GLOBAL CCS INSTITUTE

2019 PERSPECTIVE

BIOENERGY AND CARBON CAPTURE AND STORAGE

CHRISTOPHER CONSOLI
Senior Consultant – Storage

Key messages

- BECCS requires the wide-scale deployment of CCS
- Historically BECCS deployment has been slow; there are few operating facilities
- Major BECCS technologies are mature; their potential is substantial
- The availability of land, water and fertiliser to supply biomass is the major constraint on BECCS
- Most climate change scenarios use negative emissions technologies to draw CO_2 from the atmosphere; of these, BECCS is the best option
- The scale of BECCS deployment reaches gigatonnes of CO_2 stored per year to meet global warming targets set for the end of the century

3.3 gigatonne stored per year

BECCS CO_2 emission reduction target in 2100

5 facilities operating

BECCS facilities
- **Captures 1.5 Mtpa CO_2**
- **One large-scale facility**
- **Bioethanol dominates**

300 – 700 million hectares

Land use needed to meet CO_2 emission reduction target

\$15 - \$400 per tonne CO_2 avoided

Cost of BECCS
- **Varies widely, depends on sector**
- **Bioethanol cheapest**

2x

Increase compared to current annual water use for agriculture to meet BECCS targets in 2100

CCS

Key technology to enable BECCS and CO_2 removal targets

Negative emissions technologies will be needed to meet targets; BECCS is the best option

After almost thirty years of climate change negotiations, global CO_2 levels are still rising (NOAA, 2018). The UNFCCC Paris Agreement goals of holding global warming to ‘well-below’ 2°C and to ‘pursue efforts’ to limit it to 1.5°C are in stark contrast to the ever-dwindling carbon budget.

The evidence makes it clear. CO_2 needs to be removed from the atmosphere, known as carbon dioxide removal (CDR)[1], using negative emissions technologies (NETs) to meet global warming targets. Bioenergy with carbon capture and storage (BECCS) is emerging as the best solution to decarbonise emission-intensive industries and sectors and enable negative emissions (Figure 1).

BECCS is a group of different technologies to produce energy from biomass and store the CO_2

BECCS is part of the broader CCS technology group. Bioenergy has been used since the dawn of time by humans to produce heat. Today, bioenergy is used to fuel vehicles through bioethanol and provide electricity by burning biomass.

CCS has been working safely and effectively since 1972 to capture CO_2 from a wide range of industries and sectors. Today, there are 18 large-scale facilities in operation, five under construction and 20 in various stages of development. CCS is becoming the conduit for a new energy economy and enabling the decarbonisation of industry – including BECCS.

