only confirms that “For all fossil fuels, Carbon Capture and Storage will have to be applied from around 2030 onwards in the power sector in order to reach decarbonisation targets¹¹, it also recognises that CCS “combined with biomass could deliver “carbon negative” values”.

4 www.ipcc.ch/ipccreports/ar4-syr.htm, 2007

5 James E. Hansen, “Scientific reticence and sea level rise”: <http://pubs.giss.nasa.gov/abstracts/2007/Hansen.htm>; W.T. Pfeffer et al, “Kinematic Constraints on Glacier Contributions to 21st-Century Sea-Level Rise”: www.nature.com/climate/2008/0810/full/climate.2008.93.html

6 <http://m.guardian.co.uk/environment/2011/jun/05/global-warming-suck-greenhouse-gases?cat=environment&type=article>, 2011

7 www.iea.org/Textbase/npsum/weo2011sum.pdf

8 www.srren.org, May 2011

9 www.unido.org/fileadmin/user_media/News/2011/CCS_Industry_Roadmap_WEB.pdf, September 2011

10 http://ec.europa.eu/energy/energy2020/roadmap/doc/com_2011_8852_en.pdf, December 2011

11 80-95% decarbonisation overall by 2050

1.3 The EBTP/ZEP Joint Taskforce Bio-CCS: uniting high-level European stakeholders

Yet Bio-CCS is, to a large extent, an unexplored avenue of action, with a number of complex questions to be analysed and answered. In 2011, the European Biofuels Technology Platform (EBTP) and the European Technology Platform for Zero Emission Fossil Fuel Power Plants – known as the Zero Emissions Platform (ZEP) – therefore set up a Joint Taskforce (JTF) Bio-CCS¹² in order to guide and accelerate this vital work and ensure its place within EU policy and R&D priorities; Bellona Europa – a member of both ZEP and EBTP – runs the JTF Bio-CCS Secretariat.

The JTF Bio-CCS works in a similar way to its mother platforms in bringing together high-level stakeholders and experts from relevant industries, research and civil society in order to identify the most effective and appropriate means of developing and deploying Bio-CCS technologies.

The Zero Emissions Platform (ZEP)

Founded in 2005, ZEP represents a unique coalition of stakeholders united in their support for CCS as a critical solution for combating climate change. Indeed, CCS is the single biggest lever for reducing CO₂ emissions – providing almost 20% of the global cuts required by 2050, according to the IEA. Members include European utilities, oil and gas companies, equipment suppliers, national geological surveys, academic institutions and environmental NGOs. The goal: to make CCS commercially available by 2020 and accelerate wide-scale deployment.

www.zeroemissionsplatform.eu

The European Biofuels Technology Platform (EBTP)

Founded in 2006, the European Biofuels Technology Platform (EBTP) aims to contribute to the development of cost-competitive, world-class biofuels value chains, the creation of a healthy biofuels industry and the acceleration of the sustainable deployment of biofuels in the EU via a process of guidance, prioritisation and the promotion of research, technology development and demonstration. The EBTP brings together the knowledge and expertise of stakeholders from industry, biomass resources providers, research and technology development organisations and non-governmental organisations (NGOs) in a public-private partnership.

www.biofuelstp.eu

¹² See Annex I for a list of members of the Joint Taskforce Bio-CCS

2 CO₂ Capture and Storage

2.1 CCS could provide almost 20% of global emission cuts required by 2050

CO₂ Capture and Storage (CCS) describes a technological process by which *at least 90% of CO₂ emissions* is captured from large stationary sources (e.g. fossil fuel-fired power plants, heavy industry), transported to a suitable storage site, then stored in geological formations – safely and permanently – deep underground (at least 700m and up 5,000m).

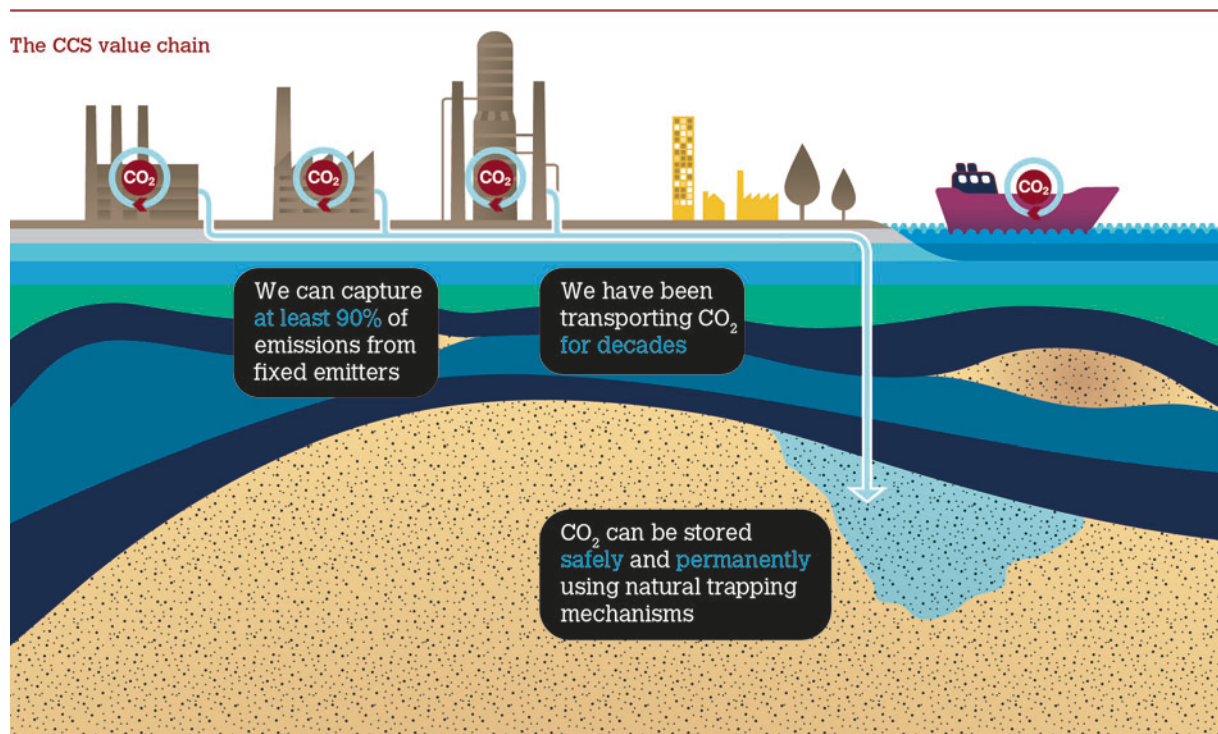


FIGURE 1 **CCS IS THE ONLY LARGE-SCALE TECHNOLOGY THAT CAN ABATE 90% OF CO₂ EMISSIONS FROM THE WORLD'S LARGEST EMITTERS**

The IEA confirms that “The scale of potential future deployment of CCS is enormous, spanning manufacturing, power generation and hydrocarbon extraction worldwide”. Indeed, it is the single biggest lever for reducing CO₂ emissions – providing almost 20% of the global cuts required by 2050. The critical role of CCS in meeting EU climate targets is therefore indisputable – as confirmed by the EU Energy Roadmap 2050 – while the IEA estimates that the costs of achieving global climate objectives *without* CCS would be over 70% higher.

The result: Europe will not only enjoy a climate-friendly economy, but new industrial growth – creating jobs and boosting competitiveness – fuelled by a diverse and reliable energy supply.

2.2 The safety of CO₂ storage actually increases over time

Each of the stages in the CCS value chain – capture, transport and storage – can be accomplished in various ways:

CO₂ capture options in power generation

- *Post-combustion*: CO₂ is removed from the exhaust gas through absorption by selective solvents.
- *Pre-combustion*: The fuel is pre-treated and converted into a mix of CO₂ and hydrogen, from which the CO₂ is separated. The hydrogen is then used as fuel, or burnt to produce electricity.
- *Oxy-fuel combustion*: The fuel is burned with oxygen instead of air, producing a flue stream of CO₂ and water vapour without nitrogen; the CO₂ is relatively easily removed from this stream.

In certain industrial processes, such as some biofuels production routes, the separation of high-purity CO₂ is already a required part of the process (see Chapter 4). Capture for storage then usually only requires some dehydration before the gas can be compressed and transported to a storage site. Capture technology options in other industries such as steel and cement are outside the scope of this report, but may be covered by future updates.

CO₂ transport options

- *Pipelines* are the main option for large-scale CO₂ transportation, but *shipping* and road transport are also possibilities.

