Biomass with carbon capture and storage (BECCS/Bio-CCS)

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Emission scenarios

Net negative emissions are crucial for achieving a 1.5°C target
Integrated assessment models (IAMs)
Representative concentration pathways (RCP) scenarios

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<tr>
<th>Description</th>
<th>IA Model</th>
<th>Publication – IA Model</th>
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<td>RCP8.5 Rising radiative forcing pathway leading to 8.5 W/m² in 2100.</td>
<td>MESSAGE</td>
<td>Riahi et al. (2007)</td>
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<td>Rao &amp; Riahi (2009)</td>
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<td>RCP6 Stabilization without overshoot pathway to 6 W/m² at stabilization after 2100</td>
<td>AIM</td>
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<tr>
<td>RCP4.5 Stabilization without overshoot pathway to 4.5 W/m² at stabilization after 2100</td>
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<td>Wise et al. (2009)</td>
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<td>RCP2.6 Peak in radiative forcing at ~ 3 W/m² before 2100 and decline</td>
<td>IMAGE</td>
<td>van Vuuren et al. (2006, 2007)</td>
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</tbody>
</table>

Note: The diagram shows data and a map for RCP 6.0 CO2 - Industry (combustion and processing) (2100)
Carbon budget

- Carbon budgets usually include fossil sources as well as land use change (LUC)
- Non-CO$_2$ greenhouse gases (GHGs) can contribute up to 33%
- Carbon budget 1750-2500 is ~3670 GtCO$_2$ → already used up half of this until 2009 → only 1800 GtCO$_2$ left (to have a 50% chance of meeting 2°C) (Allen et al. 2009)

Estimation of carbon budgets contains uncertainties
- But: current emissions rate 40 GtCO$_2$/yr → quick erosion of carbon budget
Atmospheric CO$_2$ reduction requirements

Latest CO$_2$ reading
March 05, 2017
Carbon dioxide concentration at Mauna Loa Observatory

406.72 ppm

Reducing atmospheric CO$_2$ concentration by $\frac{1}{2}$ to 1 ppm in one year
→ Need to take out 8-16 GtCO$_2$

MIT, NOAA, MLO, Azar 2010
C balance of energy systems

IEAGHG/Ecofys 2011, adapted from ecofriendlymag.com; grey denotes carbon of fossil origin, blue denotes carbon of biogenic origin)
Past/current energy systems based on the far left (fossil fuels)

Now efforts underway transitioning to the mid three technologies (Fossil-CCS, RE, bioenergy)

Should we stop at Fossil-CCS/RE/bioenergy?

Need help from the far right (NETs) to make up for “damage done” in the past
Carbon capture and storage (CCS)

CCS (carbon capture and storage)

- Process of capturing, transporting and permanently storing CO₂ emission from anthropogenic large-point sources
- Capture
  - Pre-combustion, post-combustion, oxyfuel-combustion
- Transport
  - Pipeline, ship
- Storage
  - Enhanced oil recovery (EOR), depleted oil/gas fields, deep saline aquifers

- All parts of CCS chain technically feasible, issues remain with costs and public perception
- 15 large-scale projects with 29 MtCO₂/yr in operation, 7 with additional 11 MtCO₂/yr under construction (GCCSI 2016)
Carbon capture and storage (CCS)

CO₂ capture processes (Linde AG Linde Engineering Division)
Negative emissions technologies (NETs)

NETs (negative emission technologies)

- **Bio–CCS/BECCS (bioenergy with CCS)** – using biomass that has previously taken up CO\textsubscript{2} during growth to produce power/heat/fuels, then capturing and storing the emitted CO\textsubscript{2}
- **A/R (afforestation/reforestation)** – planting trees where previously (a) there were none or (b) they have been cut down
- **DAC(S) (direct air CCS)** – capturing CO\textsubscript{2} directly from air
- **EW/MC (enhanced weathering/mineral carbonation)** – spreading pulverised rock on land/water to take up CO\textsubscript{2} and form bicarbonate
- **SOCS (soil organic carbon sequestration)** – storing CO\textsubscript{2} in soil through advanced farming methods, restoration and land creation
- **Biochar** – adding burnt/torrefied biomass to soil for long term storage
- **Ocean fertilisation** – adding Fe or N to accelerate CO\textsubscript{2} uptake by microorganisms for photosynthesis
- **Cloud/ocean treatment** – (a) using alkalis to wash CO\textsubscript{2} out of the atmosphere, (b) using lime to absorb CO\textsubscript{2} from the oceans
CO$_2$ reduction potential of negative emissions technologies (NETs)

- **Bio-CCS/ BECCS**: 3.5-20 GtCO$_2$/yr
- **SOCS**: 2.5-4.5 GtCO$_2$/yr
- **A/R**: 4-12 GtCO$_2$/yr
- **DAC(S)**: 3.6-12 GtCO$_2$/yr
- **EW**: 0.7-3.6 GtCO$_2$/yr

Required negative emissions for 1.5°C until 2100:
- ~500-1000 GtCO$_2$
- (6-12 GtCO$_2$/yr, when starting tomorrow!)

