Supplemental Information

Striving towards the deployment of Bio-Energy with Carbon Capture and Storage (BECCS): A Review of Research Priorities and Assessment Needs

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Project name	Location	Status	CO_2 capacity ($MtCO_2$/yr)	CO_2 source	CO_2 sink
Operational Projects					
Operational projects IBDP and IL-ICCS project	Decatur, IL, USA	Operating since 2011, IBDP completed	IBDP: 0.3 (1.0 in total) IL-ICCS: 1.0 (3.6 in total until 2015)	Archer Daniels Midland ethanol plant	Mount Simon sandstone
Arkalon	Liberal, KS, to Booker, TX, USA	Operating since 2009/2010	0.29 (0.105 initially)	Conestoga's Arkalon ethanol plant	EOR, Booker North Upper Marrow Field
Bonanza	Garden City to Stuart Field, KS	Operating since 2011	0.15	Conestoga's Bonanza BioEnergy ethanol plant	EOR, Stuart Field
RCI/OCAP/ROAD	Rotterdam, NL	Operating since 2011	0.1 (Abengoa) 0.3 (Shell) (2.5 planned for 2015)	Shell's Pernis refinery, Abengoa's ethanol plant, Maasvlakte power plant, various other	Nearby greenhouses, TAQA's P18-4 gas reservoir after 2015
Husky Energy	Lloydminster, SK, CA	Operating since 2012	0.1	Ethanol plant	EOR, Lashburn and Tangleflags oil fields
Norcem	Brevik, NO	Testing since 2014, CO_2 capture only	Small-scale	Cement plant, >30% biomass-fuelled	N/A
Planned projects / projects under evaluation White Rose CCS Project	Selby, UK	Planned start in 2019	2.0	Drax power station, biomass(co)-firing	Bunter sandstone
C.GEN North Killingholme Power Project	North Killingholme, UK	Evaluating, planned start in 2019	2.5	Biomass co-fired IGCC power plant	Southern North Sea
Södra	Värö, SE	Identifying and evaluating	0.8	Pulp and paper mill	Skagerrak, North Sea
Domsjö Fabriker	Domsjö, SE	Identifying and evaluating	0.26	Black liquor gasification pulp mill	Saline aquifer, North or Baltic Sea
Lantmännen Agroetanol	Norrköping, SE	Identifying and evaluating	0.17	Ethanol plant	Saline aquifer, North Sea
CPER Artenay project	Artenay and Toury, FR	Identifying and evaluating	0.045–0.2	Tereos ethanol plant	Dogger and Keuper saline aquifers, Paris Basin,
Sao Paulo	Sao Paulo state, BR	Identifying and evaluating	0.02	Ethanol plant	Saline aquifer
Biorecro/EERC	ND, USA	Identifying and evaluating	0.001–0.005	Gasification plant	Saline aquifer
Skåne	Skåne, SE	Identifying and evaluating	0.0005–0.005	Biogas plant	Saline aquifer
Completed projects					
Russel EOR research project	Russel, KS, USA	Completed 2005	0.004 (0.007 in total)	Ethanol plant	EOR, Hall-Gurny-Field
Cancelled projects					
Rufiji cluster	TZ	Cancelled	5.0-7.0	Sekab's ethanol plants	Saline aquifer

Greenville	Greenville, OH, USA	Cancelled in 2009f	1.0	Ethanol plant	Saline aquifer, Mount Simon sandstone
Wallula	Wallula, WA, USA	Cancelled	0.75	Boise Inc's pulp mill	Saline aquifer
CO_2 Sink	Ketzin, DE	Cancelled	0.08		Saline aquifer

Table S1: An overview of BECCS projects (sources: [3, 4, 5])