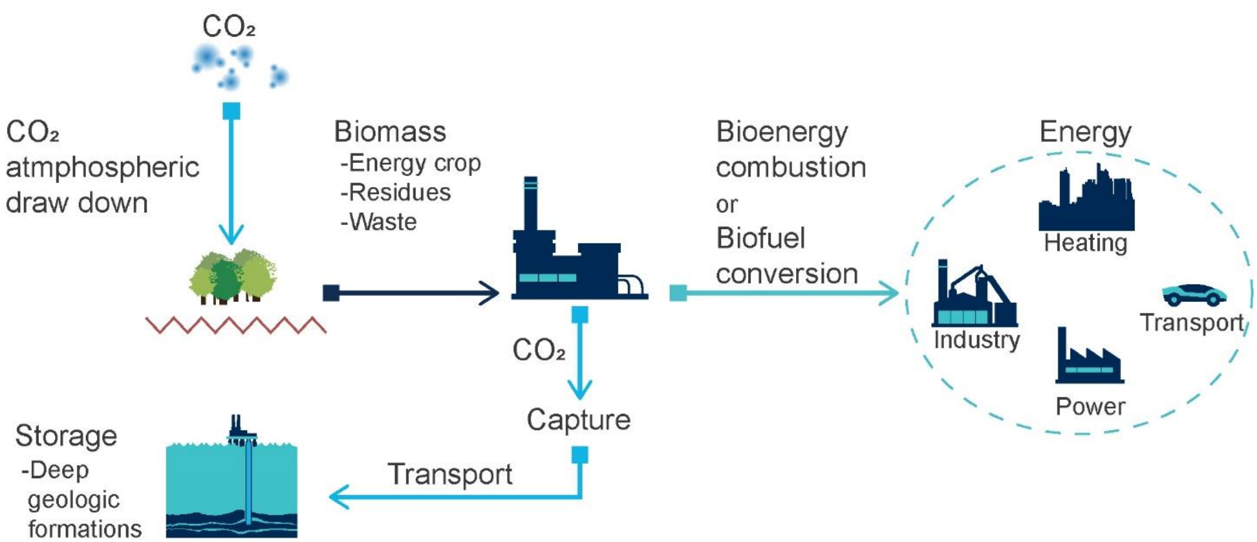

Figure 1: Bioenergy and carbon capture and storage (BECCS) schematic

[1] CDR technologies include afforestation, reforestation, ocean fertilisation, DACS, and BECCS

BECCS involves the utilisation of biomass as an energy source and the capture and permanent storage of CO_2 produced during the conversion of biomass to energy. There is no singular definition of "BECCS" since it can include a variety of industries, biomass feedstocks and methods of energy conversion. The final use of the biomass also varies widely.

What is clear is that CCS is integral to the process, which includes:

1. Biomass feedstock draws down CO_2 from the atmosphere through photosynthesis as the plants grow.
    - Biomass feedstock is derived from a residual product (e.g. sugar cane waste) or dedicated energy crops (e.g. fast-growing tree species like willows trees) planted purely as a feedstock
    - Today biomass feedstock supply is dominated by forest management schemes and agriculture
    - Algae cultivation and municipal organic solid waste is being tested
2. Biomass is then transported to the end-user or a conversion facility.
3. Biomass is combusted or is converted to biofuel using digestion/ fermentation processes. CO_2 is produced during combustion or conversion.
4. CO_2 is then captured and stored.
5. Negative emissions are possible if the CO_2 stored is greater than the CO_2 emitted during biomass production, transport, conversation and utilisation.

BECCS is applied in two overarching methods according to the utilisation of the biomass – combustion and conversion. Combustion directly uses biomass as a fuel source to produce heat for use in electricity generation or industrial applications including cement, pulp and paper making, waste incineration, steel and iron, and petrochemical to highlight a few. The CO_2 is captured from the flue gas stream produced during combustion.

The second method involves the conversion of biomass through either digestion or fermentation to produce gaseous or liquid fuels, respectively. The most common fuel is bioethanol which produces a near-pure stream of CO_2 during the fermentation process. The CO_2 is then compressed and stored, omitting the need for capture. The subsequent combustion of the biofuel or gas also produces CO_2 which, if not stored, results in overall lower emissions reduction.

Historically BECCS deployment has been slow; there are few operating facilities

Currently, five facilities around the world are actively using BECCS technologies (Figure 2; Appendix 1). Collectively, these facilities are capturing approximately 1.5 million tonnes per year (Mtpa) of CO_2.

The only large-scale[2] BECCS facility is the Illinois Industrial CCS facility that captures up to 1 Mtpa of CO_2. Owned by Archer Daniels Midland, this facility produces ethanol from corn at its Decatur plant, producing CO_2 as part of the fermentation process. The CO_2 is stored in a dedicated geological storage site deep underneath the facility.

The remaining four BECCS facilities operating today are small-scale ethanol production plants, using most of the CO_2 for enhanced oil recovery (EOR); including:

1. Kansas Arkalon (USA): 200,000 tpa of CO_2 is compressed and piped from an ethanol plant in Kansas to Booker and Farnsworth Oil Units in Texas for EOR.
2. Bonanza CCS (USA): 100,000 tpa of CO_2 is compressed and piped from an ethanol plant in Kansas to nearby Stewart Oil field for EOR.
3. Husky Energy CO_2 Injection (Canada): 250 tonnes per day (tpd) of CO_2 is compressed and trucked from an ethanol plant in Saskatchewan to nearby Lashburn and Tangleflags oil fields for EOR; the fields are shallow (~500m) and comprise heavy oil.
4. Farnsworth (USA): Over 600,000 tonnes of CO_2 was compressed from an ethanol plant (Kansas) and fertiliser plant (Texas) and piped to Farnsworth oil field for EOR. Injection has now ceased as part of DOE/NETL SouthWest Partnerships Development Phase but currently monitoring the injected CO_2 at an ongoing EOR operation.