Based on Smith et al. 2016
NET trade-offs

- Impact on soil
- Impact on albedo
- Costs
- Energy demand
- Water demand
- Land demand
"Latitude-specific deforestation experiments indicate that afforestation projects in the tropics would be clearly beneficial in mitigating global-scale warming, but would be counterproductive if implemented at high latitudes and would offer only marginal benefits in temperate regions. Although these results question the efficacy of mid- and high-latitude afforestation projects for climate mitigation, forests remain environmentally valuable resources for many reasons unrelated to climate."

Bala 2007
NET trade-offs: albedo

Bonan 2010

Anderegg 2013
Concept of BECCS

Energy crops
High biomass yield
Extensive availability
Biomass residues

Capture compression transport

CO₂

Combustion Fermentation Aerobic digestion Gasification

Fuel upgrading:
gas cleaning, liquefaction

Geological storage
Saline aquifers Depleted oil and gas fields

CO₂

Non-energy byproducts

Heat Biohydrogen Biomethane Synthetic biofuels Electricity

Energy products

Canadell and Schulze. 2014, courtesy of Nature
Concept of different NETs

a. Fossil fuel energy
b. Bioenergy
c. Carbon capture and storage (CCS)
d. Bioenergy + CCS (BECCS)
e. Direct air capture (DAC)
f. Enhanced weathering
g. Afforestation/changed agricultural practices
h. Ocean fertilization/alkalinization

Smith 2015
Global bioenergy use

Biomass produced in a sustainable way, the so-called **modern biomass**, excludes traditional uses of biomass as fuelwood and includes electricity generation and heat production, as well as transportation fuels, from agricultural and forest residues and solid waste. On the other hand, **“traditional biomass”** is produced in an unsustainable way and it is used as a non-commercial source, usually with very low efficiencies for cooking in many countries.

Notes: this figure differentiates total final consumption of heat from traditional use of biomass and from modern bioenergy; the latter is broken down into buildings and industry; Ej = exajoule.

IEA scenarios

The **2°C Scenario (2DS)** is the main focus of Energy Technology Perspectives (ETP). The 2DS lays out an energy system deployment pathway and an emissions trajectory consistent with at least a 50% chance of limiting the average global temperature increase to 2°C. The 2DS limits the total remaining cumulative energy-related CO₂ emissions between 2015 and 2100 to 1,000 GtCO₂. The 2DS reduces CO₂ emissions (including emissions from fuel combustion and process and feedstock emissions in industry) by almost 60% by 2050 (compared with 2013), with carbon emissions being projected to decline after 2050 until carbon neutrality is reached.

The **4°C Scenario (4DS)** takes into account recent pledges by countries to limit emissions and improve energy efficiency, which help limit the long-term temperature increase to 4°C. In many respects the 4DS is already an ambitious scenario, requiring significant changes in policy and technologies. Moreover, capping the long-term temperature increase at 4°C requires significant additional cuts in emissions in the period after 2050.

The **6°C Scenario (6DS)** is largely an extension of current trends. Primary energy demand and CO₂ emissions would grow by about 60% from 2013 to 2050, with about 1,700 GtCO₂ of cumulative emissions. In the absence of efforts to stabilise the atmospheric concentration of GHGs, the average global temperature rise above pre-industrial levels is projected to reach almost 5.5°C in the long term and almost 4°C by the end of this century.
Projected energy demand

Global primary energy demand

Share of fossil fuels in primary energy is in the 2DS with 45% almost halved by 2050 compared to today (81%), biomass becomes the largest energy source in 2050 in the 2DS.
Projected bioelectricity

Source: IEA analysis based on data from the Energy Technology Perspectives (ETP) 2°C Scenario (2DS) (IEA, 2016c).