Study/ Source	Main Assumptions	Main Outputs
Rhodes and Keith, 2005 ([6])	- Burning hydrogen-rich syngas to produce electricity with CCS. - Non-fuel O&M cost: Capacity factor of 0.8. - Electricity cost: Biomass fuel cost and CO_2 sequestration cost of $50 per dry ton and $10 per ton, respectively, as well as amortization of capital costs at 10% interest over 20 years. - Cost of carbon mitigation: Computed relative to pulverized coal power generation with fuel, capital, non-fuel O&M cost and net efficiency of 1.0 $GJ-1, 1.2 $W-1, 8$MWh-1, and 40% (HHV*), respectively; coal and biomass carbon intensities of 24 and 25 kgC-1GJ-1, respectively, with the same amortization and utilization assumptions outlined above. These assumptions yield coal electricity cost of 37 $MWh-1.	**Summary model results** **Biomass-IGCC** *Process performance* Capacity (MWth):444, Net generation (MWe): 149, Net efficiency: 34%, C-capture rate (% input C): 0%, Net emissions (kg C kWh^{-1}): 0. *Economic performance* Capital cost ($$kW^{-1}$): $1,250, Non-fuel O&M cost ($ $kW^{-1}y^{-1}$): $100, Electricity cost (cents kWh^{-1}): 5.9, Cost of carbon mitigation ($ tC^{-1}): $102. **Biomass-IGCC with CCS** *Process performance* *Capacity* (MWth):444, Net generation (MWe): 123, Net efficiency: 28%, C-capture rate (% input C): 44%, Net emissions (kg C kWh^{-1}): -0.14. *Economic performance* *Capital* cost ($$kW^{-1}$): $1,730, Non-fuel O&M cost ($ $kW^{-1}y^{-1}$): $131, Electricity cost (cents kWh^{-1}): 8.2, Cost of carbon mitigation ($ tC^{-1}): $123.
Keith et al., 2006 ([7])		70 USD/tCO_2 captured.
IEAGHG, 2009 ([8])	Co-firing shares 10%. Lower numbers possible when including revenues from emissions trading or green certificates.	**BECCS Cost Estimates** 94 EUR/MWh SC PC-CCS co-firing. 102 EUR/MWh SC CFB-CCS co-firing. 222 EUR/MWh Sub CFB-CCS dedicated. 301 EUR/MWh Sub BFB-CCS dedicated.
Biorecro, 2011 ([3])		**BECCS Cost Estimates** 700-900 SEK/tCO_2 combustion (~75-95 EUR/tCO_2). < 500 SEK/tCO_2 ethanol, black liquor/pulp (< 45 EUR/tCO_2).
Carbo et al., 2011 ([9])	N^{th} BioSNG plant with 500 MWth input (greenfield plant in The Netherlands, 2010) with the following assumptions: • Gasification pressure: 7 bar. • Total Capital Investment (TCI): 1,100 €/kW. • O&M cost: 5% of TCI. • Other fixed cost: 2% of TCI. • Return on Investment: 12%. • Depreciation period: 15 years. • Interest rate: 5%. • Biomass price (dry) 4 €/GJ. • Electricity price: 0.05 €/kWh. • CO_2 emission natural gas combustion: 55.0 kg/GJ.	The techno-economic analysis resulted in a BioSNG price of 13.28 €/GJ (LHV) including CCS. The BioSNG price is governed by the use of imported biomass at 4.0 €/GJ, which is as a conservative price estimate (this translates to 5.69 €/GJ of the BioSNG price). The total capital investment and related charges, O&M and fixed cost, complete most of the remaining cost. The CO_2 avoidance cost was calculated using the current natural gas commodity price of 7.50 €/GJ and an emission of 0.055 tonne CO_2/GJ for natural gas combustion. The supply chain and flue gas CO_2 emissions were deducted (0.016 tonne CO_2/GJ), therefore the cost of CO_2 avoided in comparison with fossil natural gas combustion amount approximately 62 €/tonne CO_2. This is under the assumption that negative CO_2 emissions can be accounted for. The CO_2 avoidance cost roughly double to 120 €/tonne CO_2 if negative CO_2 emissions cannot be accounted for. **Annual Cost (M€/yr)** TCI: 55.15, Biomass: 89.72, Electricity: 10.90, O&M: 28.62, Other fixed cost: 11.45, Total cost: 195.84, Result: 13.54, Revenues: 209.38. **Cost (€/GJ_{SNG})** TCI: 3.50, Biomass: 5.69, Electricity: 0.69, O&M: 1.82, Other fixed cost: 0.73, Total cost: 12.42, Result: 0.86, Revenues: 13.28.
Laude et al., 2011 ([10])	Ethanol plant	**BECCS Cost Estimates** 56-86 EUR/tCO_2 fermentation only. 131-143 EUR/tCO_2 fermentation + cogeneration.