CO₂ storage options

- *Deep saline aquifers* (saltwater-bearing rocks unsuitable for human consumption)
- *Depleted oil and gas fields* (with the potential for Enhanced Oil/Gas Recovery)
- *Deep unmineable coal beds* (with the potential to extract methane)

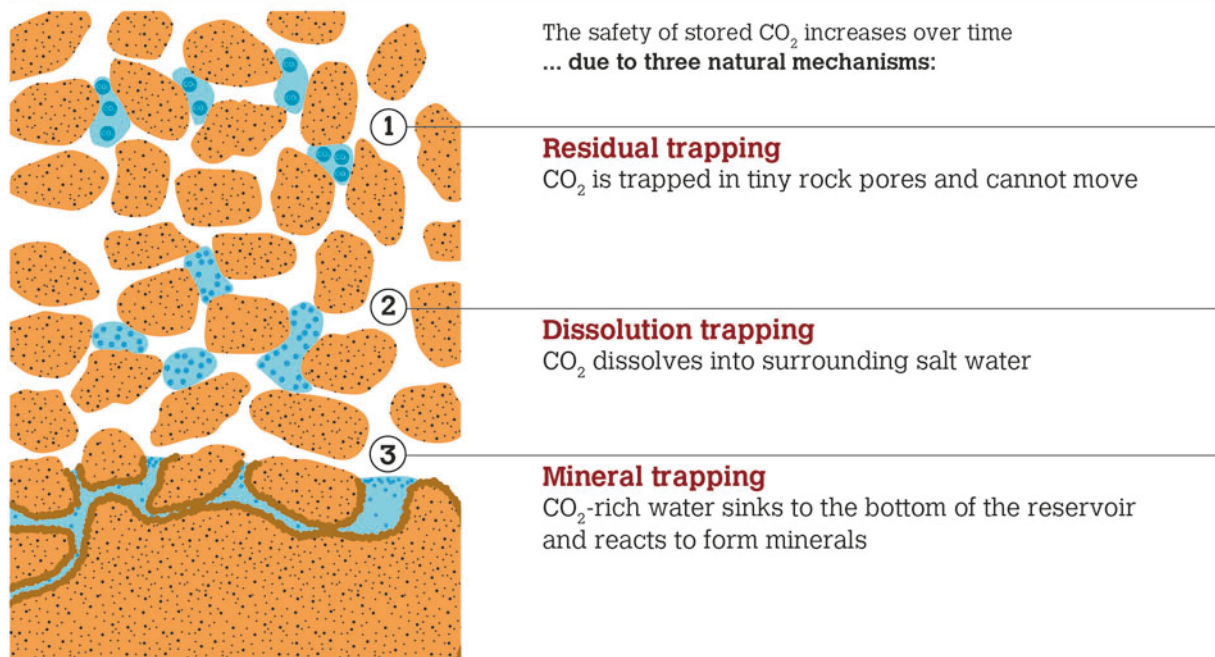


FIGURE 2 CO₂ CAN BE STORED USING THE SAME NATURAL MECHANISMS THAT HAVE ALREADY KEPT HUGE VOLUMES OF OIL, GAS AND CO₂ UNDERGROUND FOR MILLIONS OF YEARS

2.3 CCS technologies are already proven on a small scale

Although there are currently no fully integrated, commercial-scale CCS power projects in operation, many of the technologies that make up CCS have been around for decades:

- CO₂ capture is already practised on a small scale, based on technology that has been used in the chemical and refining industries for decades.
- Transportation is also well understood: CO₂ has been shipped regionally for over 20 years, while a 5,000 km pipeline network has been operating in the USA for over 30 years for Enhanced Oil Recovery (EOR).
- CO₂ storage projects have been operating successfully for over a decade, e.g. at Sleipner (Norway), Weyburn (Canada) and In Salah (Algeria). The industry can also build on knowledge obtained through the geological storage of natural gas, which has also been practised for decades.

While individual components of the CCS value chain are already proven – ready for scale-up and integration – further R&D into next-generation technologies must also be initiated *immediately* to enable rapid and wide deployment post-2020. To this end, ZEP has published a long-term R&D¹³ plan identifying key areas for improvement, together with the main strands for R&D to 2030 and beyond. To ensure maximum effectiveness, this should be coordinated at a national and EU level and include key learnings from the EU demonstration programme.

¹³ www.zeroemissionsplatform.eu/library/publication/95-zep-report-on-long-term-ccs-rad.html

3 Biomass feedstocks

3.1 Biomass use for energy is steadily increasing in the EU and beyond

Biofuels offset CO₂ emissions from fossil transportation fuels in the same way biomass can offset emissions from fossil fuels in other applications, such as energy and heat production. Most biofuels are suitable for use in existing infrastructures and prime movers, such as biomethane, bioSNG and biomass-based synthetic diesel (Biomass to Liquid or BtL).

A wide range of biomass feedstock is available worldwide for biofuel and bioenergy production, such as energy crops (e.g. miscanthus, jatropha, short-rotation copice); wastes (e.g. waste oils, food processing wastes); agricultural residues (e.g. straw, corn stover); forestry residues; and novel feedstocks (e.g. algae).

In 2008, global bioenergy use was composed primarily of solid biomass (46.9 EJ); municipal solid waste (MSW) used for heat and CHP¹⁴ (0.58 EJ); and biogas (secondary energy) for electricity and CHP (0.41 EJ), and heating (0.33 EJ). The contribution of ethanol, biodiesel and other biofuels (e.g. ethers) used in the transport sector amounted to 1.9 EJ in secondary energy terms¹⁵. In absolute terms, usage has grown steadily over the last 40 years and by 2009 biomass accounted for ~10% (50 EJ)¹⁶ of the annual global TPES¹⁷. The IEA projects that the primary bioenergy share of the global TPES will increase to ~160 EJ by 2050, providing ~24% of TPES compared to 10% today. Around 60 EJ of this would be needed for transport fuels production, with another 100 EJ (i.e. 5 billion to 7 billion dry tonnes of biomass) required to provide electricity and heat for the residential sector, industry and other sectors¹⁶.

The bioenergy share of EU TPES is relatively small but growing, mainly driven by EU incentives for renewable energy sources (RES). The 2020 target of 10% RES for the transport sector set down in the EU Renewable Energy Directive (RED)¹⁸ is expected to be composed almost entirely of biofuels. In 2020, biomass is assumed to contribute to ~11% of total EU final energy consumption and ~56% of total final renewable energy consumption, as well as ~53% of the additional effort required to reach 20% RES in the EU in 2020, based on the National Renewable Energy Action Plans (NREAPs) of the 27 EU Member States¹⁹.

3.2 A wide range of biomass feedstocks is available

A wide range of biomass feedstocks is potentially available to serve as vectors to release energy, either through combustion (bioenergy), conversion to other vectors (e.g. biogas, biochemicals or liquid biofuels), or use in biorefinery concepts to produce the so-called 4F – food, feed, fibre and fuels)²⁰:

- *Agricultural residues*: derived from field activities after harvesting the main product, e.g. straw, prunings, corn stover etc., as well as animal manure
- *Forest biomass*: residues from harvest operations that are left in the forest following stem wood removal, e.g. branches, foliage, roots etc. and complementary fellings, i.e. the difference between the maximum sustainable harvest level and the actual harvest needed to satisfy round wood demand
- *Energy crops*: annual or perennial crops specifically bred and cultivated to produce biomass with specific traits:
 - Biowaste streams

¹⁴ Combined heat and power

¹⁵ http://srren.ipcc-wg3.de/report/IPCC_SRREN_Ch02.pdf, 2011

¹⁶ www.iea.org/publications/freepublications/publication/bioenergy.pdf, 2012

¹⁷ Total Primary Energy Supply

¹⁸ <http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=Oj:L:2009:140:0016:0062:en:PDF>

¹⁹ www.aebiom.org/?p=3336#more-3336

²⁰ www.biofuelstp.eu/fuelproduction.html#first

- MSW of biological origin: mainly kitchen and garden waste, paper and cardboard, but including a proportion of other waste fractions which are of biological origin
 - Construction/demolition wood: wood offcuts from building construction and wood recovered during demolition
 - Packaging, waste wood, e.g. pallets, crates etc.
 - Household waste wood, e.g. old furniture, fencing
 - Market waste, e.g. green tops and unsold vegetables from markets
 - Sewage sludge
 - Food processing wastes: wastes from the dairy and sugar industry, wine and beer production; waste streams with lower volumes involved (e.g. orange zests from orange juice production) can also be of interest
 - Gardening wastes: grass cuttings, leaves and small branches.
- *Algae/aquaculture*: algae are usually separated into microalgae (microorganisms) and macroalgae, such as seaweed. Intense research is underway in many parts of the world to find ways to unleash the promising energy potential of these marine types of biomass. However, due to the high uncertainties and limited available data, marine biomass has not been included in the Bio-CCS potentials in Chapter 5.

3.3 The benefits of advanced and algal biofuels

Production of several types of biofuel could be combined with CCS to achieve low or even negative carbon footprint. Biofuel production is often divided into conventional or advanced, which is to some extent (though not only) connected to the feedstock; the conversion method is also relevant:

- **Conventional** biofuels' feedstock consists of energy crops (see above) and usually competes with other utilisation, e.g. food. In general, conventional biofuels are produced from cereal crops (e.g. wheat, maize), oil crops (e.g. rape, palm oil) and sugar crops (e.g. sugar beet, sugar cane). This category includes biodiesel (RME), bioethanol, ethyl tertiary butyl ether (ETBE), biogas/landfill gas, straight vegetable oils (SVO). Conventional biofuels are produced via well-known processes (e.g. cold pressing/extraction, transesterification, hydrolysis and fermentation, and chemical synthesis) and are well-established in the market.
- **Advanced** biofuels can be produced out of plant residues (i.e. they do not compete with food production) – mainly lignocellulose-rich material, which means that the lignocellulose has to be pre-treated²¹. The pre-treatment is followed by advanced processes (e.g. advanced hydrolysis and fermentation or gasification followed by fuel synthesis). Advanced biofuels include:
 - Biomass to Liquid (BtL), e.g. FT diesel and FT kerosene for aviation
 - Cellulosic ethanol
 - BioDME/Methanol
 - BioSynthetic Natural Gas (BioSNG)
 - Bio-oil/Bio-crude
 - Hydrocarbons via the catalysis of plant sugars or synthetic biology
 - Biohydrogen
 - Bioelectricity/CHP
 - Biobutanol
- **Algal** biofuels production is expected to be ready for large-scale commercialisation further into the future than most of the biofuels listed as advanced. Nevertheless, their fast growth, high oil and biomass yields, widespread availability, absent (or very reduced) competition with agricultural land, high quality, together with the versatility of by-products – not to mention efficiency in utilising CO₂ – make algae and aquatic biomass a promising resource. In principle,

²¹ The pre-treatment is hydrolysis of cellulose (enzymatic process producing sugars and pyrolysis (heating) of lignin). Many physicochemical structural and compositional factors hinder the hydrolysis of cellulose present in biomass to sugars and other organic compounds that can later be converted to fuels. The goal of pre-treatment is to make the cellulose accessible to hydrolysis for conversion to fuels: <http://ucce.ucdavis.edu/files/datastore/234-1388.pdf>

bio-technological pathways are similar to those for conventional biodiesel production (via transesterification), although gasification and subsequent BtL-processes (i.e. advanced conversion) may also prove viable.

