Biogas with CCS

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Introduction

Bio-SNG (Bio-Synthetic Natural Gas) is natural gas that is produced by gasifying wood-based biomass such as forest residue including tree tops, branches, stumps, small diameter trees from forest thinnings and decayed logs. Bio-SNG can be transmitted, distributed and utilized with the existing natural gas infrastructure (Figure 1). It is assumed that there is enough raw material for at least three large scale bio-refineries producing 4-5 TWh of bio-SNG in Finland (Vision Hunters, 2010). This is above ten percent of current natural gas use, which was 35 TWh in 2012. The Finnish Ministry of Employment and the Economy (2013) approved The National Energy and Climate Strategy in March 2013 and set a target of replacing 10 % of natural gas use with bio-SNG by the year 2025.

Bio-SNG production process includes a compulsory process step where CO_2 is separated from the syngas. This compulsory process step makes implementing CCS on a biorefinery producing Bio-SNG a very interesting option. This study examines the feasibility of implementing CCS on a bio-SNG plant, its costs and potential.

Bio-CCS is recognized as one of the few technologies that can result in negative emissions (IEAGHG, 2011). However, current European Union Emissions Trading Scheme (ETS) doesn't recognize negative CO_2 emissions.

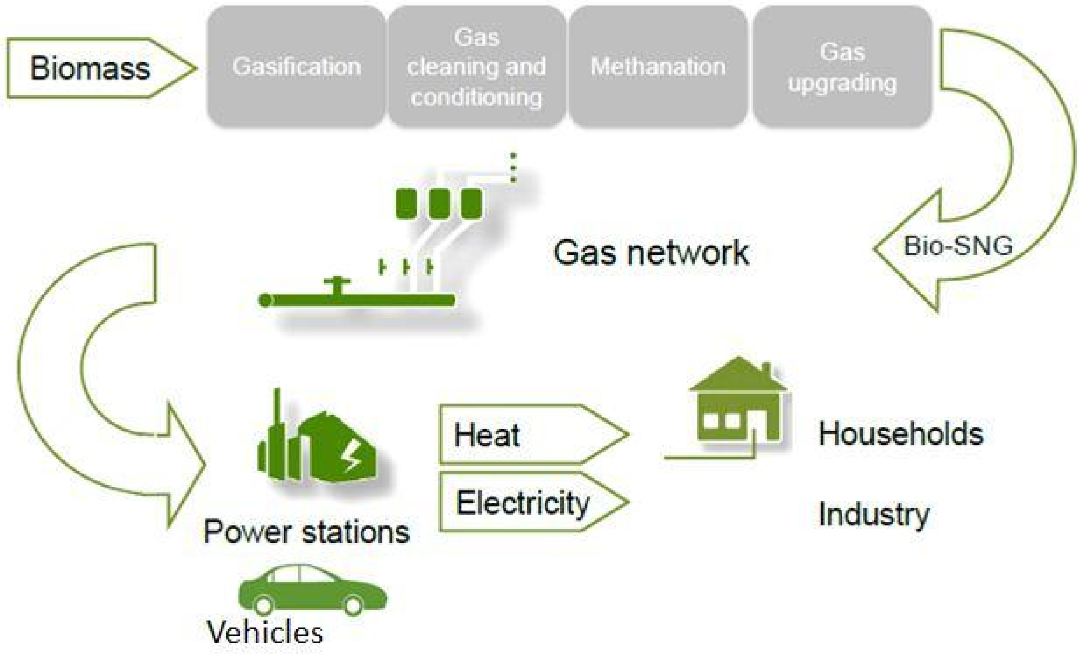

Figure 1. Bio-SNG production chain.

Research question

How much from the CO_2 that is emitted in the Bio-SNG production process can be captured and stored? What are the costs of Bio-CCS implemented on a biorefinery producing bio-SNG?

This study examines an imaginary biorefinery that is located in Southern Finland about 100 km from the shoreline. The biorefinery produces annually 1600 GWh of Bio-SNG. Niskanen (2012) built a model for calculation of greenhouse gas emissions and energy efficiency of Bio-SNG production chain. The same model was expanded in this study to cover CCS.

Literature review

Bio-CCS

Bio-CCS is the only large-scale technology that can actually remove CO_2 from the atmosphere. Certain biofuels production routes could provide "low-hanging fruits" for early low cost CCS development. Globally Bio-CCS could remove 10 billion tons of CO_2 from the atmosphere every year by 2050 and respectively 800 million tons per year in Europe. (ZEP, 2011) Global CO_2 emissions were 30.5 billion tons in year 2010 (OECD, 2013). Bio-CCS potential is therefore massive.

Critic against Bio-CCS

Smolker & Ernsting (2012) wrote a very critical article about (Bio)-CCS. They have several noteworthy opinions:

- There are high levels of uncertainty about the possibility of securely storing carbon underground and potential risks to human health and ecosystems associated with CCS;
- There is faulty reasoning about the availability of plentiful biomass feedstocks, and the "neutrality" of biomass carbon emissions based on assumed regrowth and re-sequestration: Large-scale bioenergy without CCS is already creating an enormous new demand for biomass – a root cause of deforestation, biodiversity loss, human rights violations and escalating carbon emissions;
- Carbon capture requires a lot of additional energy, resulting in significantly more fuel demand to produce the same energy output. Large-scale bioenergy with CCS would thus further increase the demand for biomass and worsen impacts.