Koornneef et al., 2012 ([11])	This study shows the global potential for combining biomass with CCS technologies (BECCS) up to 2030 and 2050. The assessment includes six bio-CCS routes for the production of power and biofuels in combination with CCS. - Electricity production PC-CCS co-firing: Co-firing share is 30% in 2030 and 50% in 2050, Post-combustion capture. - CFB-CCS dedicated: 100% biomass share, Post-combustion capture. - IGCC-CCS co-firing: Co-firing share is 30% in 2030 and 50% in 2050, Pre-combustion capture. - BIGCC-CCS dedicated: 100% biomass share, Pre-combustion capture. - Biofuel production - Bio-ethanol-advanced generation: 100% biomass share, nearly pure CO_2; only drying and compression. - FT biodiesel: 100% biomass share, Nearly pure CO_2 from pre-combustion; only compression Overall conversion costs are calculated based on a depreciation period of 30 years, a discount rate of 10% and 8000 full load hours per year. All costs are presented in €2010 unless otherwise stated.	- The economic potential for BECCS technologies is up to 20 EJ/yr for bio-electricity routes or up to 26 EJ/yr for the biofuel routes, when assuming a CO_2 price of 50 €/tonne. About one third (up to 3.5 Gt CO_2 eq./yr) of the technical potential can be considered economically attractive when producing bio-electricity; and about half (up to 3.1 Gt CO_2 eq./yr) of the technical potential is attractive in the case of biofuel production. - For the medium to long-term, the route using the BIGCC with CCS has the lowest cost of electricity production when using low cost biomass. - The largest economic potential of about 20 EJ/yr (biomass share) is in the gasification-based routes (IGCC and BIGCC) for the year 2050. The smallest economic potential is in the PC and CFB routes of about 1 EJ/yr for the year 2030. - For the biofuel routes, the economic potential is calculated to be highest for the FT-biodiesel route, at 26 EJ/yr and equivalent to −3.1 Gt CO_2eq./yr. - Estimates for the economic potential are highly sensitive to the CO_2 price, coal price and biomass price.
McGlashan et al., 2012 ([12])	Dedicated 1GW plant in a 0.1 ppm/yr reduction scenario, costs for CCS components may be underestimated due to lack of commercial experience. < 100 USD/tCO_2 possible but highly uncertain.	**BECCS Cost Estimates** 59-111 USD/tCO_2e captured.
McLaren, 2012 based on Biorecro, 2011 ([13])	150 USD/tCO_2 in 2030 possible.	70-250 USD/tCO_2 combustion. 45 USD/tCO_2 ethanol, black liquor/pulp.
IEAGHG, 2011 ([14])	Breakdown figures are 2030/2050. Reference technologies are coal PC-CCS at 4.0/2.5 and coal IGCC-CCS at 3.6/2.3.	**BECCS Cost Estimates** 0.5-8.3 EUR/GJ (capture cost, 2030), 0.4-5.1 EUR/GJ (capture cost, 2050). *Breakdown:* EUR/GJ 4.3/2.7 PC-CCS co-firing, 8.3/5.1 CFB-CCS dedicated, 3.6/2.3 IGCC-CCS co-firing, 4.0/2.5 BIGCC-CCS dedicated, 0.4/0.4 bioethanol, 1.1/1.0 FT biodiesel, 0.5/0.5 gasification, 0.8/0.7 anaerobic digestion EC&AR, 0.8/0.7 anaerobic digestion MSW, 1.1/1.0 anaerobic digestion S/M ~70-110 USD/tCO_2. ~10-90 EUR/tCO_2
Koornneef et al., 2013 ([15])	- Assessment of two BECCS routes for the production of biomethane: gasification and anaerobic digestion. - CO_2 storage costs: 1-13 € per tonne (default value of 5 € per tonne). - Natural gas prices: 6.7-11.4 €/GJ.	The economic potential reaches up to 0.8 Gt of negative GHG emissions when assuming a CO_2 price of 50 €/tonne.