Three additional projects are planning on BECCS:

1. Mikawa Power Plant (Japan): The retrofit of a 49-megawatt unit power plant in Omuta (Fukuoka Prefecture) to accept 100 per cent biomass with a CO_2 capture facility. The focus is now identifying a secure offshore storage site.
2. Drax Power Plant (UK): Biomass power generation pilot in North Yorkshire with the potential to develop CO_2 capture and storage
3. Norwegian Full-Chain CCS (Norway): BECCS integration into waste-to-energy and a cement plants:

    - Klemetsrud waste-to-energy plant: Plans to capture 400,000 tpa of CO_2.
    - Norcem Cement plant: Currently co-fires up to 30 per cent biomass and plans to capture up to 400,000 tpa of CO_2.
    - Both plants will send their CO_2 to a multi-user storage site in the Norwegian North Sea.

Several notable bioenergy facilities utilise the CO_2 for crop cultivation (greenhouses). (See Appendix 1 for details).

[2] The Global CCS Institute definition of large-scale is capturing and storing greater than 400,000 tpa CO_2 for industrial facilities; 800,000 tpa CO_2 for power generation.

Figure 2. Bioenergy and carbon capture and storage facilities worldwide (Global CCS Institute, 2019)

Major BECCS technologies are mature; the potential is substantial

The individual technologies to utilise biomass to produce energy or fuel, as well as the capture, transport and storage of CO_2, are all mature and active in commercial facilities around the world (Table 1).

There is enormous potential for BECCS. The largest (in terms of energy production) and most commercially-attractive BECCS application is the production of bioethanol and CCS. The technology is already mature. In 2017, around 68 Mtoe[3] of biomass-derived biofuels were produced; two-thirds were ethanol (IEA, 2018). The USA produces over half of the world's biofuels, but there are opportunities around the world, including developing nations across South America, Sub-Saharan Africa and South East Asia. An increase in biofuel use in the transport sector could initiate a reduction in CO_2 emissions in a traditionally difficult sector to decarbonise.

For global power generation, biomass supplies about 52 Gigawatts (GW) (CSLF, 2018). Just those 52 GW today could result in significant CO_2 reduction if the CO_2 is capture and stored. The Drax Power plant in Yorkshire, UK, completed a conversion of three 660 megawatts (MW) units to use biomass (Global CCS Institute, 2019). As stated previously, they are undertaking a pilot capture facility also.

Perhaps one of the largest BECCS applications is waste-to-energy (WtE). Burning municipal solid waste (another form of biomass) to generate heat and electricity and capturing and storing the CO_2 will result in negative emissions[4]. The technology behind capturing the CO_2 in the flue gas of a WtE plant is similar to CO_2 capture on fossil fuel plants. The numbers from the Carbon Sequestration Leadership Forum (CSLF) are staggering:

- Per cent of waste burnt for energy: Japan, 70 per cent; Norway, 53 per cent; UK, 26 per cent; USA, 13 per cent
- Number of WtE facilities per country/region: EU, 455; China, 223; USA, 74

In addition to those three specific industries, BECCS could be applied to industries that require significant heat and electricity during production. For example, biomass currently supplies six per cent of total thermal energy for cement production globally. As discussed, there is currently one planned BECCS facility on cement in Norway. However, the global pledge from cement producers is a reduction of 20-25 per cent of emissions by 2030; equivalent to 1 Gt compared to business as usual (CSLF, 2018). CCS is the only option to decarbonise for the cement industry (de Pee et al., 2018); applying BECCS could help the cement industry to meet that pledge.

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[3] Mtoe, million tonnes of oil equivalent is a unit of energy, representing the amount of energy released by burning one tonne of crude oil.
[4] The net negative emissions and energy generated by burning waste depends on ratio of biogenic to non-biogenic waste and varies from site to site.

Table 1.Technical Readiness Level (TRL) range or final level reached of the fundamental parts of bioenergy and carbon capture and storage (After: CSLF (2018); NAS (2018)

FEEDSTOCK	TRL
Lignocellulose (Forestry and Wood)	Large-scale Pilot *to* Full-Commercial
Agricultural residues	Large-scale Pilot *to* Full Commercial
Sugars/starch crops	Proof-of-concept Reached *to* Full Commercial
Organic waste	Full Commercial
Algae	Pre-commercial Demonstration
Oil crops/waste	Proof-of-concept Reached *to* Full Commercial