Even Intergovernmental Panel on Climate Change (IPCC) approves that injection of CO2 into oil reservoirs for enhanced oil recovery (EOR) is a form of CCS. This idea is absurd because it leads to production and burning of fossil fuels which would otherwise have remained underground. (Smolker & Ernsting, 2012)

Smolker & Ernsting (2012) also raise the question about the carbon neutrality of biomass. They state that "various studies have shown that, once direct and indirect land use change related changes in carbon stocks are taken into account, large-scale bioenergy including biomass combustion and other processes generally result in even more greenhouse gas emissions that the fossil fuels they are intended to replace." The European Environment Agency's Scientific Committee (2011) also raised the question about indirect land use changes. This is very important because the quantities of wood that are needed for large-scale bioenergy utilization are so huge that they simply cannot be met with wastes and residues. Additional logging is necessary.

Smolker & Ernsting (2012) also bring out the fact that the scale necessary to have any impact on climate would necessitate massive CCS infrastructure. They quote Valclav Slim: "Sequestering a mere 1/10 of today's global CO_2 emissions (less than 3 Gt CO_2) would thus call for putting in place an industry that would have to force underground every year the volume of compressed gas larger than or (with higher compression) equal to the volume of crude oil extracted globally by petroleum industry whose infrastructures and capacities have been put in place over a century of development."

Large scale in biorefinery projects in Finland

There were plans for building three large scale BtL-plants in Finland: VAPO Ajos BtL, UPM Rauma BtL and NSE Biofuels. All three applied for NER300 funding, but only Ajos BtL -plant was awarded. Ajos BtL –plant has option to capture 620 000 t(CO2)/a and when the CO2 that is emitted in, compression, liquefaction and shipping are subtracted is the net CO2 reduction roughly 570 000 t/a (=0.57 Mt/a). Therefore the "net CO2 reduction efficiency" is roughly 92 %. On the other hand in newer version of the Ajos BtL environmental impact statement the CO_2 stream is 900 000 t/a of which 80 % can be liquefied and transported for storage (WSP, 2012). This is about 720 000 t(CO2)/a.

Anaerobic biomethane production with CCS

Biogas resulting from anaerobic digestion is typically upgraded to vehicle grade biomethane with one of the following methods: adsorption (Pressure Swing Adsorption (PSA), absorption (chemical (amines), physical (Rectisol), water scrubbing), permeation (membranes) or cryogenic upgrading. These technologies, however, won't be discussed here in detail. Most technologies produce quite pure CO2 stream, but for instance with pressurized water scrubbing the off-gas comprises a lot of nitrogen because stripping of CO2 from the water is done with air. At least one company (Pentair Haffmans) offers biogas upgrading process that produces food grade carbon dioxide in addition to biomethane. CO2 can be produced in liquid form also. (Pentair Haffmans, 2013)

Cryogenic upgrading produces also liquid CO2 stream. Liquid CO2 stream comprises of CO2 >99.2 vol-% and methane <0.8 vol-% (de Pater, 2008). Normally liquid CO2 stream is utilized as an internal refrigerant fluid, but it could also be used utilized for instance as a feedstock for plants in greenhouses or cooling in storage facilities. Other uses, however, mean that refrigeration in the upgrading process has to be done with some other method, which most likely uses electricity.

Carbon dioxide emissions from selected Finnish biogas upgrading plants are presented in Table 1. It can be seen that in small scale plants the CO2 amount is very small compared to bio-SNG plant. EBTB & ZEP (2012) note that relatively small CO2 stream and seasonal feedstock variability are challenges for the economic feasibility of CCS implementation on a biomethane plant.

Table 1 Approximate CO2 exhaust streams from selected Finnish biomethane plants. Only the two first are already in operation. Data is preliminary and isn't based on actual measurements.

	Mäkikylä	Suomenoja	Kujala	Kouvola II wet digestion	Kouvola II dry digestion	Bio-SNG
Biogas production [GWh]	8	24	50	90	90	1600
CO2 amount [t/a]	1370	2490	5730	14740	14100	452270

Bio-SNG with Bio-CCS in the literature

Carbo et al. (2010) estimated that Bio-SNG with CCS will be more economic than without CSS when CO2 price is higher than approximately 25 EUR/ton CO2. When CO2 price increases to approximately 60 EUR/t, the Bio-SNG with CCS process is cheaper than natural gas (Figure 2). Their system comprises of indirect gasifier and oil-based tar scrubber, which are very different from the equipment of this study.