PROSUITE, 2013 ([16])	- CO_2 emissions captured on top of the carbon-neutral bioenergy will receive credits that can be sold at the carbon price.	**Biomass-fired power plants with CCS** **Biomass-IGCC without CCS** Net plant efficiency (%): 42.10, Net output (MW): 629.00, Capacity factor (%): 80, Biomass price (€/GJ LHV): 2.98, Fuel price (€/MMBtu of biomass): 3.17, Total Plant Cost (TPC), (€/kW): 1991.00, Total Overnight Cost (TOC), (€/kW): 2363.56, Total fixed operating costs (annual unit costs),(€/kW-net): 63.38, Total variable operating costs (€/kW-net): 0.01, CO_2 Capture: 0%, CO_2 TS & M Costs (mills €/kWh): 0.00, CO_2 Emissions (Kg/MWh): 0, Operational Period: 30 years, Discount rate (%): 10%. **Biomass-IGCC with CCS** Net plant efficiency (%): 31.20, Net output (MW): 497.00, Capacity factor (%): 80, Biomass price (€/GJ LHV): 2.98, Fuel price (€/MMBtu of biomass): 3.17, Total Plant Cost (TPC), (€/kW): 2814.79, Total Overnight Cost (TOC), (€/kW): 3354.26, Total fixed operating costs (annual unit costs),(€/kW-net): 72.42, Total variable operating costs (€/kW-net): 0.01, CO_2 Capture: 90%, CO_2 TS & M Costs (mills €/kWh): 4.17, CO_2, Emissions (Kg/MWh): -790, Operational Period: 30 years, Discount rate (%): 10%.
Akgul et al., 2014 ([17])	First figure for a reduction in carbon intensity of > 87%, second for carbon negative electricity.	**BECCS Cost Estimates** 30-50 GBP/tCO_2. 120-175 GBP/tCO_2.
Arasto et al., 2014 ([18])	For industrial BECCS depending on the technology in Finland.	**BECCS Cost Estimates** 35-300 EUR/tCO_2 stored.
IPCC, 2014 ([19])		**BECCS Cost Estimates** 60-250 USD/tCO_2.
Moreira and Pires, 2016 ([20])		Storage costs of: - 3 USD/t CO_2 for onshore depleted oil and gas fields, - 7 USD/t CO_2 for offshore depleted oil and gas fields; - 5 USD/t CO_2 for aquifers - 5-10 USD/t CO_2 for coal seams.

Moreira et al., 2016 ([21])	- Case study on a BECCS scheme, where CCS is applied to CO_2 vented from a Brazilian ethanol fermentation installation using ethanol by-products (bagasse and other sugar cane residues). The by-products are used for the production of heat and bioelectricity self-consumption, as well as for third party users through the electric grid. - Figures calculated by authors considering: ethanol w/BECCS consumer price = US$ 0.621/l, financing interest rate = 2%, equity share = 20%, IRR on equity = 6%.	**Impacts on the cost and prices of BECCS and in fuel and electricity due different government policies** **No carbon tax** **Producer cost increase** Overnight BECCS cost (US$/t$CO_2$): 27.2, Real BECCS price (US/tCO_2): 30.293, Bioelectricity (US$/MW h): 1.494, Ethanol (US$/l): 0.021, Bioelectricity (%):5.91%, Ethanol (%): 3.50%. **Consumer price increase** Overnight BECCS cost (US$/t$CO_2$): -, Real BECCS price (US/tCO_2): 47.908, Bioelectricity (US$/MW h): 2.716, Ethanol (US$/l): 0.0334, Bioelectricity (%): 2.00%, Ethanol (%): 3.50%. **Shared Consumer price increase** Overnight BECCS cost (US$/t$CO_2$): -, Real BECCS price (US/tCO_2): 48.908, Bioelectricity (US$/MW h): 0.412, Ethanol (US$/l): 0.0066, Bioelectricity (%):0.30%, Ethanol (%): 0.70%. **With carbon tax @ US$ 10/tCO_2** **Producer cost increase** Overnight BECCS cost (US$/t$CO_2$): -, Real BECCS price (US/tCO_2): 19.93, Bioelectricity (US$/MW h): 19.93, Ethanol (US$/l): 0.0141, Bioelectricity (%): 3.96%, Ethanol (%): 1.48%. **Consumer price increase** Overnight BECCS cost (US$/t$CO_2$): -, Real BECCS price (US/tCO_2): 32.094, Bioelectricity (US$/MW h): 1.819, Ethanol (US$/l): 0.0224, Bioelectricity (%):1.07%, Ethanol (%): 2.35%. **Shared Consumer price increase** Overnight BECCS cost (US$/t$CO_2$): -, Real BECCS price (US/tCO_2): 32.094, Bioelectricity (US$/MW h): 0.276, Ethanol (US$/l): 0.0044, Bioelectricity (%): 0.02%, Ethanol (%): 0.47%. **With tax moratorium** **Consumer price increase** Overnight BECCS cost (US$/t$CO_2$): -, Real BECCS price (US/tCO_2): 34.364, Bioelectricity (US$/MW h): 1.494, Ethanol (US$/l): 0.0246, Bioelectricity (%): 1.10%, Ethanol (%): 2.58%. **Shared Consumer price increase** Overnight BECCS cost (US$/t$CO_2$): -, Real BECCS price (US/tCO_2): 34.364, Bioelectricity (US$/MW h): 0.276, Ethanol (US$/l): 0.0048, Bioelectricity (%): 0.17%, Ethanol (%): 0.50%. The overall cost of capturing and storing CO_2 is US$ 53/tCO_2 and yet the study concludes that applying CCS to sugar fermentation is the less expensive option.