3.4 The importance of using sustainably produced biomass

In the face of global warming and a growing population, there is increasing local and global competition for land, feedstocks and water for food production, non-food crops and bioenergy, and there is significant debate as to whether the massive amounts of biomass required for large-scale utilisation can be harvested in a sustainable way. As biofuels gain market share and international trading of biomass, raw materials and biofuels expand, the need to ensure environmental and socio-economic sustainability along the entire supply chain becomes more pressing. This includes aspects such as land use, agricultural practices, competition with food, energy efficiency and GHG emissions, and lifecycle analysis etc.²².

Preventing the possible negative effects of growing biomass supply will, in the longer term, require a process-oriented development of refined criteria and indicators involving relevant stakeholders. International work is already taking place to ensure that communities, biodiversity and land are protected and a number of certification schemes and sustainability initiatives are already in place, e.g. for biofuels. These include initiatives by trade and standards organisations, civil society (e.g. NGOs) and government bodies.

An issue often mentioned in connection with biomass sustainability is indirect land-use change (ILUC). ILUC impacts of biofuels, especially conventional, relate to the unintended consequence of releasing CO₂ emissions due to land-use changes induced by the expansion of croplands in response to increased global biomass demand. Some studies have suggested that for certain biomass feedstocks, such emissions may indeed exceed reductions attained by replacing fossil-derived fuels with that biomass.

As it is difficult to trace such effects, this is a widely discussed subject. The European Commission has organised consultations²³ on how to address this issue within existing sustainability criteria for biofuels on the EU market and it is already being addressed by the EBTP²⁴ and several ongoing research projects, such as Biomass Futures²⁵. The Scientific Committee of the European Environment Agency has also presented a view²⁶. Please refer to work by these and other organisations for additional information on ILUC and biomass availability.

While the EU debate has mainly focused on biofuels, similar kinds of ILUC and other environmental and socio-economic impacts may be assumed to be connected with an increase in the use of solid or gaseous biomass. The European Commission has gone some way in acknowledging this, launching two consultations²⁷ on whether similar sustainability criteria for biofuels should be applied to solid and gaseous biomass. The follow-up on these consultations is as yet uncertain.

This document does not aim to provide the answers to these questions, but focuses on how sustainably produced biomass, when and where available, can be combined with CCS to attain negative emissions on a large scale.

²² www.biofuelstp.eu/sustainability.html#enviro

²³ http://ec.europa.eu/energy/renewables/consultations/2010_10_31_iluc_and_biofuels_en.htm

²⁴ www.biofuelstp.eu/sustainability.html#indirect

²⁵ www.biomassfutures.eu

²⁶ www.eea.europa.eu/about-us/governance/scientific-committee/sc-opinions/opinions-on-scientific-issues/sc-opinion-on-greenhouse-gas/view

²⁷ http://ec.europa.eu/energy/renewables/consultations/20110329_biomass_en.htm

http://ec.europa.eu/energy/renewables/consultations/20120207_renewable_energy_strategy_en.htm

4 Bio-CCS technology routes

Several routes are suitable for the conversion of biomass into final energy products or chemicals in combination with CCS, as shown in Figure 3 below. These can be divided into bio-chemical biofuels production, thermo-chemical production of biofuels and biochemicals, and biomass combustion for the production of electricity and/or heat.

A significant amount of the carbon present in the feedstock typically ends up in biofuels or biochemicals, resulting in smaller CO₂ streams compared to electricity generation. However, the impact of CO₂ capture on overall process yields is usually much smaller in the case of biofuels or biochemicals production. The CO₂ can either be easily separated, or in some cases, the fuel production process itself requires separation to ensure that downstream synthesis processes work properly.

Conventional biofuels from sugar/starch crops currently represent the largest capacity of all biofuel/biochemicals production routes, while scale-up efforts are ongoing for thermo-chemical production routes.

4.1 Bio-chemical production of biofuels

Biomethane

Fermentation or anaerobic digestion is a process whereby organic material is broken down in several steps by different micro-organisms. Most organic raw materials can be used as feedstock as long as they are biologically degradable – including animal, human, food and organic waste streams and green crops (but not woody feedstock). Process products include biogas (containing 45-70% CH₄ and 25-45% CO₂ with trace amounts of sulphurous components) and a solid fraction called digestate.

Biogas can be upgraded to biomethane by separating CO₂ and removing sulphurous components and results in properties comparable to natural gas and facilitates grid injection. CO₂ separation is a commercially proven technology for the production of biomethane, but faces certain challenges for purposes of CCS, such as seasonal feedstock variability and a relatively small CO₂ stream. The economic feasibility of biomethane production with CCS is governed by relatively small output capacities up to 15 MW.

Bioethanol

During ethanol fermentation, sugars from conventional biofuel feedstocks (e.g. sugar cane/beet, the starch part of corn) are fermented into ethanol and CO₂. Two-thirds of the carbon contained in the sugars ends up in the ethanol; the remaining third forms near-pure CO₂. The CO₂ stream can then be separated via a gas liquid separation, while the ethanol/water mixture is typically separated via distillation. A typical ethanol plant in the U.S. produces ~200 million litres per year, which corresponds to a pure CO₂ stream of 140,000 tonnes per year.

Lignocellulosic feedstocks can also be used for ethanol production, although these require a pre-treatment step to isolate the cellulose from the lignin. Subsequent chemical or enzymatic hydrolysis converts complex cellulose chains into simple sugars that can be fermented into ethanol. Figure 4 illustrates the fate of carbon in a typical lignocellulosic ethanol plant. Around 62% of the carbon present in the feedstock ends up in the lignin stream, 25% in the ethanol product and half of that in the pure CO₂ stream. Lignin can be used for under-firing during the ethanol/water distillation or as fuel for a CHP unit, although post-combustion CO₂ capture should be added to these processes to increase significantly the CO₂ capture potential.