Note: this example is particularly interesting in that it sets a global target over 8% of electricity generation from bioenergy by 2050 and it provides a breakdown for key world regions, in line with IEA models that integrate the technical and economic characteristics of existing technologies and aspects specific to each market. The underlying approach can be used at national or regional level to determine the cost-effective mix of biomass resource and technologies in the bioenergy roadmap.
BECCS and the IEA 2DS

- Bioenergy provides around 10% and CCS 12% of the cumulative reductions.
- Bio-CCS accounts for 2% of the cumulative reductions.
Almost **1 Gt of CO₂** captured in 2050 is linked to biomass with CCS, corresponding to 16% of total CO₂ captured globally.
Biomass feedstocks

1. Dedicated energy crops
   a. Conventional annual crops
      i. Oil crops *(palm, canola, sunflower, etc.)*
      ii. Sugar/starch crops *(sugar cane, sugar beet, corn, all types of cereals, etc.)*
   b. Perennial crops and energy grasses *(Miscanthus, switchgrass, etc.)*

2. Forestry and forestry residues
   a. Short rotation forestry (SRF) *(alder, ash, Southern Beech, birch, eucalyptus, paper mulberry, Australian Blackwood, sycamore etc.)*
   b. Short rotation coppice (SRC) *(willow, poplar, etc.)*
   c. Forestry residues
      i. Primary *(wood chips from branches/tips/poor quality stemwood etc.)*
      ii. Secondary *(saw mill by-products: chips sawdust, bark etc.)*
      iii. Tertiary *(material from municipal tree management, waste wood etc.)*

3. Other residues and wastes
   a. Agricultural crop residues *(straw from cereals/oil seeds, bagasse etc.)*
   b. Municipal organic waste *(paper/cardboard, food, garden, textiles etc.)*
   c. Sewage sludge
   d. Animal manure
   e. Land fill gas

4. Marine biomass *(microalgae/phytoplankton and macroalgae/seaweed)*
Biomass tree
BECCS – 10 years ago

IPCC’s SRCCS 2005
- Merely described BECCS as “CCS in which feedstock is biomass”
- Acknowledged negative emissions potential if sustainable harvesting
- Cost estimate 22-110 $/tCO₂
- Conclusion: BECCS at small scale and high costs

IPCC’s 4th Assessment Report (AR4) 2007
- Information spread out and not very coherent
- Global bioenergy potential 100-300 EJ/yr (total range 50-1000)
- No numbers for BECCS potential and costs
BECCS – 10 years ago

IEA Bioenergy (set up in 1978)
- Biomass gasification
- Liquid biofuels
- Biomass co-firing
- Biogas production and utilisation
- Availability and sustainability of biomass feedstocks

Only small number of small-scale BECCS projects starting to come online:
- Russel EOR project: first negative emissions delivery at small scale (7.7 ktCO₂) [completed 2005]
- Arkalon: CO₂ from ethanol plant for EOR, 0.1-0.3 MtCO₂/yr [operating since 2009]
BECCS – now

EBTP/ZEP BECCS Joint Task Force 2011

IPCC’s Special Report on Renewable Energy (SRREN) 2011
- First time bioenergy got dedicated chapter

Lots of organisations working on bioenergy (e.g. in UK: SUPERGEN, ETI, E4Tech)

IEAGHG reports on BECCS potential and accounting

IPCC’s 5th Assessment Report (AR5) 2014
- Relies on SRREN for biomass related discussion
- Highlights BECCS as one of the few technologies to remove historic CO₂ emissions from the atmosphere
- Considers competing land use and impacts of sourcing biomass (dedicated appendix)
- Update: “agreement” on 100 EJ/yr bioenergy potential
- Global BECCS potential: 10 GtCO₂/yr (total range 0-20)
- No info on levelised cost of electricity (LCOEL of BECCS, citing other reviews’ ballpark range of 60-250 $/tCO₂
- In general: downward revision of potentials and upward revision of costs
- Overall impact of LUC remains unclear
- Biomass options with low life-cycle emissions already exist (e.g. miscanthus, SRCs, SRF, sugarcane, residues)
BECCS – brief status summary

Many studies conclude: BECCS, incl. its CCS components, technically feasible as of today (TRL 3-7) [except microalgal biomass]

Perceived „double benefit“: heat/power + negative emissions

5 operating BECCS projects 0.1-1 MtCO₂/yr (all EtOH, 3 for EOR, 4 in US, 1 rather BECCU), several more underway

GHG accounting: only 2006 IPCC GLs, CDM/JI, Ca LCFS and EU RED/FQD cover BECCS

Plenty of research on public perception of CCS but very limited and contradictory on BECCS
  - BECCS generally has lower profile than Fossil-CCS

Main drivers/barriers for BECCS:
  - CO₂/NG price, infrastructure/clusters, sustainable feedstocks, public perception
The technical potential (TP) was determined by the net energy conversion efficiency (including the energy penalty) and the carbon removal efficiency of the BECCS route.

The realisable potential (RP) adds limitations to the technical potential by including energy demand, capital stock turnover and possible deployment rate.