PROCESS	TRL
Combustion	Full Commercial
Gasification	Basic Concept *to* First-of-Kind Commercial
Fermentation	Prototype Pilot *to* Full Commercial
Anaerobic digestion	Full Commercial
Extraction	Pre-commercial Demonstration *to* Full Commercial
Densification	Full Commercial
Pyrolysis	Large-scale Pilot *to* Full Commercial

PRODUCT	TRL
Steam/Heat	Full Commercial
Ethanol	Full Commercial
Biodiesel	Full Commercial
Liquid hydrocarbon	Concept Validation *to* Pre-commercial Demonstration
Methane	Full Commercial
Vegetable oil	Full Commercial
Pellets	Full Commercial
Biochar/Charcoal	Full Commercial

The costs of BECCS

The cost of implementing BECCS technology varies widely. A review of the entire literature on BECCS by Fuss et al. (2018) found a cost range between US$15-400 per tonne of CO_2 avoided depending on the sector (Table 2).

Table 2. Cost of CCS applied to different sectors (After Fuss et al. (2018); NAS (2018)

BECCS	Sector	CO_2 avoided cost (US$/t$CO_2$)
	Combustion	88-288
	Ethanol	20- 175
	Pulp and paper mills	20-70
	Biomass gasification	30-76

Most climate change scenarios use BECCS to meet targets at gigatonne scale

Climate change integrated assessment models (IAMs)[5] have a firm reliance on CDR because the models assume CDR deployment in the future is lower cost than reducing current emissions (Anderson & Peters, 2016). This assumption means deploying BECCS in the future, even at a gigatonne industrial-scale is still cheaper than reducing emissions today. BECCS is the most widely used CDR technology from around 2030 till 2100 because the technology:

- Enables negative emissions
- Produces bioenergy to offset or replace current fossil fuel-derived sources

The most widely used average for BECCS contribution in the literature is 3.3 gigatonne per annum (Gtpa) CO_2 in 2100 derived from the IPCC's last full Climate Change Assessment Report in 2014 (Smith et al., 2015).

However, the dwindling carbon budget creates ever-increasing reliance on negative emissions to meet climate change targets; especially for the target that limits global warming to 1.5^{o}C as detailed in the IPCC SR15 report. The SR15 report identifies the cumulative BECCS contribution of between 0 and 1191 GtCO_2, depending on the scenario pathway. Those pathways remove between 0-8 Gtpa CO_2 in 2030 through BECCS. In 2100, the upper range of the 1.5^{o}C scenarios is 16 Gtpa of CO_2. Figure 3 shows the growing role of BECCS throughout this century across the various scenarios of the IPCC and the IEA.

The wide variation in BECCS contribution to climate change scenarios is due to the different scenarios. In general terms, scenarios that assume more aggressive reductions in demand for energy and emissions-intensive products (e.g. chemicals, cement, steel) require fewer NETs and less BECCS. Alternatively, scenarios that more closely resemble current trends with comparable patterns of energy use and demand for emissions-intensive products require more NETs and therefore more BECCS (Allen et al., 2018).

What is clear is that by the end of the century, BECCS needs to be deployed at a gigatonne of CO_2 per year scale (Figure 3).

[5] IAMs are computer models that integrate physical and social-economic factors related to climate change based on assumptions, historical data and scenario designs to assess various outcomes of policy, technology and climate impacts.