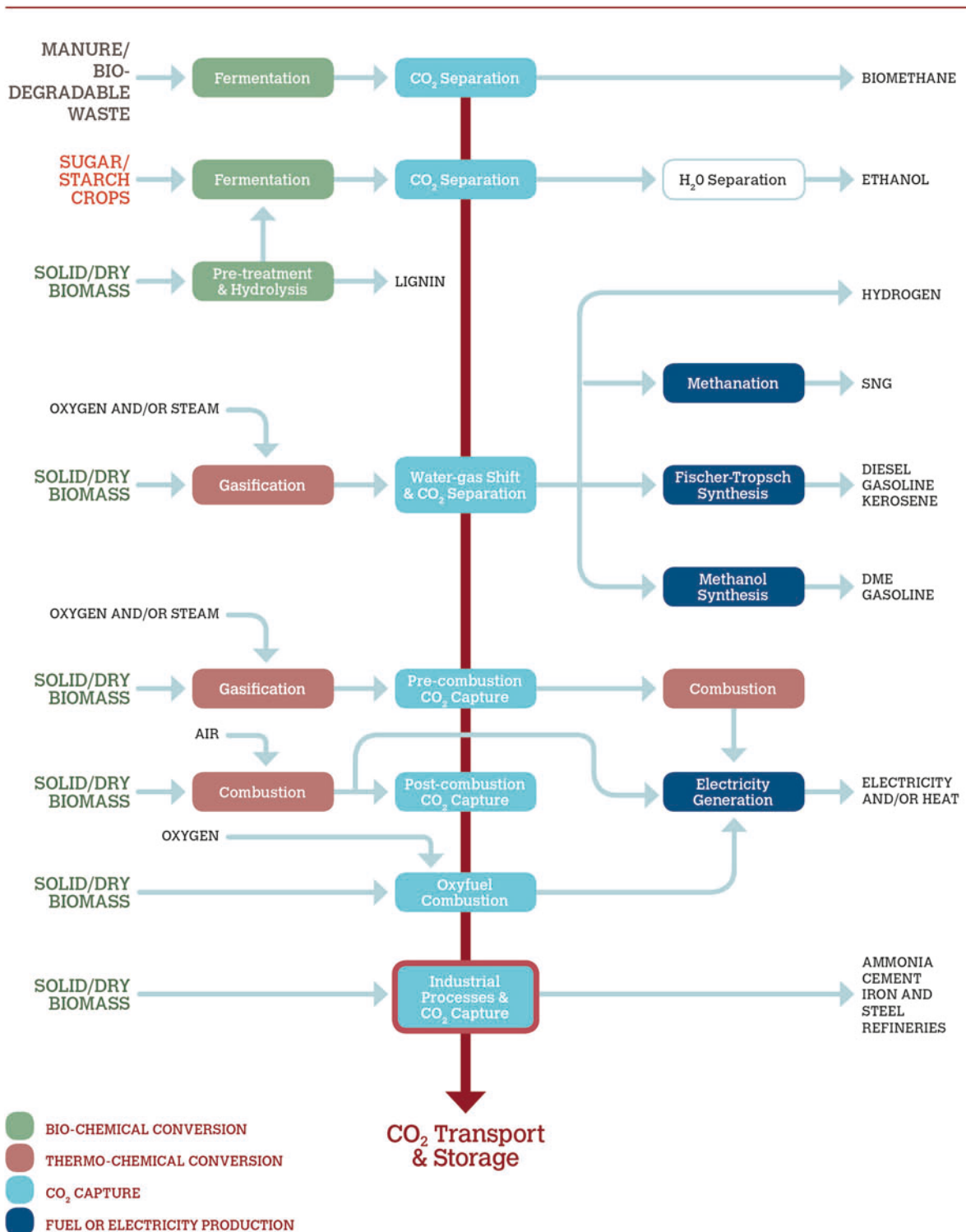


FIGURE 3 SCHEMATIC OVERVIEW OF BIOMASS-BASED CONVERSION ROUTES WITH CCS²⁸

Source: M. Carbo et al, ECN 2012

²⁸ www.ecn.nl

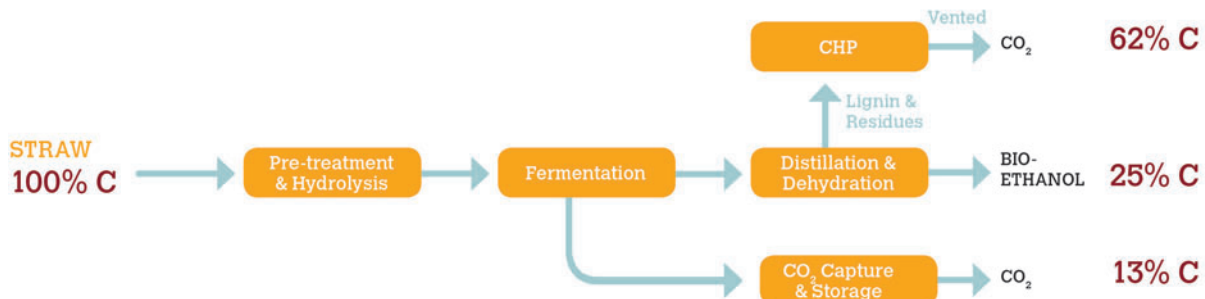


FIGURE 4 EXAMPLE OF TYPICAL CARBON DISTRIBUTION IN OUTLET STREAMS OF A LIGNOCELLULOSIC ETHANOL PLANT²⁹

Source: M. Carbo et al, ECN 2010

4.2 Thermo-chemical production of biofuels and biochemicals

During thermo-chemical conversion, lignocellulosic/non-edible feedstocks are dried and ground, and subsequently gasified with oxygen and/or steam. The product gas from gasification is then cleaned and processed to form a so-called synthesis gas, which can be used in commercially available synthesis processes to form fuels and chemicals:

- *Hydrogen* (and further synthesised into ammonia and urea)
- *Substitute Natural Gas* (SNG) via methanation
- *Diesel, gasoline and kerosene* (jet fuel) via fuel synthesis (e.g. Fischer-Tropsch) and refining (often described as Biomass-to-Liquid or BtL)
- *Methanol synthesis and upgrading to DME* (dimethyl ether, a fuel additive) and gasoline; but also plastics, formaldehyde and acetic acid.

The required hydrogen-to-carbon monoxide ratio varies for different synthesis routes. Methanol or Fischer-Tropsch synthesis requires two hydrogen molecules per carbon monoxide molecule, while methane synthesis requires three hydrogen molecules per carbon monoxide molecule. This can be adjusted by the water-gas shift reaction and CO₂ separation, resulting in a relatively pure CO₂ stream. The capture technology is similar to pre-combustion CO₂ capture in Integrated Gasification Combined Cycle (IGCC) power plants and is usually based on the use of physical absorption in solvents.

Figure 5 below shows an example of the fate of carbon in a typical FT diesel plant, based on oxygen-blown Circulating Fluidized Bed (CFB) gasification. Slightly over 50% of the carbon in the feedstock is released as relatively pure CO₂, while 37% ends up in the diesel stream. The CO₂ vented from the power island, and carbon in the char from the gasifier, make up the balance.

²⁹ M.C. Carbo et al., "Bio Energy with CO₂ Capture and Storage (BECCS): conversion routes for negative CO₂ emissions", Proceedings of the 4th International Freiberg Conference on IGCC & XtL, Germany, 2010

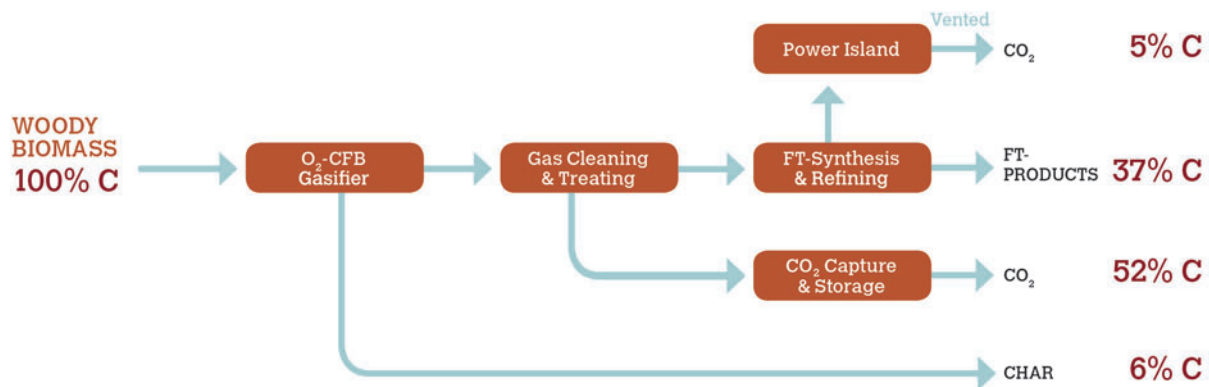


FIGURE 5 TYPICAL CARBON DISTRIBUTION IN THE OUTLET STREAMS OF A FISCHER-TROPSCH DIESEL PLANT²⁹

Source: M. Carbo et al, ECN 2010

4.3 Biomass combustion for electricity and/or heat production

Biomass co-firing

There are several technical routes for biomass co-firing which may be divided into indirect and direct. Indirect co-firing relies on the dedicated conversion of biomass in a fluidized bed gasifier. This produces a combustible gas with a Low Calorific Value (LCV) that can be injected into an existing boiler. During direct co-firing, biomass is blended with coal, milled and transported to the burners in the boiler. Biomass can also be ground in a dedicated biomass mill or modified coal mill. The ground biomass can be blended with pulverised coal and fed to the burners, or fed via a dedicated biomass burner, or simply injected into the boiler.

Biomass co-firing ratios strongly depend on the characteristics of the biomass used and the layout of the power plant. Achieving elevated co-firing ratios has proved difficult as untreated biomass is typically fibrous and inhomogeneous in nature. It has a lower energy density and different inorganic composition to hard coal; it is also vulnerable to biodegradation and hydrophilic in nature. Significant plant modifications are therefore usually required, entailing additional, high investment costs.

An alternative is to use thermal pre-treatment technologies that increase the homogeneity, brittleness and/or energy density of biomass. These take place at temperatures between ~250°C and 550°C with torrefaction³⁰ at the lower end of the range, pyrolysis³¹ at the upper end. The biomass co-firing share can be significantly increased with such pre-treatment technologies without major plant modifications. As most methods do not affect the inorganic content of biomass, boiler fouling, corrosion and emissions could still pose technical bottlenecks. However, high-temperature entrained flow gasification, as used in IGCC power plants, could reduce limitations since part of the inorganic content of the pre-treated biomass is removed through slag.

³⁰ Torrefaction technologies aim to produce a stable, more homogeneous and energy-dense fuel from biomass, which allows the use of existing infrastructure during logistics, grinding and feeding to existing coal-fired power plants. The fibrous nature of the biomass is weakened by these processes; this facilitates grinding and densification (pelletising).

³¹ Pyrolysis technologies aim to produce solid charcoal and pyrolysis oil. Pyrolysis oil is a complex liquid that contains a significant amount of oxygen, which could be fed through a liquid burner in an existing coal-fired power plant

100% biomass combustion in CHP plants and CFB boilers

100% biomass combustion occurs in certain, smaller modified pulverised coal boilers and could also be facilitated in existing, medium-sized CHP plants fired with coal or lignite. The latter are theoretically suited to fire up to 100% biomass and are generally based on CFB technology. CFB boilers are usually smaller than large utility boilers – ranging from 50 to 500 MW_{th} – more flexible regarding fuels and typically located in close proximity to urban areas or industrial facilities in order to supply heat. The above-mentioned technologies could also be converted to allow 100% biomass oxy-fuel firing.

Biomethane/bio-SNG for power/heat production

Biomethane obtained from fermentation and upgraded by CO₂ separation or gasification-based bio-SNG could be used as fuel in gas-fired combined cycle power plants (NGCCs) or CHP plants. For gas-fired applications, there are in principle no co-firing ratio limitations and biomethane/bioSNG can be co-fired at any rate between 0 and 100%. There are also no fundamental restrictions to applying “conventional” post-combustion CO₂ capture technologies in these power plants (apart from economies of scale for CHP).

BIGCC

Gasification of biomass allows the utilisation of a variety of biomass feedstocks and, in theory, the use of pre-combustion CO₂ capture technologies that are also proposed for IGCC power plants. Technical improvements to future biomass-based IGCC (BIGCC) plants can therefore build on the experience and further development of gasification technology in the (petro)chemical sectors which produce base chemicals and transport fuels (e.g. FT diesel).

4.4 Bio-CCS in industrial applications

Fuel substitution

Large industrial operations could present potential Bio-CCS opportunities where a local heat or power requirement exists – particularly in industrial clusters where CCS infrastructure can be shared, ensuring continuity and efficiency of operation. Further synergies may be possible where systems are combined or shared, such as the application of low-grade heat to pre-dry biomass, reducing the moisture content and improving the energy density of the feedstock.

The use of biomass in industry to replace fossil fuels includes a variety of potential applications: small- and medium-scale heat and power for industrial and domestic use (< 50 MW); as a fuel substitute in cement kilns; in the refining and chemicals industries as synthesis gas from gasification or pyrolysis oil; and via injection in blast furnace steel and iron-making.

Pulp and paper

In the pulp and paper industry, the majority of emissions originate from biogenic sources, since most of the on-site processes utilise biomass as a raw material. Although total site emissions are significant, they are scattered among different stacks – with the recovery boiler usually the largest source by far. Other sources are the lime kiln, bark boiler and possibly other on-site heat/power production.