The economic potential (EP) further considers the costs of biomass resources, biomass conversion and CCS for selected BECCS routes.
Negative emissions potential for BECCS

- TP up to 10 GtCO$_2$eq/yr, significant cp. to IEA scenarios
- EP up to 3.5 GtCO$_2$eq/yr (~1/3 of TP)
- IGCC, BIGCC and FT biodiesel most promising
- CO$_2$ price 50 €/t
- Co-firing shares 30% in 2030, 50% in 2050
- Numbers not additive, assessment route-by-route

IEAGHG/Ecofys 2011
Negative emissions potential for biomethane BECCS routes

- TP up to 3.5 GtCO\textsubscript{2}eq/yr, smaller than previous routes
- Significant potential only for gasification & AD (EC & AR)
- EP up to 0.4 GtCO\textsubscript{2}eq/yr, only fraction of TP
- Gasification & AD (MSW & S/M) most promising
- Only economically viable at natural gas prices over 11 €/GJ and CO\textsubscript{2} prices of at least 20 €/t (except AD MSW & S/M @ 6.7 €/GJ)

IEAGHG/Ecofys 2013

EC & AR = energy crops & agricultural residues
MSW = biogenic municipal solid waste
S/M = animal manure / sewage sludge
Overview BECCS projects

Status of Bio-CCS projects:
- Green: Completed
- Yellow: Operational
- Blue: Planned / under evaluation
- Red: Cancelled

# Overview BECCS projects

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<th>Project name</th>
<th>Location</th>
<th>Status</th>
<th>CO₂ capacity MtCO₂/yr</th>
<th>CO₂ source</th>
<th>CO₂ sink</th>
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<tr>
<td>IL-ICCS project (expected to continue operation in Q2 2017)</td>
<td>Decatur, IL, USA</td>
<td>Second phase to continue operation in early 2017, awaiting permits</td>
<td>1.0</td>
<td>Archer Daniels Midland ethanol plant, other</td>
<td>Mount Simon sandstone</td>
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<tr>
<td>Arkalon</td>
<td>Liberal, KS, USA</td>
<td>Operating since 2009</td>
<td>0.18-0.29</td>
<td>Conestoga’s Aralon ethanol plant</td>
<td>EOR, Booker and Farnsworth oil fields, TX</td>
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<tr>
<td>Bonanza</td>
<td>Garden City, KS, USA</td>
<td>Operating since 2011</td>
<td>0.10-0.15</td>
<td>Conestoga’s Bonanza BioEnergy ethanol plant</td>
<td>EOR, Stuart oil field, KS</td>
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<tr>
<td>RCI/OCAP/ROAD</td>
<td>Rotterdam, NL</td>
<td>Operating since 2011</td>
<td>0.1 (Abengoa) 0.3 (Shell)</td>
<td>Shell’s Pernis refinery, Abengoa’s ethanol plant, Maasvlakte power plant, various other</td>
<td>Nearby greenhouses, TAQA’s P18-4 gas reservoir after 2015</td>
</tr>
<tr>
<td>Husky Energy</td>
<td>Lloydminster, SK, CA</td>
<td>Operating since 2012</td>
<td>0.09-0.1</td>
<td>Ethanol plant</td>
<td>EOR, Lashburn and Tangleflags oil fields</td>
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<td>Saga City</td>
<td>Saga City, Saga, JP</td>
<td>Operating since 2016</td>
<td>0.004</td>
<td>Waste-to-energy plant</td>
<td>Crop and algae cultivation</td>
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<tr>
<td><strong>Planned projects / projects under evaluation</strong></td>
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<tr>
<td>Klemetsrud</td>
<td>Oslo, NO</td>
<td>Planned start in</td>
<td>0.3</td>
<td>Waste-to-energy plant, 50-60% biomass</td>
<td>Smeaheia, North Sea</td>
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<td>Norcem</td>
<td>Brevik, NO</td>
<td>Planned start in</td>
<td>0.4</td>
<td>Cement plant, &gt;30% biomass</td>
<td>Smeaheia, North Sea</td>
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<td>AVR Duiven</td>
<td>Duiven, NL</td>
<td>Planned start in 2018</td>
<td>0.05</td>
<td>Waste-to-energy plant, 54% biomass</td>
<td>Nearby greenhouses</td>
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<td>Mikawa power plant</td>
<td>Omuta, Fukuoka, JP</td>
<td>Planned start in 2020, pilot-scale CO₂ capture since 2009</td>
<td>0.18</td>
<td>Mikawa power plant (coal and/or biomass)</td>
<td>?</td>
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<td>C.GEN North Killingholme Power Project</td>
<td>North Killingholme, UK</td>
<td>Evaluating, planned start in 2019, now likely cancelled</td>
<td>2.5</td>
<td>Biomass co-fired IGCC power plant</td>
<td>Southern North Sea</td>
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<td>Södra</td>
<td>Vårö, SE</td>
<td>Identifying and evaluating</td>
<td>0.8</td>
<td>Pulp and paper mill</td>
<td>Skagerrak, North Sea</td>
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# Overview BECCS projects (ctd.)