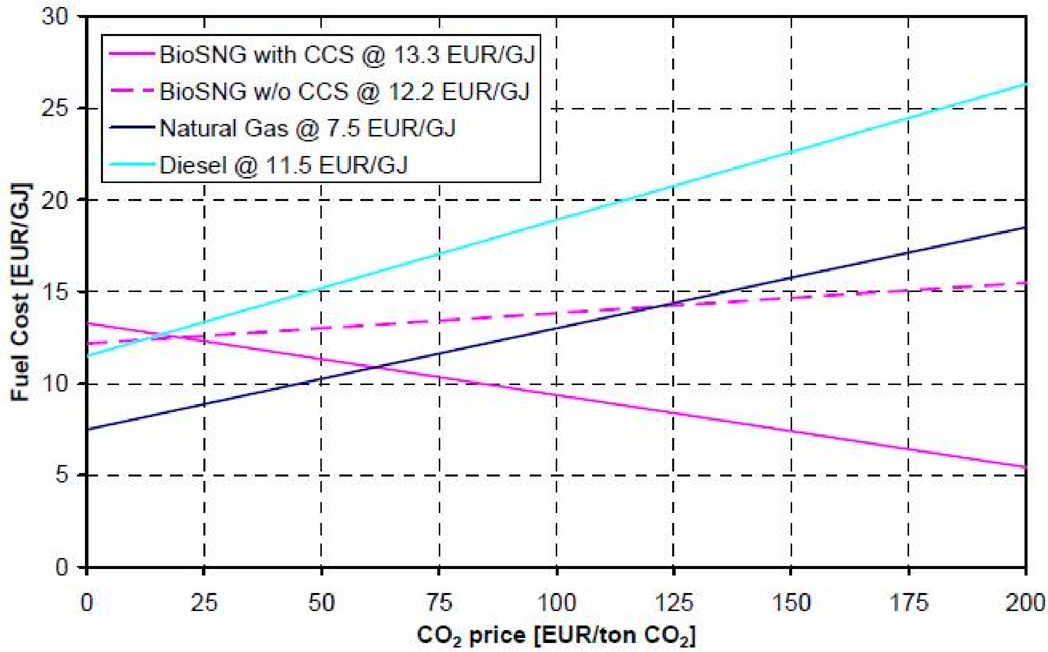

Figure 2. Price of Bio-SNG with and without CCS compared to natural gas and diesel. (Carbo et al., 2010)

Research methods

The amount of captured carbon dioxide was calculated with the same in house model that was used for calculating the energy efficiency and greenhouse gas emissions according to RES directive (Master's thesis: Niskanen, 2012). Power demand and costs of compressor, pump and pipeline was modeled with a spread sheet model. The rest of the CCS-costs are calculated with literature values.

Bio-SNG and Bio-CCS process description and initial data

Raw material is delivered to the biorefinery by trucks and train and then crushed to an appropriate particle size, which is gasifier depended. The crushed raw material is led into a belt drier, where the moisture content is decreased from about 50 % to 20 %. Dried wood chips are then led into a pressurized bubbling fluidized bed (BFB) gasifier. Wood chips are gasified with oxygen and steam and the needed heat is produced by partial oxidation of raw material. Produced gas comprises of hydrogen, carbon monoxide, carbon dioxide, water vapor, methane and some impurities such as tars and hydrogen sulphide. Tars are cracked partly inside the gasifier and the remaining tars in a catalytic tar reformer. Tar-free gas is led to filtering, which removes particles, chlorides and heavy metals. Filtered gas is then scrubbed in a water scrubber, which removes ammonia, hydrogen cyanide and chlorides. Water gas shift -reactor then adjusts the hydrogen to carbon monoxide -ratio for methanation process. Acid gas removal (AGR), which is located before the methanation removes carbon dioxide and hydrogen sulphide from the syngas. Hydrogen sulphide is a catalyst poison and therefore must be removed prior the methanation process. Hydrogen and carbon monoxide react in the methanation process forming methane and water vapor. Three consecutive methanation reactors increase the methane content of syngas above 95 % (after water removal). Water is condensed from the gas by cooling and final dryness is achieved by tri-ethylene-glycol (TEG) washing. Synthetic natural gas is then compressed to the natural gas transmission network. (Figure 3)