Table S2: Key assumptions and findings from cost assessment studies on BECCS

Study/ Source	Main Assumptions	Main Outputs
Kraxner et al., 2003 ([22])	Average carbon sequestration, BECCS associated with single 'typical' temperate forest. 90% capture rate, scenario based approach to forest management.	Net emissions: 2.5 tC/yr/ha.
Rhodes and Keith, 2005 ([6])	Biomass IGCC 44% capture rate; net efficiency 28%. Biomass IGCC, with Steam reforming 55% capture rate; net efficiency 25%.	Biomass IGCC: Net emissions: -140 gC/KWh. Biomass IGCC, with Steam reforming: Net emissions: -200 gC/KWh.
Corti and Lombardi, 2004 ([23])	Technology: BIGCC Biomass type: Poplar Biomass ratio (%): 100 Co-firing ratio (%):100 Capacity (MW): 205 Capture technology: Upstream Chemical Absorption Environmental themes covered: GHG	Life cycle CO_2 emissions (g/kW h): 70-130. Net life cycle CO_2 emissions (g/kW h): -410.
Spath and Mann, 2004 ([24])	Technology: BIGCC and Co-firing Biomass type: Urban Waste-Energy crops Biomass ratio (%):100% and 0–15 Co-firing ratio (%):15 Capacity (MW): 600 Capture technology: Post combustion with MEA Environmental themes covered: GHG	Life cycle CO_2 emissions (g/kW h): 270. Net life cycle CO_2 emissions (g/kW h): 43.
Carpentieri et al., 2005 ([25])	Technology: BIGCC Biomass type: Poplar Biomass ratio (%): 100 Co-firing ratio (%):100 Capacity (MW): 191 Capture technology: Upstream Chemical Absorption Environmental themes covered: ALL	Life cycle CO_2 emissions (g/kW h): 227. Net life cycle CO_2 emissions (g/kW h): -594.
IEAGHG, 2009 ([8])	- CFB boiler, biomass only: Net plant efficiency: 33.8% (LHV*) 90% capture rate. - CFB, 10% biomass co-fired: Net plant efficiency: 25.8% (LHV*) 90% capture rate *LHV – lower heat value (heat gained) from combustion, excluding energy released in water vapor.	- CFB boiler, biomass only: Net emissions: -1573 gCO_2 eq/KWh. - CFB, 10% biomass co-fired: Net emissions: -32 gCO_2 eq /KWh.
Laude et al., 2011 ([10])	Investigated potential carbon and energy footprints for BECCS from ethanol production in the CPER Artenay project.	BECCS from fermentation only would reduce the carbon footprint by 60% and BECCS from fermentation and cogeneration could decrease the carbon footprint by 115%, i.e. produce negative emissions.