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<tr>
<th>Project name</th>
<th>Location</th>
<th>Status</th>
<th>CO₂ capacity MtCO₂/yr</th>
<th>CO₂ source</th>
<th>CO₂ sink</th>
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<tbody>
<tr>
<td>Domsjö Fabriker</td>
<td>Domsjö, SE</td>
<td>Identifying and evaluating</td>
<td>0.26</td>
<td>Black liquor gasification pulp mill</td>
<td>Saline aquifer, North or Baltic Sea</td>
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<td>Lantmännens Agroetanol</td>
<td>Norrköping, SE</td>
<td>Identifying and evaluating</td>
<td>0.17</td>
<td>Ethanol plant</td>
<td>Saline aquifer, North Sea</td>
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<td>CPER Artenay project</td>
<td>Artenay and Toury, FR</td>
<td>Identifying and evaluating</td>
<td>0.045-0.2</td>
<td>Tereos ethanol plant</td>
<td>Dogger and Keuper saline aquifers, Paris Basin,</td>
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<td>Sao Paulo</td>
<td>Sao Paulo state, BR</td>
<td>Identifying and evaluating</td>
<td>0.02</td>
<td>Ethanol plant</td>
<td>Saline aquifer</td>
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<tr>
<td>Biorecro/EERC</td>
<td>ND, USA</td>
<td>Identifying and evaluating</td>
<td>0.001-0.005</td>
<td>Gasification plant</td>
<td>Saline aquifer</td>
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<td>Skåne</td>
<td>Skåne, SE</td>
<td>Identifying and evaluating</td>
<td>0.0005-0.005</td>
<td>Biogas plant</td>
<td>Saline aquifer</td>
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<tr>
<td><strong>Completed projects</strong></td>
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<tr>
<td>Russel EOR research project</td>
<td>Russel, KS, USA</td>
<td>Completed 2005</td>
<td>0.004 (0.007 in total)</td>
<td>Ethanol plant</td>
<td>EOR, Hall-Gurny-Field</td>
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<tr>
<td>Norcem</td>
<td>Brevik, NO</td>
<td>Testing 2014-2016, CO₂ capture only</td>
<td>Small-scale</td>
<td>Cement plant, &gt;30% biomass-fuelled</td>
<td>N/A</td>
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<td>IBDP</td>
<td>Decatur, IL, USA</td>
<td>First phase completed in 2014, now monitoring</td>
<td>0.3 (1.0 in total)</td>
<td>Archer Daniels Midland ethanol plant</td>
<td>Mount Simon sandstone</td>
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<tr>
<td><strong>Cancelled projects</strong></td>
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<tr>
<td>White Rose CCS Project</td>
<td>Selby, UK</td>
<td>Planned start in 2019</td>
<td>2.0</td>
<td>Drax power station, biomass (co)-firing</td>
<td>Bunter sandstone</td>
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<td>Rufiji cluster</td>
<td>TZ</td>
<td>Cancelled</td>
<td>5.0-7.0</td>
<td>Sekab’s ethanol plants</td>
<td>Saline aquifer</td>
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<td>Greenville</td>
<td>Greenville, OH, USA</td>
<td>Cancelled in 2009</td>
<td>1.0</td>
<td>Ethanol plant</td>
<td>Saline aquifer, Mount Simon sandstone</td>
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<tr>
<td>Wallula</td>
<td>Wallula, WA, USA</td>
<td>Cancelled</td>
<td>0.75</td>
<td>Boise Inc’s pulp mill</td>
<td>Saline aquifer</td>
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<tr>
<td>CO₂ Sink</td>
<td>Ketzin, DE</td>
<td>Cancelled</td>
<td>0.08</td>
<td></td>
<td>Saline aquifer</td>
</tr>
</tbody>
</table>

Illinois Industrial CCS Project

• IBDP (Illinois Basin Decatur Project)
  ▪ CO₂ source: ADM’s corn EtOH plant (350 Mgal/yr)
  ▪ Captured ~ 0.3 MtCO₂/yr over more than 3 years (total 1.0 MtCO₂ achieved in Nov 2014)
  ▪ Stored in Mount Simon sandstone
  ▪ 3-year post-injection monitoring

• IL-ICCS (Illinois Industrial CCS Project)
  ▪ Will capture 1.0 MtCO₂/yr over 3 years
  ▪ Expected to be operational later in 2017
  ▪ Close the gap to Fossil-CCS demo scale
  ▪ Biggest hurdle: permits and regulations
  ▪ Credits off-set operational costs