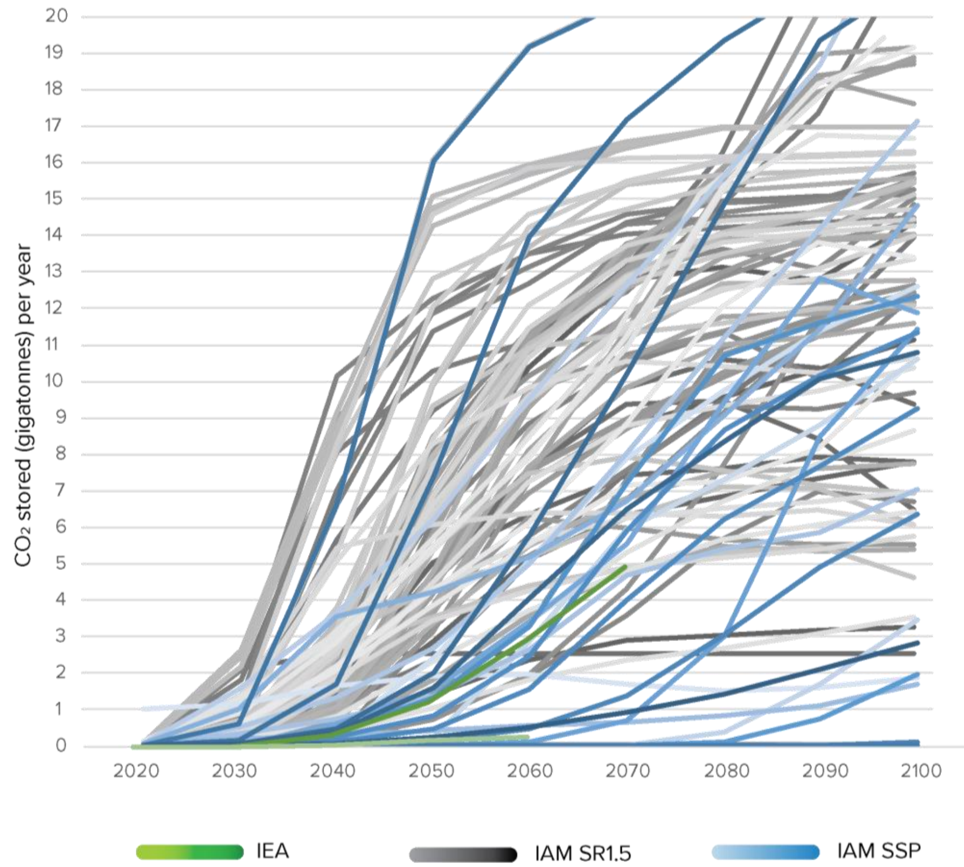

Figure 3. Total CO_2 stored from bioenergy and carbon capture and storage in climate change models according to recent data (Data from Huppmann et al. (2018) and IEA (2018). The Shared Socioeconomic Pathways (SSP) are a series of socio-economic pathways that guide future development in the integrated assessment models (See IIASA (2018) for more information on SSP)

Biomass supply is a constraint on BECCS

Integrated assessment models used to develop climate change scenarios generally assume that constraints on biomass production, such as the availability of land, water and fertiliser, do not prevent sufficient biomass supply.

A review of the literature identifies that the limiting factor of BECCS is not technology; it is the supply of biomass.

NAS (2018) found that in negative emissions scenarios using BECCS, every gigatonne of CO_2 stored per year requires approximately 30-40 million hectares of BECCS feedstock (NAS, 2018). According to the CSLF (2018) this equates to approximately 300-700 million hectares of

land devoted to bioenergy crops[6]. The CSLF estimated that using only dedicated bioenergy crops (an efficient method to produce bioenergy) may require up to one-third of arable land around the world (CSLF, 2018).

[6] Land requirement based on BECCS contribution of 3.3 Gtpa CO_2 stored according to Smith et al. (2015).

To put those numbers into perspective, according to Anderson and Peters (2016) an area one to two times the size of India is required to meet the BECCS targets based on published IAMs (Anderson & Peters, 2016).

In terms of specific increases in biomass, meeting the upper bounds of the BECCS targets, according to Fajardy and Mac Dowell (2017) equals:

- Three times the world's total cereal production
- Twice the annual world use of water for agriculture
- Twenty times the annual use of nutrients

Meeting the BECCS targets requires a fundamental revolution of the production of food and energy crops. However, modelling according to Fajardy and Mac Dowell (2017) indicates that BECCS can be sustainable when targeting the correct energy crops and best land-use practices.

BECCS requires the wide-scale deployment of CCS

There is no doubt that negative emission technologies, mainly BECCS, are critical to climate stabilisation. There is however significant uncertainty about the scale of that contribution. Especially if the technology is expected to meet gigatonne per year CO_2 storage scale. The most notable constraint is the supply of sustainable biomass.

The potential, future deployment of BECCS should not be considered as an alternative to achieving critical, cross-sector emissions reductions today. BECCS should be seen as an essential complement to the required, wide-scale deployment of CCS to meet climate change targets.