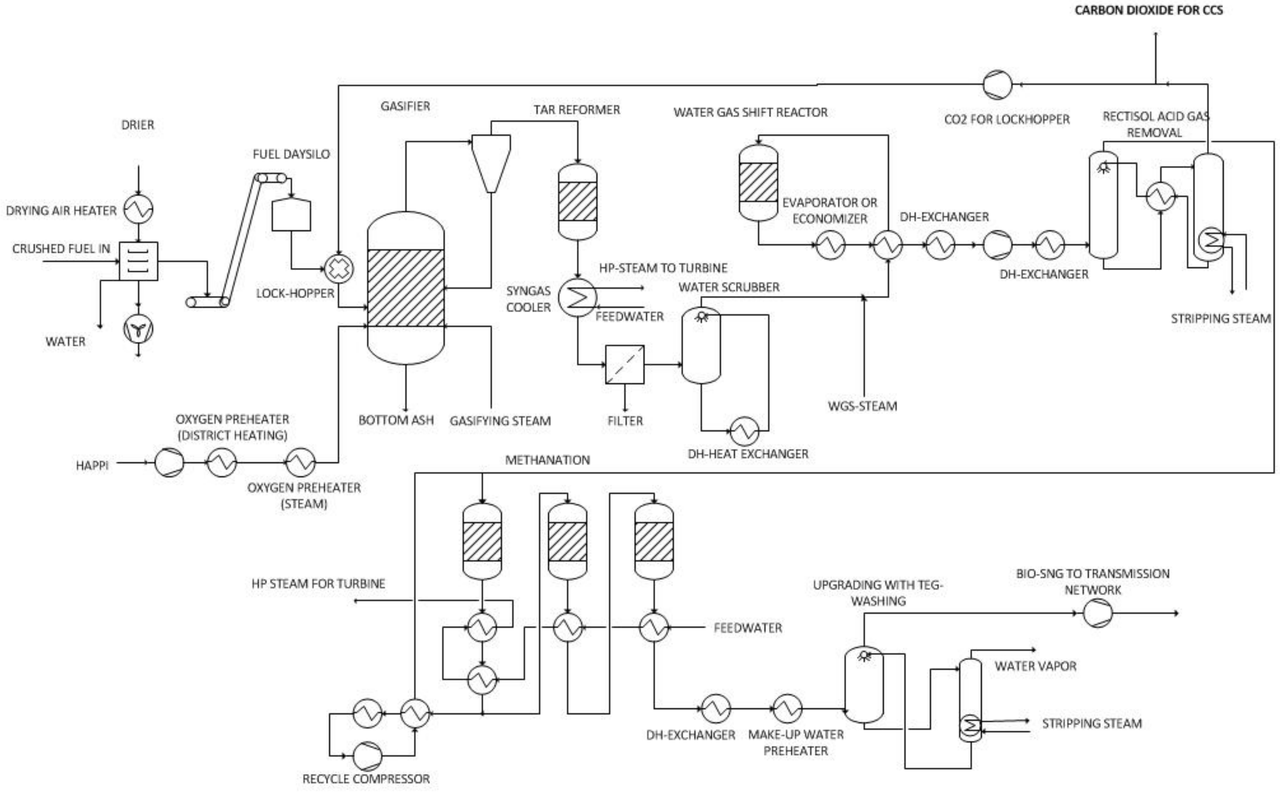

Figure 3. BIO-SNG production process. (Niskanen, 2012)

Bio-CCS chain is presented in Figure 4.

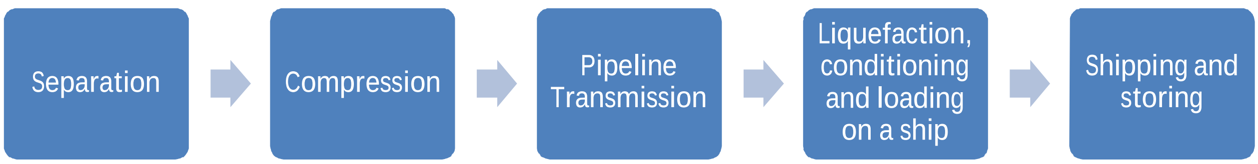

Figure 4. (Bio)-CCS chain.

Carbon dioxide separation with Rectisol-process

Carbon dioxide separation is an essential step in the SNG production. Rectisol process is an acid gas removal (AGR) process that uses chilled methanol as a washing solvent (Figure 5). Chilled methanol at the temperature of -28 °C is sprayed from the top of H_2S absorber which removes hydrogen sulphide from the syngas. H_2S free gas is then led to the bottom part of CO2 absorber. CO2 absorber is divided in two parts. The lower part uses methanol from flash generator and does the bulk CO2 removal. Upper part is the fine CO2 removal and it uses the purest methanol in the circuit from the hot regeneration. Methanol that comes from hot regeneration has been chilled to -60 °C with refrigerator. Absorbed CO2 is removed from the methanol in a flash regenerator. Typically if raw gas pressure is 49 bar(g), about 60-75 % of the CO2 would be recoverable at 2.75-4.1 bar(g). H_2S stripper is a flash tank where absorbed hydrogen and carbon monoxide are stripped from methanol and mixed back to the syngas stream. Rich methanol is then regenerated in the H_2S desorber. (Miller & Tillman, 2008)

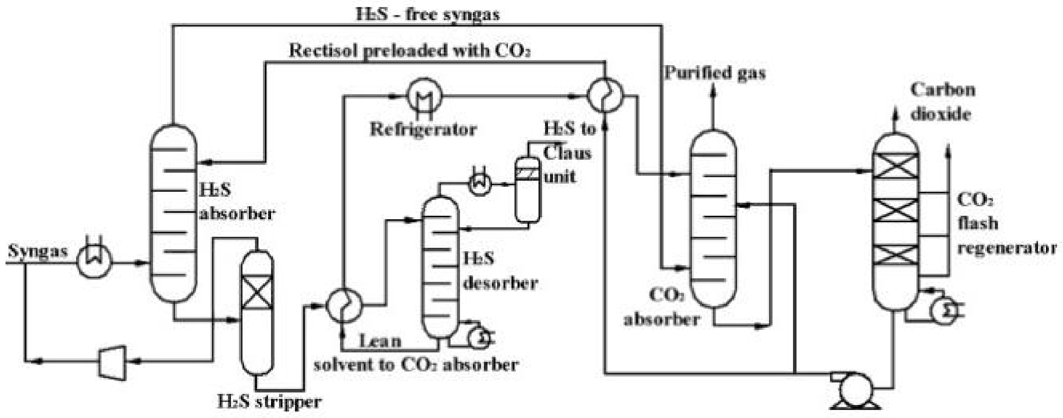

Figure 5. Rectisol-process flow diagram (Padurean et al. 2012)

CO_2 quality recommendations

CO_2 quality recommendations are presented in Table 2.