As for other industries, the potential for process integration could reduce the energy penalty from CCS, and associated capture costs, substantially. However, the size of single sources, as well as heavily integrated processes on modern pulp and paper mills, pose challenges in applying CCS to existing installations. Layout restrictions and impurities in the flue gas also pose a challenge. Nevertheless, as aging recovery boilers are replaced in the future, a window of opportunity could open for the gasification of black liquor³² which entails more feasible capture options.

³² Black liquor is a liquid process stream in chemical pulping processes which contains cooking chemicals and dissolved lignin. In a recovery boiler, cooking chemicals are recovered to be re-used in the process and lignin is burned to produce power and heat for the site.

5 Bio-CCS potentials in 2030 and 2050

5.1 Negative emissions are *additional* to any abatement from replacing fossil fuels with biomass

In a recent report by the IEA GHG³³, various potentials were assessed, including a first assessment of the global and European³⁴ “technical potential” for Bio-CCS in the power and (bio)fuel production sectors (Table 1 below). This includes technologies for co-firing and co-gasification of biomass and coal, as well as those fed solely with biomass feedstock.

The technical potential of Bio-CCS: a definition

The technical potential describes the maximum amount of resources (i.e. biomass) that can be used or converted, depending on the technical performance of conversion technologies. This performance varies over time due to technological progress. For Bio-CCS technologies, the technical potential is constrained by the availability of sustainable biomass, CO₂ storage capacity and the (future) technological performance of biomass conversion and CO₂ capture technologies. The net energy conversion efficiency (including the energy penalty) and the carbon removal efficiency of the Bio-CCS technology then determine the technical potential for Bio-CCS in terms of primary energy converted, final energy and net (negative) GHG emissions.

It should be noted that 1 Mt³⁵ of negative emissions (carbon-negative) is not the same as 1 Mt of emission reductions – emission reductions always depend on a reference scenario. For example, a large coal-fired power plant emits 5 Mt of CO₂ per year. If it is replaced by a low-carbon technology that still emits 1 Mt per year, then an emission reduction of (5-1 =) 4 Mt is achieved. Bio-CCS technologies may replace fossil-fuel power plants *and* deliver negative emissions by storing CO₂ originating from biomass. If, in this example, the coal-fired power plant is replaced by a Bio-CCS power plant that delivers 4 Mt of negative emissions, then the total emission reduction achieved is (5+4 =) 9 Mt.

In other words, carbon-negative = carbon abatement only if Bio-CCS replaces zero-emission technologies. If it replaces carbon-emitting technologies, the abatement of their emissions is then added for the total carbon abatement.

5.2 Globally, Bio-CCS could remove 10 Gt³⁶ of CO₂ from the atmosphere every year by 2050

The results of the IEA GHG study indicate a large global technical potential for Bio-CCS: a removal of ~10 billion tonnes of CO₂ from the atmosphere every year by 2050 – equivalent to around a third of all current energy-related CO₂ emissions worldwide.

As in the EU, this technical potential is, in most regions, mainly limited by the supply of sustainable biomass as there is likely to be sufficient CO₂ storage capacity³⁷. In the biofuel routes, a relatively small fraction of CO₂ is captured, therefore a relatively small storage capacity is required. In the 100% biomass-fired routes for power generation, less storage capacity is required compared to co-firing routes in order to realise the full carbon-negative potential.

³³ www.ecofys.com/en/project/biomass-combined-with-ccs-bio-ccs/

³⁴ OECD Europe: Austria, Belgium, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Luxembourg, Netherlands, Norway, Poland, Portugal, the Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Turkey and the United Kingdom. N.B. This region does not completely match the EU27.

³⁵ Mt = megatonne = million tonnes

³⁶ Gt = gigatonne = billion tonnes

³⁷ For details of storage capacity in Europe, see the EU GeoCapacity project: www.geology.cz/geocapacity

Bio-CCS technology	Technical potential in net negative GHG emissions (Gt CO ₂ -equivalent)			
	Global ¹		OECD Europe ²	
	2030	2050	2030	2050
Electricity generation with CCS				
Co-firing in coal-fired power plant (post-, pre-, oxy-fuel combustion)	-4.3	-9.9	-0.3	-0.7
Dedicated combustion and gasification of biomass (post-, pre-, oxy-fuel)	-5.7	-10.4	-0.5	-0.8
Biofuels production with CCS				
Bio-ethanol (lignocellulosic biomass)	-0.5	-1.1	-0.04	-0.1
Synthetic biofuels via thermochemical processes	-3.3	-5.8	-0.3	-0.4

¹ The global supply of biomass feedstock is assumed to be equal for all selected Bio-CCS technologies: 73 and 126 EJ/yr in 2030 and 2050, respectively.

² The potential supply of biomass feedstock from OECD Europe is assumed to be equal for all selected Bio-CCS technologies: 5.8 and 9.6 EJ/yr in 2030 and 2050, respectively.

TABLE 1 OVERVIEW OF GLOBAL AND OECD EUROPE'S TECHNICAL POTENTIAL FOR VARIOUS BIO-CCS TECHNOLOGIES IN 2030 AND 2050

N.B. The technical potentials shown in Table 1 are calculated under the assumption that all available biomass is allocated to one specific Bio-CCS route at a time. The results for the various Bio-CCS technologies thus cannot be totalled. The results presented here reflect a limited set of Bio-CCS technologies and are not exhaustive. Work is currently being carried out by the IEA GHG to estimate the potential for Bio-CCS technologies where biogas is combined with CCS.

5.3 In Europe, Bio-CCS could remove 800 Mt of CO₂ from the atmosphere every year by 2050

While the market for biomass is assumed to be global, this report focuses on Bio-CCS potentials based on projected available biomass in (OECD) Europe. According to the IEA GHG study, Bio-CCS could remove 800 million tonnes of CO₂ from the atmosphere every year by 2050 – equivalent to more than half of all current EU energy-related emissions.

For the IEA GHG study, estimates of ~6 and 10 EJ were used for the years 2030 and 2050 respectively, including dedicated energy crops, agricultural residues and forestry residues. Longer term (2020 and beyond) estimates for biomass potential in the EU show a wide range in literature, for example:

- Panoutsou et al 2009³⁸ estimate a biomass potential in the EU27 of 7.8 EJ for 2020, including agricultural biomass, forest biomass, industrial biomass and waste biomass.
- The EU RESHAPING project³⁹ estimates between 0.6 to 10.3 EJ for 2020 for dedicated energy crops alone.
- GREEN-X and REFUEL estimates for dedicated energy crops are 1.8-6.8 EJ and 2.3-9.0 EJ for 2020 and 2030 respectively⁴⁰.

³⁸ www.sciencedirect.com/science/article/pii/S0301421509006193

³⁹ [http://igitur-archive.library.uu.nl/chem/2012-0320-200511/Long-term%20potentials%20and%20cost%20of%20RES%20-%20part%201%20\(Re-Shaping%20report,%202011\).pdf](http://igitur-archive.library.uu.nl/chem/2012-0320-200511/Long-term%20potentials%20and%20cost%20of%20RES%20-%20part%201%20(Re-Shaping%20report,%202011).pdf)

⁴⁰ [http://igitur-archive.library.uu.nl/chem/2012-0320-200511/Long-term%20potentials%20and%20cost%20of%20RES%20-%20part%201%20\(Re-Shaping%20report,%202011\).pdf](http://igitur-archive.library.uu.nl/chem/2012-0320-200511/Long-term%20potentials%20and%20cost%20of%20RES%20-%20part%201%20(Re-Shaping%20report,%202011).pdf)

For reference, current biomass use in the EU27 is ~4 EJ, of which 2 EJ is used to generate electricity⁴¹. As uncertainties are high regarding future biomass supply, the IEA GHG 2030 and 2050 estimates have been derived from the medium to lower range of available projections published over the last decade.

5.4 800 Mt of CO₂ is equivalent to over 50% of current emissions from the EU power sector

A potential of 800 Mt of negative emissions is highly significant in relation to the EU Low-Carbon Economy Roadmap⁴² for delivering an overall decarbonisation target of 80-95% by 2050 – as called for by EU leaders in the European Council.

This target translates into emissions reductions required in various sectors of the economy, e.g. 93-99% in the power sector, 54-67% in the transport sector. In absolute numbers, this equals up to 1.4 Gt in the power sector and ~1 Gt in the transport sector. 800 Mt of negative emissions is therefore equivalent to over 50% of current emissions from the EU power sector.

In the long-term, when deployed within a portfolio of other low-carbon technologies, Bio-CCS could actually result in carbon-negative sectors, i.e. overall sectorial emissions below zero. This would then provide the EU with the possibility of offsetting emissions in other industry sectors where substantial reductions are more difficult to attain.

Even taking uncertainties into account, research therefore indicates that the technical potential for Bio-CCS to combat climate change is highly significant. However, before this can be realised, economic conditions for application, location (matching infrastructures), regulatory framework and social aspects must also be taken into account, as described below.

⁴¹ http://ec.europa.eu/research/energy/eu/research/bioenergy/background/index_en.htm

⁴² "A Roadmap for moving to a competitive low carbon economy in 2050", 2011:
<http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2011:0112:FIN:EN:PDF>

6 Economic factors

Costs for the large-scale deployment of Bio-CCS technologies have not yet been comprehensively assessed, either for Europe or globally. Given the substantial differences between the various technology routes, a generalised description would not be appropriate and more detailed work is needed. Nevertheless, a number of observations can be made.

6.1 Biofuels production with CCS is a key “low-hanging fruit” for CCS deployment

Several biofuels production routes, notably bioethanol and FT syngas production, have a near-pure CO₂ stream (CO₂ separation is already part of the production processes, with very low impact on thermal efficiency), providing CCS deployment options with very low additional costs once units reach a certain scale, or can be clustered in terms of infrastructure. Indeed, the IEA Technology Roadmap for CCS in Industrial Applications⁴³ highlights biofuels production with CCS as one of the key “low-hanging fruits” for CCS deployment.