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APPENDIX 1

	Name	Capture Source	Location	Scale	Status	Operation Year	Capacity Max (tpa)	Industry
Large Scale BECCS Facilities								
1	Illinois Industrial Carbon Capture and Storage	ADM corn-to-ethanol plant	Decatur, Illinois, US	Large	Operating	2017	1,000,000	Ethanol Production
				Demonstration and Pilot	Completed	2011-2014	300,000	
2	Norway Full Chain CCS	Brevik (Norcem AS), Herøya (Yara Norge AS), Klemetsrud (Klemetsrudanlegget AS)	Norway	Large scale	Advanced development	2023-2024	800,000	Cement Production (>30% biomass), Waste-to-energy (50-60 biomass)
				CO_2 Capture Test Facility at Norcem Brevik Cement, Pilot	Completed	2013	Variable	
3	Occidental/White Energy	Hereford Plant and Plainview Bioenergy	Texas, United States	In evaluation	In evaluation	TBC	600,000 - 700,000	Ethanol Production
Demonstration and Pilot Scale BECCS Facilities								
4	Russel CO_2 injection plant	ICM ethanol plant	Russel, Kansas, United States	Demonstration and Pilot	Completed	2003-2005	7,700 tonnes (total)	Ethanol Production
5	Arkalon CO_2 Compression Facility	Arkalon Energy ethanol plant	Liberal, Kansas, US	Demonstration and Pilot	Operational	2009	290,000	Ethanol Production
6	Bonanza BioEnergy CCUS EOR	Bonanza BioEnergy ethanol plant	Garden City, Kansas, US	Demonstration and Pilot	Operational	2012	100,000	Ethanol Production
7	Husky Energy Lashburn and Tangleflags CO_2 Injection in Heavy Oil Reservoirs Project	Lloydminster ethanol plant	Lloydminster, Saskatchewan, Canada	Demonstration and Pilot	Operational	2012	90,000	Ethanol Production
8	Mikawa Post Combustion Capture Demonstration Plant	Sigma Power Ariake Co. Ltd.'s Mikawa thermal power plant	Omuta City, Fukuoka Prefecture, Japan	Demonstration	Development Planning	2020	180,000	Power generation (coal and biomass)
				Pilot	Completed	2009	3,000	
9	Drax bioenergy carbon capture storage (BECCS) project	North Yorkshire power station	North Yorkshire, England	Pilot	Development Planning	2018	330	Power generation (coal and biomass)
10	CPER Artenay project	Artenay Sugar Refinery in the Loiret	Artenay, Orleans, France	Demonstration and Pilot	Development Planning	TBC	45,000	Ethanol Production
11	Biorecro/EERC project	Biomass gasification plant	North Dakota, USA	Demonstration and Pilot	Development Planning	TBC	1,000 - 5,000	Biomass Gasification
Notable BECCS Facilities								
12	OCAP	Abengoa's ethanol plant	Rotterdam, Netherland	Utilisation	Operational	2011	400,000 (100,000 from ethanol production)	Ethanol Production and Oil Refinery
13	Lantmännen Agroetanol purification facility	Lantmännen Agroetanol plant	Norrköping, Sweden	Utilisation	Operational	2015	200,000	Ethanol Production
14	Calgren Renewable Fuels CO_2 recovery plant	Calgren Renewable Fuels ethanol plant	California, US	Utilisation	Operational	2015	150,000	Ethanol Production
15	Alco Bio Fuel (ABF) bio-refinery CO_2 recovery plant	Alco Bio Fuel (ABF) bio-refinery	Ghent, Belgium	Utilisation	Operational	2016	100,000	Ethanol Production
16	Cargill wheat processing CO_2 purification plant	Cargill wheat processing plant	Trafford Park, Manchester, UK	Utilisation	Operational	2016	100,000	Ethanol Production
17	Saga City Waste Incineration Plant	Saga municipal waste incineration plant	Saga City, Saga Prefecture, Japan	Utilisation	Operational	2016	3,000	Waste-to-Energy
18	Saint-Felicien Pulp Mill and Greenhouse Carbon Capture Project	Resolute softwood kraft pulp mill	Quebec, Canada	Utilisation	Development Planning	2018	11,000	Pulp and papers

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AMERICAS

Washington DC, United States

americasoffice@globalccsinstitute.com

EUROPE & MIDDLE EAST

Brussels, Belgium

europeoffice@globalccsinstitute.com

AUSTRALIA

Melbourne, Australia

info@globalccsinstitute.com

UNITED KINGDOM

London, United Kingdom

ukoffice@globalccsinstitute.com

CHINA

Beijing, China

chinaoffice@globalccsinstitute.com

JAPAN

Tokyo, Japan

japanoffice@globalccsinstitute.com