Table 2 Recommendations for CO2 quality. (VTT, 2009)

		Quality recommendation	pipeline transportation	ship transportation	storage	EOR
water	H_2O	< 20-500 ppm	500 ppm	50 ppm	-	< 20 ppm
volatile components	N_2	< 300 ppm (EOR) - 4 % (all volatiles)	< 4 % (all volatiles)	< 0.2-0.5 % (all volatiles)	< 4 % (all volatiles)	< 300-4800 ppm
	O_2	< 100 ppm (EOR) - 4 % (all volatiles)				< 100-1000 ppm
	Ar	< 0.2-4 % (all volatiles)				-
	H_2	< 0.2-4 % (all volatiles)				-
	CH_4	< 0.2-4 % (all volatiles)				< 2 %
harmful components	H_2S	< 200 - 9000 ppm	200 ppm	200 ppm	-	< 1500-9000 ppm
	CO	< 10 - 2000 ppm	2000 ppm	2000 ppm	-	< 10 - 1000 ppm
sulphur and nitrogen oxides	NO_x	< 50 - 100 ppm	100 ppm	100 ppm	-	< 50 ppm
	SO_2	< 10 - 100 ppm	100 ppm	100 ppm	-	< 10 ppm
carbon dioxide	CO_2	> 95.5-99.5 %	> 95.5 %	> 99.5 %	> 95.5 %	> 95.5 %

Rectisol process typically produces very pure CO2 gas stream. Typical Rectisol CO_2 stream compositions are presented in Table 3. It can be seen that Rectisol CO2 stream clearly fulfills the quality recommendation for pipeline transportation, storage and Enhanced Oil Recovery (EOR). Ship transportation on the other hand requires extremely pure CO2 stream (> 99.5 %). Linde promises ≥ 98.5 % CO_2 purity (SummitPower, 2010). VTT (Arasto, 2013) considers Rectisol CO2 stream clean enough for ship transportation. It is therefore assumed that pretreatment of the CO2 stream is unnecessary and only investments to the biorefinery site are the compressor and the pump.

Table 3 Typical Rectisol CO2-stream compositions. (TrinityConsultants, 2008; SummitPower, 2010; Doctor et al., 1994)

AGR stream composition	Kentucky NewGas [mol-%]	LINDE Odessa [mol-%]	Doctor et al. [mol-%]
H2	0.34		0.11
N2	0.01		0.83
CO	0.31		0.04
Ar	0		0.03
CH4	0.72		0.13
CO2	97.72	98.5	98.72
H2S	0.0003	2-10 mg/Nm3 ~5ppm	0.01
COS	0.0002		0.00
CH3OH	0.01	0.025-0.03	-
H2O	0.89	0.000001	0.06
other			0.07

Carbon dioxide transport and storage

Several studies recognize the Sleipner gas field in Utsira formation as a suitable CO_2 storage. Utsira deep saline formation is estimated to have a storage capacity of 600 Gt, which is equivalent to all the CO_2 emissions from all the power stations in Europe for the next 500 years. (INSA, 2012)

Separated CO2 stream is pressurized and transmitted to coastline via pipeline for liquefaction and conditioning. Liquid CO_2 is stored in intermediate storage tanks and loaded from there to the ships. The captured CO_2 will be shipped from some of the harbors in Southern Finland to the Sleipner Gas field for storage. Transportation distance is about 2000 km. For industrial applications transportation by road or railway lack the needed capacity and can't be realistically seen as cost effective options for CCS infrastructure (VTT.

Figure 6. Approximate route of the ship transportation.

Compressor, pump and pipeline calculations

Simplified compressor power demand and cost calculation model was built according to McCollum & Ogden (2006).

Initial pressure was assumed to be 0.1 MPa and the cut-off pressure 7.38 MPa. Number of compressor stages is assumed to be 5 which leads to compression ratio (CR) of 2.36. The compression power ratio for each stage is calculated with the following equation:

$$W_{s,i} = \frac{mZ_sRT_{in}}{M\eta_{is}} \times \frac{k_s}{k_s-1} \times \left[(CR)^{\frac{k_s-1}{k_s}} - 1\right], \qquad (1)$$

where
- m = CO2 mass flow rate (kg/s)
- Z_s = average CO2 compressibility for each individual stage [-]
- R = gas constant [kJ/kmol-K]
- T_{in} = CO2 temperature at compressor inlet [K]
- M = molecular weight of CO2 [kg/kmol]
- η_{is} = isentropic efficiency of compressor [-]
- k_s = (Cp/Cv) = average ratio of specific heats of CO2 for each individual stage [-]
- CR = compression ratio of each stage [-]

For all stages: R = 8.314 kJ/kmol-K, M = 44.01 kg/kmol, T_{in}=313.15 K (= 40 °C), η_{is} = 0.75. Z_s and k_s vary for each stage and they are presented in Table 4.

Table 4 Average compressibility factor and ratio of specific heats for CO2 at different compressor stages. (McCollum & Odgen, 2006)

	Z_s	k_s
stage 1	0.995	1.277
stage 2	0.985	1.286
stage 3	0.97	1.309
stage 4	0.935	1.379
stage 5	0.845	1.704

Total compressor power requirement is calculated by adding the power requirement of each stage. Unlike in McCollum & Odgen (2006) here also the mechanical and electrical efficiencies are taken into account for. Mechanical efficiency of 95 % and electrical efficiency of 98 % were assumed.