McDonald 2016, Archer Daniels Midland, openclipart.org
OCAP

- Rotterdam, NL
- 0.1 MtCO₂/yr from Abengoa ethanol plant
- CO₂ utilisation in nearby greenhouses
- Operating since 2011
- Part of wider cluster development under RCI, which plans to store total of 2.5 MtCO₂/yr in the North Sea, including a “BECCS ready” power plant
BECC(U)S: Waste-to-energy

**ARV Duiven**
- Duiven, The Netherlands
- Aim: capture 50,000 tCO₂/yr
- 70 MWth
- 126 GWhₑ
- 54% biomass
- Flue gas: 10% CO₂ (dry)
- Capture rate 78%
- MEA solvent
- CO₂ used for horticulture

**Klemetsrud Plant AS**
- Oslo, Norway
- Aim: capture 300,000 tCO₂/yr
- 55 MWth
- 175 GWhₑ / 10 MMₑ
- 50-60% biomass
- Flue gas: 10% CO₂
- Capture rate: 90%
- Aker Solutions’ amine process
- Pilot capturing 2,000 tCO₂/yr

Koornneef et al. 2016, AVR, Aker Solutions
Case study: BECCS in UK

- BECCS essential for power sector
- Forest biomass from USA/CA will be key
- Uncertainty about Bio-CCS’ role in transport
- Excl. biomass/BECCS, could cost the UK ~£44 billion (ETI 2015)
Case study: BECCS in UK

ETI 2015
## Technology readiness level (TRL)

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<tr>
<th>Stage</th>
<th>TRL</th>
<th>Description</th>
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<tbody>
<tr>
<td>Research</td>
<td>9</td>
<td>Normal commercial service</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>Commercial demonstration, full scale deployment in final form</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>Sub-scale demonstration, fully functional prototype</td>
</tr>
<tr>
<td>Development</td>
<td>6</td>
<td>Fully integrated pilot tested in a relevant environment</td>
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<tr>
<td></td>
<td>5</td>
<td>Sub-system validation in a relevant environment</td>
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<tr>
<td></td>
<td>4</td>
<td>System validation in a laboratory environment</td>
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<tr>
<td>Research</td>
<td>3</td>
<td>Proof-of-concept test, component level</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Formulation of the application</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>Basic principles, observed initial concept</td>
</tr>
</tbody>
</table>

**Note:**
- TRL is not necessarily an indication of the amount of time and effort required to achieve commercialisation.
- TRL 9 does not necessarily represent the be-all and end-all.
Cost and TRL of BECCS

McLaren 2012
## Accounting frameworks

<table>
<thead>
<tr>
<th>Scheme</th>
<th>CCS</th>
<th>Biomass growth/ harvesting/ combustion/ processing</th>
<th>dLUC/iLUC</th>
<th>Life cycle emissions</th>
<th>Negative emissions</th>
</tr>
</thead>
<tbody>
<tr>
<td>2006 IPCC GLs</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
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</tr>
<tr>
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<td>✔</td>
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<tr>
<td>EU RED/FQD</td>
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<td>✔</td>
<td>✔</td>
<td>✔</td>
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<td>US GHGRP</td>
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<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>California ETS</td>
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<tr>
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<td>✔</td>
<td>✔</td>
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<tr>
<td>Australia CPM#$</td>
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<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>UNFCCC KP’s CDM/JI</td>
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<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
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</table>

# Note that the Australian Senate repealed the CPM on 17th July 2014, taking effect from 1st July 2014. The repeal has no effect on entities’ reporting obligations under the NGER.
Accounting frameworks

- 2006 IPCC Guidelines for National Greenhouse Gas Inventories (2006 GLs)
- United Nations Framework Convention on Climate Change (UNFCCC) Kyoto Protocol’s (KP) Clean Development Mechanism (CDM) and Joint Implementation (JI)
- EU Emission Trading System (EU ETS)
- EU Renewable Energy Directive (RED)
- EU Fuel Quality Directive (FQD)
- US Greenhouse Gas Reporting Program (GHGRP)
- Australia National Greenhouse and Energy Reporting Determination (NGER) and Carbon Pricing Mechanism (CPM)
- California Emissions Trading System (California ETS)
- California Low Carbon Fuel Standard (California LCFS)
BECCS public perception

- Research on BECCS public perception limited
- Contradicting results
- Socio-cultural context of stakeholders important
BECCS in nexus context
BECCS in nexus context

Main nexus concerns

- Competition between food and bioenergy crops
- Shift of GHG/CO₂ emissions from one sector to another ("carbon leakage")
- Impact of large-scale biomass infrastructure, trade, and supply chains
- Impact of climate change on crop yields
- Water footprint of BECCS systems
- Effects of increased fertiliser use
- Land availability and lock-in
- Land use change (LUC) impacts
- Biomass sustainability
Life cycle assessment (LCA)

RMA = raw material acquisition  
RMT = raw material transport  
ECF = energy conversion facility  
PT = product transport

Biomass co-firing without CCS

NETL 2012
Life cycle assessment (LCA)

Biomass co-firing without CCS

RMA = raw material acquisition
RMT = raw material transport
ECF = energy conversion facility
PT = product transport

NETL 2012
Life cycle assessment (LCA)

Schakel 2014
Land use change (LUC)

1. **Direct LUC** (dLUC) occurs when additional biomass feedstock demand leads to the cultivation of new areas (see circle A in figure) for biomass production.