Cuellar, 2012 ([26])	Technology: Coal co-firing plant Biomass type: Farmed trees, switch grass, forest residue Biomass ratio (%):0–100 Co-firing ratio (%): 20 Capacity (MW): 75-200 Capture technology: Post combustion with MEA Environmental themes covered: GHG.	Life cycle CO_2 emissions (g/kW h): Not reported. Net life cycle CO_2 emissions (g/kW h): -129.5.
Koornneef et al., 2012 ([11])	This study shows the global potential for combining biomass with CCS technologies (BECCS) up to 2030 and 2050. The assessment includes six bio-CCS routes for the production of power and biofuels in combination with CCS. - Electricity production PC-CCS co-firing: Co-firing share is 30% in 2030 and 50% in 2050, Post-combustion capture. - CFB-CCS dedicated: 100% biomass share, Post-combustion capture - IGCC-CCS co-firing: Co-firing share is 30% in 2030 and 50% in 2050, Pre-combustion capture. - BIGCC-CCS dedicated: 100% biomass share, Pre-combustion capture. - Biofuel production - Bio-ethanol-advanced generation: 100% biomass share, nearly pure CO_2; only drying and compression. - FT biodiesel: 100% biomass share, Nearly pure CO_2 from pre-combustion; only compression.	- The global technical potential for BECCS technologies is large and, if deployed, can result in negative greenhouse gas emissions. The economic potential for BECCS technologies is up to 20 EJ/yr for bio-electricity routes or up to 26 EJ/yr for the biofuel routes, when assuming a CO_2 price of 50 €/tonne. About one third (up to 3.5 Gt CO_2 eq./yr) of the technical potential can be considered economically attractive when producing bio-electricity; and about half (up to 3.1 Gt CO_2 eq./yr) of the technical potential is attractive in the case of biofuel production. - The amount of sustainable biomass that can be harvested and supplied greatly determines the potential for BECCS technologies. - Up to 59 EJ/yr of bio-electricity, or 47 EJ/yr of biofuels can be produced when deploying the full technical potential. - The amount of CO_2 stored by conversion routes ranges between 0.7 and 20.9 Gt CO_2/yr. - Negative emissions up to 10.4 Gt CO_2 eq./yr are the highest for the dedicated routes with CCS: BIGCC and CFB. The negative emissions for the biofuel routes with CCS are the lowest, ranging between 0.5 and 5.8 Gt CO_2 eq./yr.
NETL (vol.1), 2012 ([27])	Technology: IGCC Biomass type: Switch grass Biomass ratio (%):0–100 Co-firing ratio (%): 30 (weight) Capacity (MW): 451–654 Capture technology: Post combustion with MEA and Oxyfuel Environmental themes covered: GHG	Life cycle CO_2 emissions (g/kW h): Not reported. Net life cycle CO_2 emissions (g/kW h): -6 to -105.
Koornneef et al., 2013 ([15])	- Assessment of two BECCS routes for the production of biomethane: gasification and anaerobic digestion.	Negative greenhouse gas emissions (GHG) up to 3.5 Gt CO_2-eq. on an annual basis in 2050. Including avoided emissions by replacing natural gas, the annual greenhouse gas emission savings could add up to almost 8 Gt of CO_2-eq in 2050.
Volkart et al., 2013 ([28])	Evaluating three types of wood power plants without/with CO_2 capture to examine if combustion or gasification of wood from sustainable forestry is "CO_2-neutral".	All the three types of wood power plants were found to have very low life-cycle GHG emissions without CO_2 capture and negative life-cycle GHG emissions with CO_2 capture. Conclusions: - Combustion or gasification of wood from sustainable forestry is "CO_2-neutral", i.e. using only the natural growth and keeping the carbon stock in the forest at a constant level. - The carbon in the biogenic CO_2 emissions from wood combustion or gasification was taken up by the trees during their growth and is therefore permanently removed from the atmosphere by CCS.