Transmission pipeline pressure loss is assumed to be 35 Pa/m (Knoope et al., 2013), which leads to total pressure loss of 35 bars at 100 km distance. ZEP (2011) starts liquefaction process form 70 bar(g), which is used as the final pressure at the coastline . Therefore the initial pressure of pipeline is set to 105 bar(g). This is the pressure after pump.

Pump power consumption [kW] is calculated with: (McCollum & Ogden, 2006)

$$W_p = \frac{1000 \times 10}{24 \times 36} \times \left[\frac{m(P_{final} - P_{cut-off}}{\rho \eta_p}\right], \quad (2)$$

where m = CO2 mass flow rate (t/d)
P_{final} = final pressure = 10.5 MPa
$P_{cut-off}$ = cut-off pressure = 7.38 MPa
ρ = density = 630 kg/m^3
η_p = pump efficiency= 0.75

Compressor and pump capital costs and O&M costs are calculated according to McCollum & Ogden (2006).

Capital cost of compressor is calculated with equation:

$$C_{comp} = m_{train} N_{train} \left[(0.13 \times 10^6)(m_{train})^{-0,71} + (1.40 \times 10^6)(m_{train})^{-0,60} \times ln\left(\frac{P_{cut-off}}{P_{initial}}\right)\right], \quad (3)$$

where m_{train} = mass flow rate through each compressor train [kg/s]
N_{train} = number of trains

Maximum size of one compressor train is 40 000 kW and therefore in this case the number of trains is one.

Capital cost of pump is calculated with equation:

$$C_{pump} = \left[(1.11 \times 10^6) \times \left(\frac{W_p}{1000}\right)\right] + 0.07 \times 10^6, \quad (4)$$

where W_p = pump power consumption [kW]

Pipeline capital cost is calculated with equation:

$$C_{pipeline}\left[\frac{\$}{km}\right] = (9970 \times m^{0.35}) \times L^{0,13}, \tag{5}$$

where m = CO_2 mass flow rate [t/d]
L = pipeline length [km]

Annual costs are calculated with 25 years of operational time and 5 % rate. O&M costs are assumed to be 4 % of the capital costs. Electricity price of 50 EUR/MWh will be used in calculations.

In capital cost calculations, the 2005 US dollars are scaled to 2012 US dollars with the IHS CERA (2013) indexes. UCCI (Upstream Capital Cost Index) is used for pipeline capital costs and DCCI (Downstream Capital Cost Index) for compressor and pump capital costs. 2012 US dollars are transferred to euros with the 2012 average rate of 0.809 €/$ (IRS, 2013).

Liquefaction, intermediate storage, loading, shipping and offloading & geological storage

Liquefaction, intermediate storage, loading, shipping and offloading & geological storage costs are calculated with the preliminary data given by VTT. The actual publication will most likely be published in summer 2013. The preliminary value is 37.2 EUR/t($CO_{2,\ captured}$) (Arasto, 2013).

Results

Bio-SNG plant produces 1.6 TWh of Bio-SNG. Furthermore the net district heating power is 316 GWh and net electric power -34 GWh (Niskanen, 2012). Thus some of the electricity has to be bought from the national grid. Rectisol process separates 0.452 Mt(CO2)/a (=15.7 kg/s). 55 % of the carbon in feed stream is captured as CO2 (39 % of carbon in bio-SNG). With chain efficiency of 92 %, the CO2-reduction from the atmosphere is roughly 0.416 Mt(CO2)/a. Three to four Bio-SNG plants in Finland would lead to a total reduction of 1.2-1.7 Mt(CO2)/a.

CO_2 stream compressing and pumping power demands are 6094 kW and 104 kW respectively.

Compression and pipeline transportation costs from inland to the coastline are 17.1 EUR/t($CO_{2,\ captured}$). Liquefaction, intermediate storage, loading, shipping and offloading & geological storage costs are 24.8 EUR/t($CO_{2,\ captured}$). This leads to total bio-CCS cost of 41.8 EUR/t($CO_{2,\ captured}$). In Ajos BtL environmental impact statement the actual reduced amount of CO2 in the atmosphere was 92 % of the captured CO2. With this value, the cost for actual net CO2 reduction is 45.5 EUR/t($CO_{2,\ net}$). Cost summary is presented in Table 5 and Figure 7.