While no comprehensive cost calculations are available for biofuels production with CCS, data from ADM⁴⁴ in the U.S. – an early mover in industrial-scale bioethanol production with CCS – indicates that the cost per tonne of CO₂ captured, transported and stored is lower than for early movers in electricity production with CCS⁴⁵. The U.S. does not currently have a CO₂ pricing system, but the ADM project receives subsidies from the Department of Energy (DoE) to inject 2.5 Mt of CO₂ over three years⁴⁶.

Without more in-depth cost analyses, it is premature to identify biofuels with CCS as *the* low-hanging fruit for Bio-CCS, based on the costs of a single project with a limited time-span. Yet the ADM project indicates that for certain biofuels production routes, CCS deployment could be commercialised in the EU at a significantly lower Emissions Unit Allowance (EUA) price than for electricity production, assuming that the EU ETS – or other future incentivising mechanisms – reward emissions below the baseline (see Chapter 7).

6.2 Biomass co-firing at moderate percentages can be flexibly applied

ZEP has recently undertaken a ground-breaking study on the costs of CO₂ capture⁴⁷, transport⁴⁸ and storage⁴⁹, with resulting integrated CCS value chains presented in a summary report⁵⁰. This showed that following a successful demonstration, the current suite of CCS technologies will be cost-competitive⁵¹ with the full range of low-carbon power options. The study focused on fossil fuel power plants and did not cover CCS applications where biomass is used as a feedstock. While this will be covered in future updates, it is possible to make some general comments.

Looking at the levelised cost of electricity (LCOE), Bio-CCS is generally more expensive than fossil CCS due to the relatively higher cost of biomass (see below). However, co-firing biomass with coal or lignite at moderate percentages (at least up to 10%) is not expected to require additional investment in CCS equipment compared to CCS for coal or lignite only. Generally speaking, it is therefore the cost of the biomass fuel which causes variations in the costs of deploying CCS.

For higher co-firing rates and dedicated biomass combustion, the relatively lower energy content per volume of biomass feedstock compared to coal potentially leads to efficiency penalties and higher costs.

⁴³ www.iea.org/roadmaps/ccs_industrial_applications.asp

⁴⁴ <http://sequestration.org>

⁴⁵ www.nytimes.com/cwire/2011/09/12/12climatewire-ethanol-carbon-sequestration-plant-holds-les-18588.html?pagewanted=2

⁴⁶ <http://origin.adm.com/en-US/news/layouts/PressReleaseDetail.aspx?ID=247>

⁴⁷ www.zeroemissionsplatform.eu/library/publication/166-zep-cost-report-capture.html

⁴⁸ www.zeroemissionsplatform.eu/library/publication/167-zep-cost-report-transport.html

⁴⁹ www.zeroemissionsplatform.eu/library/publication/168-zep-cost-report-storage.html

⁵⁰ www.zeroemissionsplatform.eu/library/publication/165-zep-cost-report-summary.html

⁵¹ €70-90/MWh for CCS with coal, €70-120/MWh with gas, operating in baseload (7,500 hours equivalent full load each year)

While the composition of biomass fuels is variable, their generally higher alkaline content compared to coal can also lead to ash deposition and corrosion when co-firing in existing boilers, which will drive up costs. More data and research is needed on these issues, as well as other potential technological challenges.

The (co-)firing of biomethane or bioSNG in NGCCs to replace natural gas is not expected to result in any additional costs when NGCCs are equipped with CCS.

6.3 Biomass prices will increase unless novel feedstocks are sufficiently up-scaled

As mentioned above, the LCOE from firing with biomass is generally higher than for fossil fuels due to the difference in fuel cost. Generally, this also holds for the transport sector. The deployment of biofuels and bioenergy in the EU is therefore driven mainly by RES targets (see page 10), which in many countries translates into dedicated incentives such as feed-in tariffs or mandatory, blend-in values for biofuels.

It is difficult to predict the price of biomass far into the future, as there are a large number of unknowns:

- Supply
 - Sustainable agricultural yield, sustainable wood supply
 - Availability, suitability and scalability of novel feedstocks, e.g. micro- and macroalgae etc.
- Demand
 - Global demand for biofuels and bioenergy
 - Population growth and demand for meat
 - Availability and cost of petroleum and other energy sources
 - Demand for other bio-products and chemicals
 - Demand in other biomass-based sectors, e.g. pulp/paper, wooden materials etc.

Nevertheless, biomass prices in the EU can be expected to rise as demand grows – driven by RES targets – unless novel feedstock sources are sufficiently up-scaled. With the potential introduction of sustainability criteria for solid and gaseous biomass, this effect is likely to increase further.

7 Accelerating deployment

This chapter provides some initial recommendations for how the EU could accelerate the development and deployment of Bio-CCS technologies in order to realise their significant carbon-negative potential.

A key prerequisite is the maturation and commercialisation of CCS and advanced, sustainable biofuels production. Bio-CCS is already being carried out on an industrial scale⁵² – but not in Europe, mainly because negative emissions are not rewarded in the EU ETS. Dedicated funding for pilot projects to prove advanced technologies and close any knowledge gaps is also urgently required.

7.1 Take urgent action at EU/Member State level to support CCS demonstration projects

In recognition of CCS as a critical low-carbon energy technology, the EU has moved rapidly from development to demonstration on the road to wide deployment: billions of euros have been invested or pledged by industry, funding has been achieved for a CCS demonstration programme and an EU-wide legal framework for CO₂ storage⁵³ has been established. As importantly, the ZEP cost reports⁵⁴ now provide confidence that following a successful demonstration, the current suite of CCS technologies will be cost-competitive⁵⁵ with the full range of low-carbon power options.

In short, there is no doubt that CCS can deliver, as confirmed by international developments where FID has already been taken on large-scale demonstration projects in Australia, Canada and the U.S. However, while confidence in the technology remains high, the fall in the EUA price – from ~€30 per tonne in 2008 to ~€8 today – could have a severe impact on both CCS demonstration *and* deployment: not only is significantly less funding available for the “NER 300”⁵⁶, but the long-term business case for CCS has been seriously undermined.

It means CCS has now reached a “tipping point” in Europe and urgent action is needed at EU and Member State level to counteract these developments. As the IEA has declared, “Deploying CCS requires policy action; it is not something the market will do on its own.” The following actions are therefore urgently required:

- *Strengthen the EUA price* as it not only underpins the long-term business case for CCS, but also partly the short-term, as even demonstration projects will need to recover their investment over the medium to long term.
- As this will take some years to deliver, *establish additional economic measures at Member State/EU level* to enable demonstration projects to take FID. National governments are already moving in this direction, underlining the urgency of the situation. ZEP’s report, “CO₂ capture and Storage (CCS) – Creating a secure environment for investment in Europe”⁵⁷ provides concrete recommendations for additional, non-ETS measures needed – plus any complementary adjustments to the ETS required.
- Industry has already demonstrated its willingness to take on a major portion of the costs and risks of investing in CCS. However, as the NER 300 may now deliver as little as €2.5 billion for CCS and innovative renewable energy technologies, *additional financial support from Member States is also vital*⁵⁸.

⁵² E.g. the ADM bioethanol-CCS project – see page 21

⁵³ <http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:140:0114:0135:EN:PDF>

⁵⁴ Zero Emissions Platform, July 2011: www.zeroemissionsplatform.eu/library/publication/165-zep-cost-report-summary.html

⁵⁵ €70-90/MWh for CCS with coal, €70-120/MWh with gas, operating in baseload (7,500 hours equivalent full load each year)

⁵⁶ In 2008, the EU agreed to set aside 300 million Emission Unit Allowances from the New Entrant Reserve under the EU ETS Directive to demonstrate CCS and innovative renewable energy technologies

⁵⁷ To be published shortly and viewable in the ZEP website library: www.zeroemissionsplatform.eu/library.html

⁵⁸ Even if Member States replicate the contribution of NER 300 funding, a gap of hundreds of millions of euros in incremental costs could remain per project (except under specific conditions such as the use of CO₂ for EOR)

- *Provide storage site operators with greater clarity on the precise modalities for site hand-over and financial security at Member State level and accelerate the validation of storage permits.*

7.2 Identify the most effective Bio-CCS options for the short to medium term

In order to obtain a semi-quantitative comparison of biofuels, biomass co-firing, CCS and Bio-CCS deployment potentials for Europe, a preliminary assessment of scenarios presented by, a.o., the European Commission, EBTP, ZEP and JTF Bio-CCS member, IEA GHG, was undertaken (Figure 6 below). These were combined in order to identify the most significant abatement options for the short to medium term – and the most important areas of focus for RD&D.

The following projections and targets were taken into consideration:

- The IEA estimates that the deployment of CCS in Europe could result in the abatement of 950 Mt of CO₂ per year by 2050⁵⁹. This is included in order to show the magnitude of potential negative emissions relative to projected overall CCS deployment.
- The potential amount of biogenic CO₂ that could be abated from co-firing biomass and bioelectricity production is based on two different approaches:
 - The maximum potential of biogenic carbon that could be abated from co-firing is based on the estimations of the Refuel project⁶⁰ and the Chalmers boiler database.⁶¹ This includes co-firing in existing boilers and thus represents maximum Bio-CCS retrofit potential in Europe.
 - The biogenic CO₂ abatement potential from electricity generation is based on RES targets and the NREAPs of Member States for biomass use in electricity generation⁶². This represents the potential for Bio-CCS in power generation by 2020.
- The abatement potential for liquid biofuels is based on estimates for future utilisation and production:
 - EU 2020 target is 10% renewable energy in the transport sector, of which nearly 100 % will be fulfilled with biofuels according to the NREAPs
 - EBTP's 2030 target is 25% biofuels in road transportation (of which a quarter is bioethanol, three-quarters is FT diesel)⁶³. Based on current technology and a 90% capture rate, ~3.5 Mt of CO₂ can be abated from the production of 1 Mtoe⁶⁴ FT diesel and ~1.6 Mt of CO₂ from the fermentation process of 1 Mtoe ethanol.
 - The European Commission has recently outlined a vision for an even higher percentage for aviation biofuels: 40% of the aviation fuels market by 2050⁶⁵.
- Bio-CCS potential in the pulp and paper industry is based on current production in Europe, which is not expected to increase significantly in the future. Existing large- and medium-size boilers (140 MW_{th} to 700 MW_{th}) were taken into consideration – a total of 38 identified in Europe⁶⁶.
- The IEA GHG's carbon-negative potentials for 2030 and 2050, as described in Chapter 5.