2. **Indirect LUC** (iLUC) occurs when existing production areas cover the additional feedstock demand (see B), displacing the previous production function of the land, which can trigger expansion of land to new areas (e.g. to B’ and/or B’”).

Hamelinck 2014, adapted from Dehue 2006
Land use change (LUC)

- Factors include:
  - Labour conditions
  - Protection of areas with high ecological, historical or cultural value
  - Food prices and security
  - Avoidance of direct and indirect land use change (dLUC & iLUC)
  - Water supply and quality
  - Land rights of local communities

- GHG emissions from LUC can be substantial
- Role of “additional biomass”
- Bioenergy crops with low life cycle emissions exist

Hamelinck 2014, adapted from Dehue 2006
Carbon debt

Land use change and carbon stock changes?

"Non-sustainable" bioenergy due to land use change
- Direct land use change
- Indirect land use change (ILUC)

Impact of temporal scale?

How long time CO2 stays in the atmosphere?

23/11/2016

Koponen 2016
Land based GHG emissions

Data Source: Food and Agriculture Organization of the United Nations (FAO)
Example: switchgrass gasification plant with BECCS

- Capturing and storing 1 GtC = 3.67 GtCO₂ could need fixation of up to 2.11 GtC = 7.7 GtCO₂
Resource demand of NETs

~3% of the freshwater currently appropriated for human use

380–700 Mha

138 billion

Water requirement is shown as water droplets, with quantities in km³ per year. All values are for the year 2100 except relative costs, which are for 2050.

Source: Smith et al 2015; Global Carbon Budget 2015
Food vs fuel
Food vs fuel

- Food price
- Biomass price
- Carbon price
- Oil price
- ?
Several contributing aspects:

- Crude oil price
- Natural disasters (e.g. droughts, storms, floods)
- Financial speculation
- Declining stockpiles
- Demand/dietary changes
- Bioenergy
- Trade liberalisation
- Subsidies
- Pest and diseases
- Soil losses
- Decreasing productivity and yields
- Increase in ozone levels

FAO 2017, Chefurka 2014
Current land use

Agricultural land area in 2014 in Mha (FAOSTAT 2016), BECCS min. Land requirement

- 3315 Mha: pasture
- 1585 Mha: crops
- 1205 Mha: energy crops needed, lower end of estimates

Agricultural land area in 2014 in Mha (FAOSTAT 2016), BECCS max. land requirement

- 3315 Mha: pasture
- 1585 Mha: crops
- 990 Mha: energy crops needed, higher end of estimates

Global land area ~13,000 Mha
Marginal lands ~428-1,035 Mha

How to overcome the “lack” of land?
- Demand-side changes
- Yield increases
- Marginal land
Case study: BECCS in NL

- Biomass imports very likely necessary in this case
- Very specific case, results for other countries can be very different

1.9 Mha in use for agriculture in 2010 (Eurostat 2012)

Land area in Mha for 0.3 EJ, 25MtCO2 by 2030 in The Netherlands (Mastop et al. 2014)
Freeing land via diet change