Arasto et al., 2014 ([18])	The emission reduction potential in different technologies is very much bound to the scale of installations which again is generally limited by the scale of technologies and availability of biomass raw material.	The biggest reduction potential for the studied cases per industrial site: - iron and steel industry (~3 Mt/a), -pulp and paper industry (~1.3 Mt/a) -combined heat power (CHP) production (~2.5 Mt/a) - straw ethanol production of smaller scale (~0.1 Mt/a). The CO_2 avoidance potential per unit of biomass raw material utilized is highest in co-firing (20 tCO_2/toe), iron and steel industry (10 tCO_2/toe) and in CHP production (8 tCO_2/toe). Straw ethanol has lowest potential (1.5 tCO_2/toe). The cost estimations show a theoretical economic advantage of BECCS over fossil CCS on carbon prices when the carbon sink effect is accounted for. The total costs for BECCS vary from 35€/ton to 300€/ton CO_2 stored depending on the technology.
Schakel et al., 2014 ([29])	Technology: PC, IGCC. Biomass type: Wood pellets/straw pellets (residues) Biomass ratio (%):0–100 Co-firing ratio (%): 30 Capacity (MW): 550 Capture technology: pre-combustion CO_2 capture Environmental themes covered: ALL	Life cycle CO_2 emissions (g/kW h): 281-291, 253-262. Net life cycle CO_2 emissions (g/kW h): -67 to -72, -81 to -85.

Table S3: Key assumptions and findings from LCA literature studies on BECCS

References

[1] BELLONA, "The Carbon-Negative Solution: Incentivizing BIO-CCS in Europe," The Bellona Foundation, Oslo, Norway, 2015.

[2] ZEP and EBTP, "Biomass with CO2 Capture and Storage (Bio-CCS). The Way Forward for Europe," Zero Emissions Platform and European Biofuels Technology Platform, 2012.

[3] Biorecro, "Global Status of BECCS Projects 2010," Global Carbon Capture and Storage Institute and Biorecro team, 2011.

[4] J. Kemper, "Biomass and carbon dioxide capture and storage: A review," *International Journal of Greenhouse Gas Control,* vol. 40, p. 401–430, 2015.

[5] J. L. Milne and C. B. Field, "Assessment Report from the GCEP Workshop on Energy Supply with Negative," Stanford University. Global Climate and Energy Project, https://gcep.stanford.edu/pdfs/rfpp/Report%20from%20GCEP%20Workshop%20on%20Energy%20Supply%20with%20Negative%20Emissions.pdf. Accessed 4 March 2017, 2012.

[6] J. S. Rhodes and D. W. Keith, "Engineering economic analysis of biomass IGCC with carbon capture and storage," *Biomass and Bioenergy,* vol. 29, no. 6, p. 440–450, 2005.

[7] D. W. Keith, M. Ha-Duong and J. K. Stolaroff, "Climate Strategy with CO2 Capture from the Air," *Climatic Change,* vol. 74, no. 1-3, p. 17–45, 2006.

[8] IEAGHG, "Biomass CCS Study, 2009/9," IEA Greenhouse Gas R&D Programme, November 2009, 2009.

[9] M. C. Carbo, R. Smit, B. van der Drift and D. Jansen, "Bio energy with CCS (BECCS): Large potential for BioSNG at low CO2 avoidance cost," *Energy Procedia,* vol. 4, p. 2950–2954, 2011.

[10] A. Laude, O. Ricci, G. Bureau, J. Royer-Adnot and A. Fabbri, "CO2 capture and storage from a bioethanol plant: Carbon and energy footprint and economic assessment," *International Journal of Greenhouse Gas Control,* vol. 5, no. 5, p. 1220–1231, 2011.

[11] J. Koornneef, P. van Breevoort, C. Hamelinck, C. Hendriks, M. Hoogwijk, K. Koop, M. Koper, T. Dixon and A. Camps, "Global potential for biomass and carbon dioxide capture, transport and storage up to 2050," *International Journal of Greenhouse Gas Control,* vol. 11, p. 117–132, 2012.

[12] N. McGlashan, N. Shah, B. Caldecott and M. Workman, "High-level techno-economic assessment of negative emissions technologies," *Process Safety and Environmental Protection,* vol. 90, pp. 501-510, 2012.