⁵⁹ www.iea.org/papers/2009/CCS_Roadmap.pdf

⁶⁰ www.refuel.eu/

⁶¹ <http://cpmdatabase.cpm.chalmers.se/>

⁶² http://ec.europa.eu/energy/renewables/action_plan_en.htm

⁶³ http://biofuelstp.eu/srasdd/SRA_2010_update_web.pdf

⁶⁴ Million Tonnes of Oil Equivalent

⁶⁵ www.biofuelstp.eu/spm4/pres/kyriakos_maniatis.pdf

⁶⁶ Pöyry boiler database, 2011

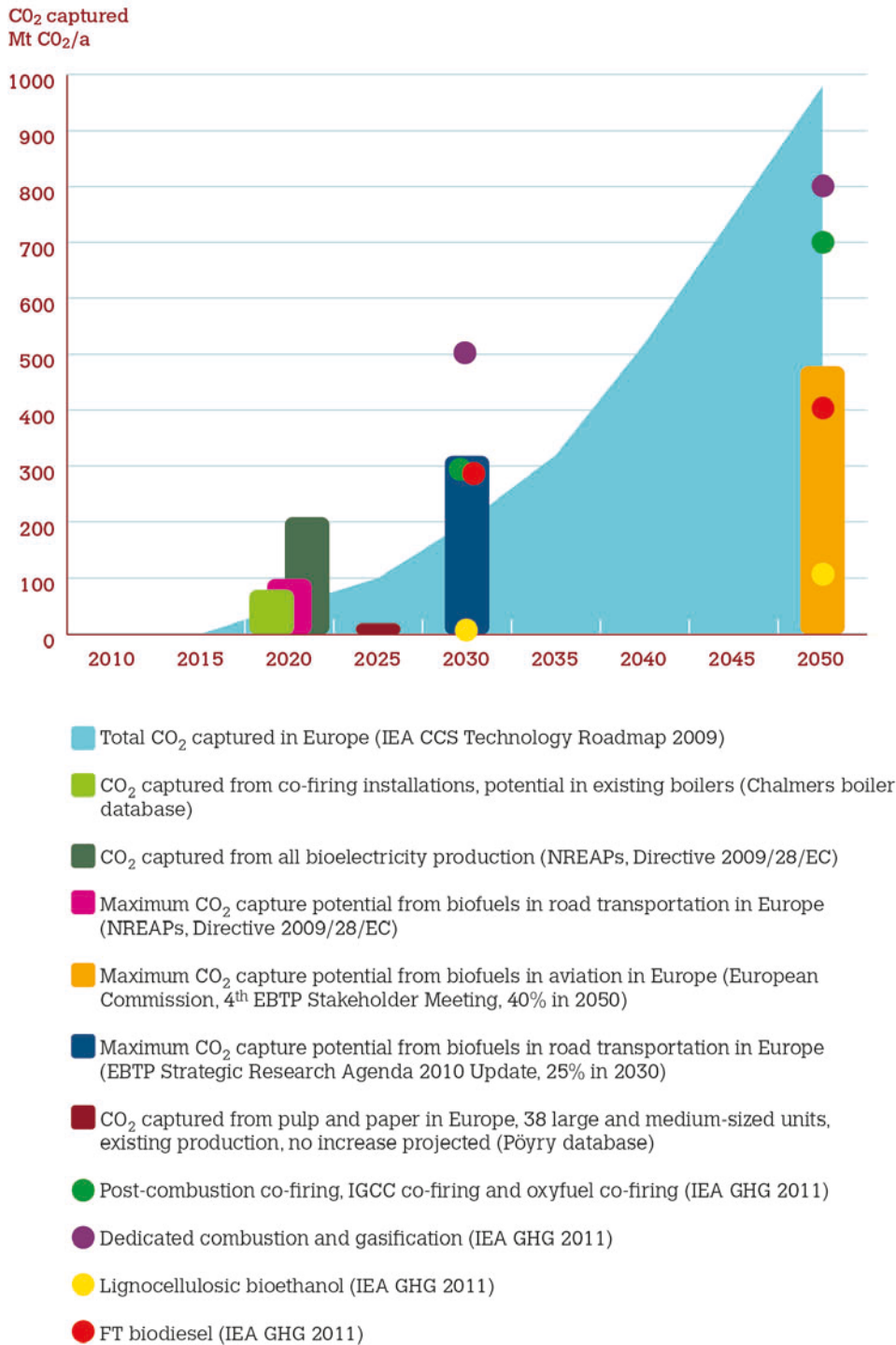


FIGURE 6 THE ABATEMENT POTENTIAL OF DIFFERENT BIO-CCS OPTIONS IN RELATION TO VARIOUS DEPLOYMENT SCENARIOS FOR EUROPE

Source: A. Arasto et al, VTT 2012

N.B. The aim is not to assess the energy sector as a whole, but the potential role and scale of Bio-CCS in Europe in the light of current policy targets. This simplified analysis therefore focuses on the capture and storage of biogenic CO₂ emissions and does not take into account (the abatement of) fossil CCS. The maximum amount of sustainable biomass available in Europe for combination with CCS is based on the IEA GHG's potentials, but it is important to bear in mind that these assume that all available sustainable biomass is channelled via only one route at a time.

While Figure 6 does not aim to provide clear conclusions, the following observations may be made:

- Abating all bioenergy-related CO₂ emissions induced by EU RES policy (and NREAPs) by 2020 amounts to 200 Mt of negative emissions – in addition to emissions reductions resulting from the shift from fossil to renewable fuels (in this case, biomass) as foreseen in the Renewable Energy Directive (RED).
- Following the dedicated combustion and gasification route of the IEA GHG, the maximum amount of negative emissions achievable using European biomass in 2050 almost equals the IEA's maximum projected potential for CCS deployment in Europe – in addition to emissions reductions resulting from replacing fossil fuels with biomass.
- The maximum abatement potential from the EBTP's 25% biofuels target for 2030 is very similar to the maximum negative emissions potential in Europe for FT diesel of 300 Mt of CO₂ – assuming all the biomass is channelled via this production route – at a potentially low additional cost for CCS, using European biomass feedstock only.

7.3 Accelerate RD&D for sustainable advanced biofuels

There is considerable potential for the production of advanced biofuels, which are expected to be superior to conventional biofuels in terms of GHG reductions, land use requirements and competition for land, food, fibre and water⁶⁷. The main reason this has not yet taken up speed is that the conversion technologies needed to reduce the costs of the value chain are still approaching wide-scale deployment.

Much work therefore needs to be done to improve advanced biofuel technology pathways in order to achieve economic feasibility and enhance the performance and reliability of conversion processes. This requires intensive RD&D⁶⁸ activities, in particular:

- Investments in agricultural production and infrastructure improvements which promote rural development and significantly improve the framework for an advanced biofuel industry
- Agricultural and forestry residues as the feedstock of choice in the initial stages of deployment since they are readily available and do not require additional land cultivation
- More detailed research to ensure that advanced biofuels provide economic benefits for developing countries⁶⁹
- Pilot and demonstration projects outside, as well as within, the OECD in order to develop supply chain concepts, assess feedstock characteristics and analyse production costs in different parts of the world
- The collection of field data on commercial, advanced biofuel production from residues in order to better understand impacts on agricultural markets and the overall economic situation in developing countries
- Improved data accuracy on sustainably available land in developing countries in order to determine the potential for dedicated energy crops.

⁶⁷ www.iea.org/papers/2008/second_biofuel_gen.pdf

⁶⁸ Research, development and deployment

⁶⁹ www.biofuelstp.eu/viewreport.php?viewid=81

In order to improve the support mechanisms leading to the large-scale deployment of advanced sustainable biofuels, the following measures would be beneficial:

On the demand side:

- *The double counting measure*: gives an administrative energy bonus and thus economic value to some biofuel production pathways (those that produce biofuels from wastes, residues or lignocellulose); it has no budgetary impact
- *Binding blend-in target*: an achievable sub-target for advanced biofuels would secure a market share. It would also reduce investment risk and lower competition with well-established biofuel production pathways
- *Tax incentives*: could be implemented in the EU Energy Taxation Directive, which is currently under revision
- *Production support/feed-in tariff*: initial fixed sales prices or fixed premiums help improve the business case for the investors that are needed to build the first wave of commercial-scale projects.

On the supply side:

- *Feedstock collection and supply-chain incentives*: in most EU countries there is no or limited experience with the large-scale collection and storage of biomass. Incentives are therefore essential to help establish agriculture and forestry biomass supply-chains and reduce feedstock uncertainty and the overall risk of advanced biofuel scale-up investments.

On the investment side:

- *Realistic investment support* for both demonstration and first-of-a-kind commercial-scale projects, e.g. via the European Industrial Bioenergy Initiative (EIBI).

7.4 Establish Bio-CCS value chains in Europe

As discussed, biofuels and bioenergy use is increasing in the EU, driven by the EU RED and its binding targets for RES in 2020. In addition to almost 10% biofuels in the transport sector, this will result in a steep increase in bioenergy use, as outlined in the NREAPs. This means the potential for Bio-CCS will increase significantly in the coming decade.

7.4.1 Reward negative emissions in the EU ETS

The key driver for all low-carbon energy technologies is the overall policies to reduce GHG emissions, which directly affect the economic viability of such technologies by dictating the cost of emissions, either through mandatory requirements (e.g. emissions performance standards), incentives (e.g. the EU ETS) and/or taxes on emissions.