Peters 2016
Freeing land via diet change

<table>
<thead>
<tr>
<th>Group</th>
<th>Description</th>
<th>Name</th>
<th>Symbol</th>
<th>Key attributes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current consumption</td>
<td>Based on USDA estimates of per capita loss-adjusted food availability.</td>
<td>Baseline</td>
<td>BAS</td>
<td>Food intake equals loss-adjusted food availability for individual food commodities.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Positive control</td>
<td>POS</td>
<td>As above, except intake of fats and sweeteners is reduced to make diet energy-balanced.</td>
</tr>
<tr>
<td>Healthy diet, omnivorous</td>
<td>Complies with 2010 Dietary Guidelines for Americans. Includes animal flesh.</td>
<td>100% healthy</td>
<td>OMNI 100</td>
<td>100% of person-meals follow an omnivorous healthy diet pattern.</td>
</tr>
<tr>
<td></td>
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<td>omnivorous</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>80% healthy</td>
<td>OMNI 80</td>
<td>80% of person-meals follow an omnivorous healthy diet pattern and 20% follow a ovo-lacto vegetarian healthy diet pattern.</td>
</tr>
<tr>
<td></td>
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<td>omnivorous</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>60% healthy</td>
<td>OMNI 60</td>
<td>60% of person-meals follow an omnivorous healthy diet pattern and 40% follow a ovo-lacto vegetarian healthy diet pattern.</td>
</tr>
<tr>
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<td>omnivorous</td>
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<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>40% healthy</td>
<td>OMNI 40</td>
<td>40% of person-meals follow an omnivorous healthy diet pattern and 60% follow a ovo-lacto vegetarian healthy diet pattern.</td>
</tr>
<tr>
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<td>omnivorous</td>
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<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>20% healthy</td>
<td>OMNI 20</td>
<td>20% of person-meals follow an omnivorous healthy diet pattern and 80% follow a ovo-lacto vegetarian healthy diet pattern.</td>
</tr>
<tr>
<td></td>
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<td>omnivorous</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Healthy diet, vegetarian</td>
<td>Complies with 2010 Dietary Guidelines for Americans. Excludes animal flesh.</td>
<td>Ovolacto</td>
<td>OVO</td>
<td>Includes both eggs and dairy products.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>vegetarian</td>
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<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lacto vegetarian</td>
<td>LAC</td>
<td>Includes dairy products. Excludes eggs.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Vegan</td>
<td>VEG</td>
<td>Excludes all livestock products.</td>
</tr>
</tbody>
</table>

Peters 2016
Freeing land via diet change

PER MILLION KILOCALORIES CONSUMED

PLANT-BASED

ANIMAL-BASED

LAND USE (ha)
- Pasture
- Cropland

FRESHWATER CONSUMPTION (1,000 m³)
- Renewable
- Irrigation

GHG EMISSIONS (t CO₂)
- Land-use change
- Agricultural production

Sources: GdAgri model (land use and greenhouse gas emissions), authors’ calculations from Meinzen and Hoekstra (2011, 2012) (freshwater consumption), and Waite et al. (2014) (farmed fish freshwater consumption).

WRI 2016
Freeing land by reducing waste

Grown kcals per person and day are ~6000 (Berners-Lee 2016)

- average use per person
- processing/distribution/household waste
- bioenergy
- fed to animals and end up in meat/dairy

- agricultural waste
- post-harvest waste
- fed to animals but wasted due to inefficiency
Freeing land by reducing waste

Part of the initial global production lost or wasted

- Land area associated with food waste = 1,400 Mha

Food waste = 1.3 billion t (> 30% of total)

Footprint of food waste = 3.3 GtCO₂ (excl. LUC emissions)

FAO 2013, HLPE 2014, Wirsenius 2010
Improving yields

- Improve using the non-food part of biomass
- 2nd/3rd generation biomass

Byrt et al. 2016
BECCS – research needs

- More research on some gasification technologies necessary
- Verification for high amounts of co-firing >30% re pre-treatment and boiler modifications
- Bio-CCS scale-up issues
- Overcome uncertainty and lack of standard methodology for estimating bioenergy potentials and costs
- Inclusion of NETs/BECCS in more policies and accounting frameworks
- Clarify circumstances of double benefit (zero-carbon energy + negative emissions permits)
- Approaches to prevent carbon leakage
- Open question/debate: Does BECCS need more support than other NETs/Fossil-CCS?
- Need to explore other financial instruments than the CDM
- More research on impacts of BECCS on global trade and commodity markets

- Address the whole food-water-energy-climate nexus of BECCS, integrated approaches
- Water and carbon intensity of BECCS systems
- Address LUC issues, esp. iLUC (incl. measurement/quantification) and carbon debts
- Opportunities to free land for bioenergy production
- Monitoring systems for land management activities need improvement
- Investigating competition for land, feedstock and storage resources
- Supply chain optimisation for non-forest biomass
- Identify more “sweet spots” for BECCS
- Clarification of BECCS public perception and impact of CCS perception on BECCS, public outreach efforts, building up trust
Conclusions

- Ability of BECCS to deliver negative emissions important to achieve climate mitigation targets
- Majority of research suggests bioenergy potential of ~100 EJ/yr and BECCS potential of ~10 GtCO₂/yr
- Costs of BECCS comparable to Fossil-CCS, in the region of 60 – 250 $/tCO₂
- Several projects underway but lots more needed to build up confidence
- Policy, regulations and financial instruments for BECCS need development
- BECCS deployment will hinge on case-specific details, with sustainable biomass supply likely to be the linchpin
- Nexus-approach required due to complex sustainability issues
BECCS – good or bad thing?

My main conclusions:

- Will be very case-specific
- BECCS no silver bullet or complimentary ticket but deserves our fullest attention as we are running out of time and options
Thank you, any questions?

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