[13] D. McLaren, "A comparative global assessment of potential negative emissions technologies," *Process Safety and Environmental Protection,* vol. 90, pp. 489-500, 2012.

[14] IEAGHG, "Potential for Biomass and Carbon Dioxide Capture and Storage," Report 2011/06. IEA Greenhouse Gas R&D Programme, Cheltenham, UK, 2011.

[15] J. Koornneef, P. van Breevoort, P. Noothout, C. Hendriks and .. Luning, uchien and Camps, "Global potential for Biomethane production with carbon capture, transport and storage up to 2050," *Energy Procedia,* vol. 37, p. 6043–6052, 2013.

[16] PROSUITE, "Final Deliverable W6, D6.4: Coal power plants with carbon capture and storage - A sustainability assessment," PROSUITE project, Development and application of a standardized methodology for the PROspective SUstaInability assessment of Technologies, 2013.

[17] O. Akgul, N. Mac Dowell, L. G. Papageorgiou and N. Shah, "A mixed integer nonlinear programming (MINLP) supply chain optimization framework for carbon negative electricity generation using biomass to energy with CCS (BECCS) in the UK," *International Journal of Greenhouse Gas Control,* vol. 28, pp. 189-202, 2014.

[18] A. Arasto, K. Onarheim, E. Tsupari and J. Kärki, "Bio-CCS: Feasibility comparison of large scale carbon-negative solutions," *Energy Procedia,* vol. 63, p. 6756–6769, 2014b.

[19] IPCC, "Intergovernmental Panel on Climate Change.Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change," [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2014.

[20] D. Moreira and J. M. Pires, "Atmospheric CO2 capture by algae: Negative carbon dioxide emission path," *Bioresource Technology,* vol. 215, p. 371–379, 2016.

[21] J. R. Moreira, V. Romeiro, S. Fuss, F. Kraxner and S. A. Pacca, "BECCS potential in Brazil: Achieving negative emissions in ethanol and electricity production based on sugar cane bagasse and other residues," *Applied Energy,* vol. 179, p. 55–63, 2016.

[22] F. Kraxner, S. Nilsson and M. Obersteiner, "Negative emissions from BioEnergy use, carbon capture and sequestration (BECS)-the case of biomass production by sustainable forest management from semi-natural temperate forests," *Biomass and Bio-energy,* vol. 24, pp. 285-296, 2003.

[23] A. Corti and L. Lombardi, "End life tyres: Alternative final disposal processes compared by LCA," *Energy,* vol. 29, no. 12–15, pp. 2089-2108, 2004.

[24] P. L. Spath and M. K. Mann, "Biomass Power and Conventional Fossil Systems with and without CO2 Sequestration – Comparing the Energy Balance, Greenhouse Gas Emissions and Economics," NREL/TP-510-32575 , U.S. Department of Energy Laboratory, Colorado, U.S.A., 2014.

[25] M. Carpentieri, A. Corti and L. Lombardi, "Life cycle assessment (LCA) of an integrated biomass gasification combined cycle (IBGCC) with CO2 removal," *Energy Conversion and Management,* vol. 46, no. 11-12, p. 1790–1808, 2005.

[26] A. D. Cuellar, "Plant Power: The cost of using biomass for power generation and potential for decreased greenhouse gas emissions," Technology and Policy Program, Engineering Systems Division, Massachusetts Institute of Technology, 2012.

[27] NETL, "Greenhouse Gas Reductions in the Power Industry Using Domestic Coal and Biomass (IGCC)," National Energy Technology Laboratory, Vol. 1, No. DOE/NETL-2012/1546, 2012.

[28] K. Volkart, C. Bauer and C. Boulet, "Life cycle assessment of carbon capture and storage in power generation and industry in Europe," *International Journal of Greenhouse Gas Control,* vol. 16, p. 91–106, 2013.

[29] W. Schakel, H. Meerman, A. Talaei, A. Ramírez and A. Faaij, "Comparative life cycle assessment of biomass co-firing plants with carbon capture and storage," *Applied Energy,* vol. 131, p. 441–467, 2014.