In the EU, the main policy tool is the EU ETS. However, being a cap-and-trade scheme where the maximum incentive is provided to projects which reduce emissions to zero, it does not easily reward activities which go *beyond* zero and achieve negative emissions – as in the case of Bio-CCS. Biomass-based power production is not eligible for such rewarding, while industrial projects which fire with biomass may be eligible, but there remains uncertainty as to how this would work in practice. There are therefore no clear options for incentivising Bio-CCS without changing the ETS or relevant rules.

In short, because CO₂ emissions resulting from biomass conversion are not rewarded in the ETS (or rather, they are regarded as neutral and therefore not accounted for), there is no incentive to abate those emissions – even where it can be done at very low additional cost. In fact, co-firing biomass in a fossil fuel power plant actually *reduces* the business case for CCS, if the biomass

share exceeds the rate of CO₂ not abated by CCS – typically 10% – because capturing the biogenic CO₂ yields no reward.

If negative emissions were rewarded, the EUA price, once high enough, could make Bio-CCS economically viable. However, due to current and expected feedstock prices, EUA prices and the existence of RES targets and Member State incentives for energy, such rewarding is unlikely in itself to lead to any increase in, for example, biomass co-firing in coal-fired power plants or biofuels production volumes; but it could lead to CCS being deployed where biomass replaces fossil fuels, once CCS technologies are commercially proven.

If biomass prices were to decrease steeply due to novel feedstocks – while the EUA price simultaneously increases – an improved business case could also be envisaged in the longer term as a result of such rewarding, especially for biofuels routes where CCS deployment is available at a lower cost.

The Clean Development Mechanism

The Clean Development Mechanism (CDM) is a global policy tool for incentivising low-carbon projects in developing countries by creating carbon credits. As the UNFCCC guidelines allow for emissions below the baseline, this may be used to incentivise Bio-CCS projects, now that CCS in principle has been acknowledged as an eligible technology at COP 17 in Durban. However, while this may accelerate Bio-CCS deployment in developing countries, it will not facilitate deployment in the EU.

7.4.2 Deploy advanced biofuels production with CCS

Although some biofuels production routes provide very cost-efficient CCS opportunities, bioethanol production in Europe is still typically at a smaller scale than elsewhere, while FT diesel and kerosene production still require up-scaling and further commercialisation. This means that unit sizes are generally too small for the economies of scale required for CO₂ transport and storage.

Combining several biomass sources of “low-hanging fruit” – possibly in combination with other sources of CO₂ – in common CO₂ transport and storage infrastructures will facilitate deployment, where geography allows. Another option could be to ship CO₂ to storage sites, where an emission source is close to navigable waterways, removing the need for large upfront investments in pipeline infrastructure.

As the combination of RES targets, increasing petroleum prices and energy security concerns increase the utilisation of advanced biofuels, production units may be expected to increase in size, especially if plans for CCS deployment are taken into account. As the majority of the increase in biofuels production is expected to come from FT-derived products such as diesel and kerosene, their production becomes an obvious target for CCS, both from a logistics and cost point of view. As shown in Chapter 4, more than half of the carbon content of the feedstock is separated in the production process, so the potential for carbon-negative fuels is significant.

7.4.3 Maximise the potential for biomass (co-)firing with CCS

As shown in Chapter 5, the potential for Bio-CCS in co-firing applications is significant. While two-thirds of the projected 2020 potential from bioelectricity production is of a smaller scale and therefore more expensive in terms of CCS application, the remaining third consists of co-firing in large-scale utility boilers.

Large-scale utility boilers are considered the highest potential targets for CCS with fossil fuels in the early CCS commercialisation phase. Co-firing of biomass could realise negative emissions in many of these utilities – with no significant increase in the CAPEX cost of capture (although, as mentioned in Chapter 6, more research is needed to obtain a clearer picture). Co-firing also offers flexibility in terms of

input: it can be undertaken when the biomass price is relatively low, but is not required as part of the process.

To enable cost reductions and the demonstration of Bio-CCS on electricity and CHP installations for both co-firing and dedicated biomass units, dedicated incentives for biomass utilisation are likely to remain necessary in addition to very high EUA prices, unless novel feedstocks help reduce the price of biomass.

While the pulp and paper industry can be a significant emitter of biogenic CO₂ in some geographic areas (namely Finland and Sweden), it is not a significant source of CO₂ on a European level. Based on current understanding, capturing biogenic CO₂ from the pulp and paper industry is also more expensive than CCS for large utility boilers, which are generally considered the baseline for a feasibility comparison. Hence the pulp and paper sector is not expected to be a major contributor to Bio-CCS in the EU as a whole.

7.5 Address issues specific to Bio-CCS deployment

Recommendations for further research include:

- Undertake comprehensive cost assessments and life-cycle analyses (LCAs) of Bio-CCS value chains for the various technology routes
- Up-scale biomass conversion processes for improved economies of scale for CCS deployment
- Assess potentials for biogas co-firing in gas power plants; the potential for hydrogen production
- Determine the effect of the composition of biogenic CO₂ on the CCS value chain in power plants (corrosion, effect on amine/ammonia solvents etc.)
- Identify any specific storage properties for biogenic CO₂, i.e. biogenic impurities in the CO₂ stream
- Study algal (macro/micro) biomass feedstock in terms of fuel properties and CO₂ capture
- Match biomass sources with CO₂ sinks per Member State and/or EU-wide; any specific issues regarding CO₂ clustering and/or shipping (not only for Bio-CCS, but particularly relevant for small-scale CCS).
- Establish an EU Roadmap for Bio-CCS deployment towards 2050.

7.6 Build on public support for Bio-CCS

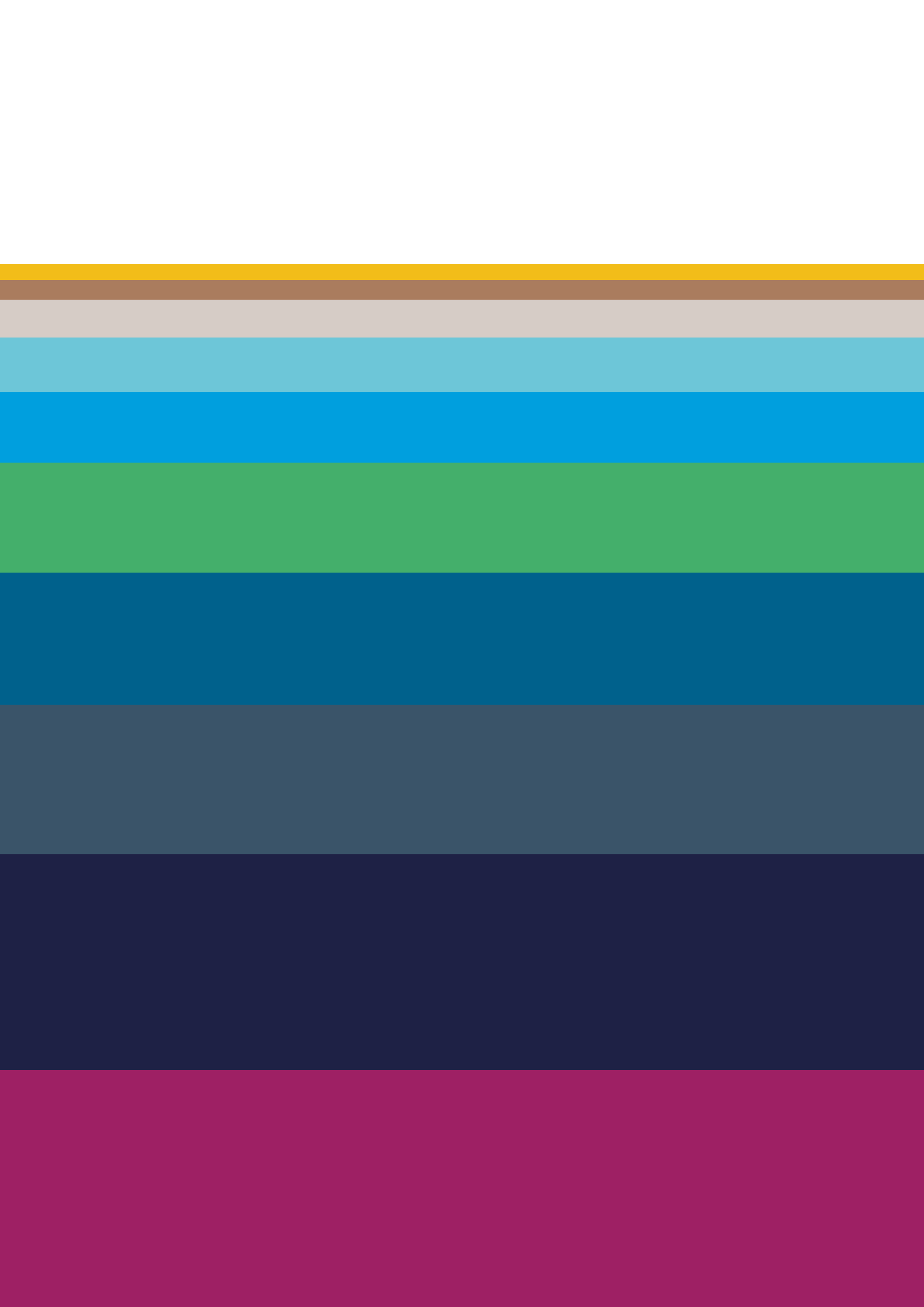
While the issue of public awareness has not been specifically addressed by the Joint Taskforce Bio-CCS, a recent study⁷⁰ indicates that there is a difference in perception and attitude of the general public towards Bio-CCS projects compared to fossil CCS projects – notably a decrease in the so-called NIMBY⁷¹ effect. The Taskforce therefore recommends that further research be undertaken on this important issue.

⁷⁰ Wallquist et al, 2011: www.elsevier.com/locate/jigcc

⁷¹ Not In My Backyard

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