Table 5 CCS costs for 200 MW(SNG) plant

Costs	EUR/t(CO2, captured)	EUR/t(CO2, net)
Pump & Compressor power cost	5.48	5.96
Pump & Compressor capital cost	3.77	4.10
Pump & Compressor O&M cost	2.12	2.31
Pipeline capital and O&M cost	5.1	6.21
Liquefaction & conditioning, intermediate storage, loading, shipping,	24.76	26.93

offloading & geological storage		
total cost	41.84	45.51

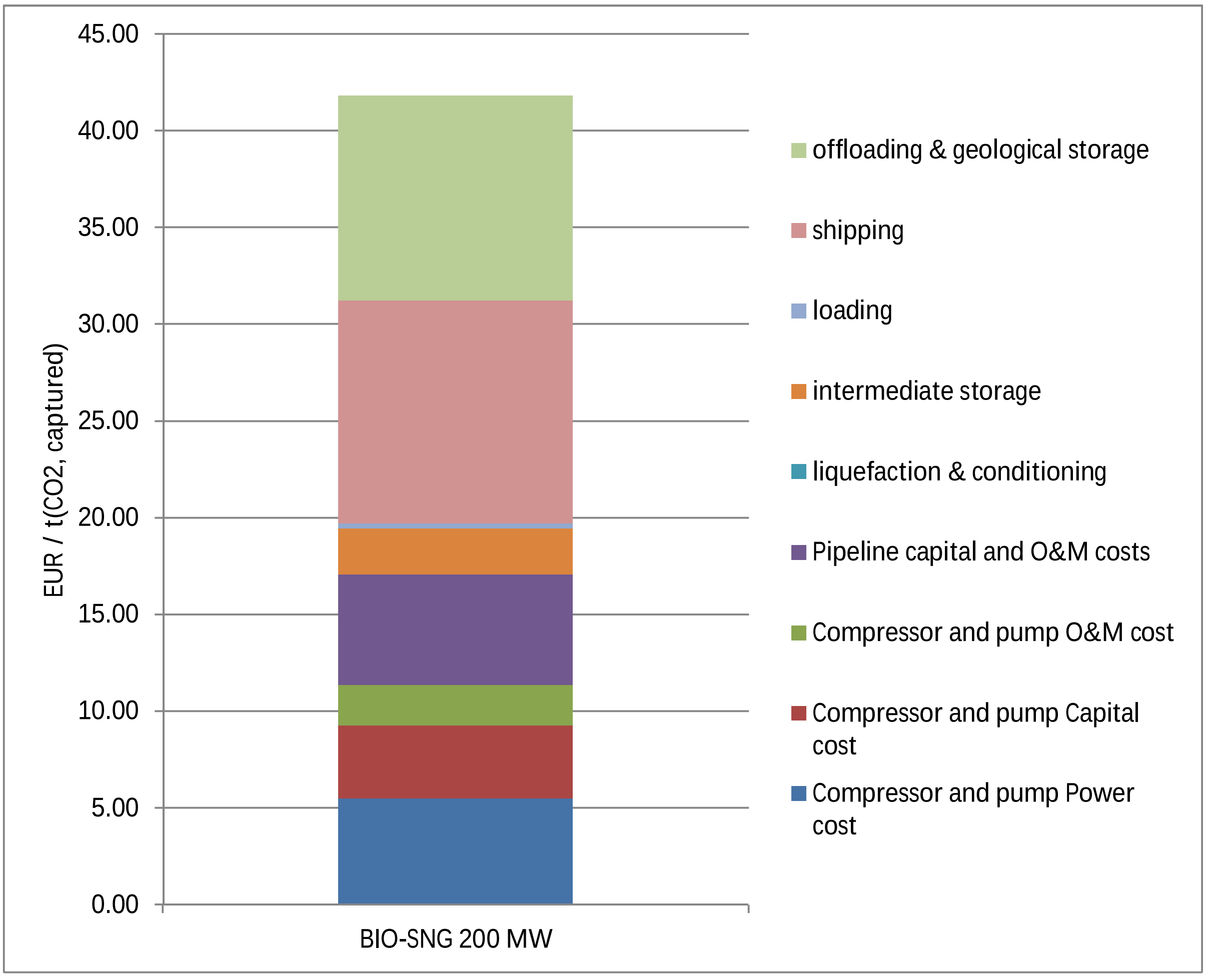

Figure 7. Bio-CCS costs for a 200 MW Bio-SNG plant with 0.452 Mt(CO2,captured)/a.

Sensitivity analysis

Capital costs higher in Europe than in the USA

The Capital cost calculation of compressor, pump and pipeline were adopted from an American study and transferred to 2012 euros with IHS indexes. However, these costs are probably lower in the USA and therefore should be treated with some caution. Global CCS Institute (2011) presented regional indices, which help to transfer their US Gulf Coast reference project to specific locations (Table 6). Even though the data is a couple of years old, it is assumed that compressor, pump and pipeline costs that were from American study are most likely at least 20 % higher in Europe.

Table 6 Regional indices used to transfer projects from USGC to specific locations. (GCCSI, 2011)

	Equipment	Materials	Labor	Land/Right of Way
Euro Region	1.19	1.16	1.33	1

(Germany)				

Total costs are 45.3 EUR/($CO_{2,\ captured}$) and 49.2 EUR/($CO_{2,\ net}$) when compressor, pump and pipeline costs are 20 % higher (Figure 8). Total costs are 8 % higher than in the base case.

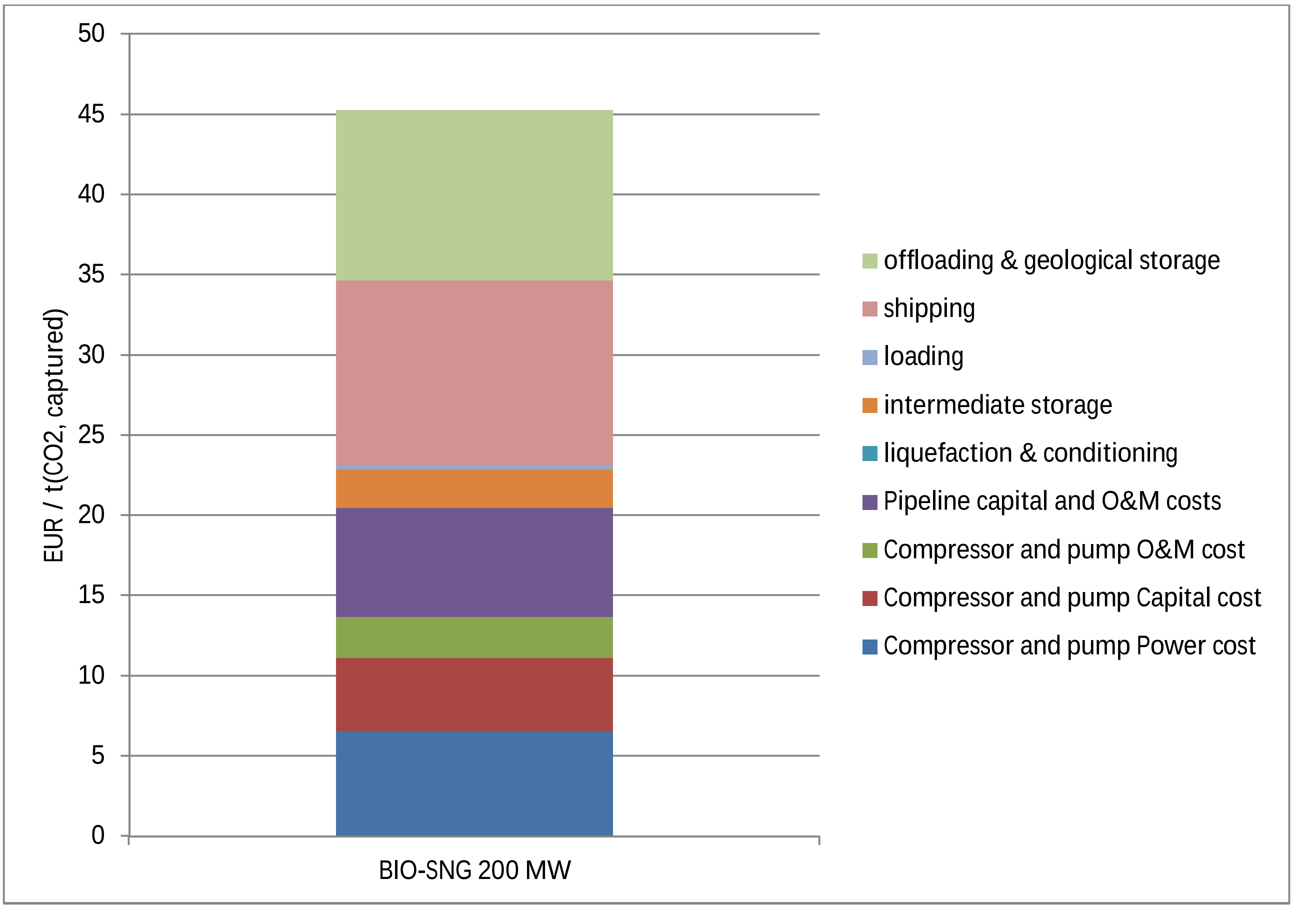

Figure 8. Total bio-CCS cost for a 200 MW bio-SNG plant with 0,535 Mt(CO2, captured)/a, in a case when compressor, pump and pipeline costs are 20 % higher.

Rectisol producing CO_2 streams on different pressure levels.

If Rectisol produces 60 % of the CO_2 stream on a 2.75 bar(g) pressure the compressor electricity consumption reduces from 6094 kW to 5156 kW, which is over 15 % reduction in electricity consumption. With electricity price of 50 EUR/MWh, the total costs reduce about 0.8 EUR/t(CO_2) resulting in 41 EUR/($CO_{2,\ captured}$), which is about 2 percent less than in the base case where the whole CO_2 stream is recovered in atmospheric pressure. Yearly this means about 375 KEUR savings in electricity costs.

Conclusions

Bio-CCS is seen as the only large-scale technology that can actually remove CO_2 from the atmosphere. Implementing Bio-CCS on certain biofuels routes could provide “low-hanging fruits” for early low cost CCS development. Bio-SNG is one of those applications as its production process includes a compulsory CO_2 separation step. This study examined an imaginary biorefinery that is located in Southern Finland about 100 km from the shoreline.

Bio-CCS system at hand comprises of CO_2 compression, pumping, pipeline transportation from inland to seashore, liquefaction and conditioning, intermediate storage and loading to ship, shipping and storage. Total cost for the whole chain is 41.8 EUR/($CO_{2,\ captured}$). Compression, pumping and pipeline investment and O&M cost are 17.1 EUR/t($CO_{2,\ captured}$), which is quite high value. One reason for this is very small CO_2 stream (less than half a million tons per year) compared to most cases. Most costs come from liquefaction, conditioning and shipping. More realistic case would be some sort of trunkline that carries CO_2 from all the big producers (Pulp & Paper mills) in Southeastern Finland.

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