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# Bio-CCS: feasibility comparison of large scale carbon-negative solutions

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## Abstract

The urgency to stabilize the global temperature rise at 2°C as highlighted in the IPCC Fifth Assessment Report calls for solutions that can remove $CO_2$ from the atmosphere. Achieving negative $CO_2$ emissions by removing $CO_2$ from the atmosphere is possible by applying carbon capture in processes using biomass (Bio-CCS). Biomass has the capability of withdrawing and storing atmospheric $CO_2$. As a result, $CO_2$ released during biomass combustion can be captured and stored permanently underground, thus depriving the atmosphere of $CO_2$.

The objective of this paper is to assess the background for most rational deployment opportunities of Bio-CCS from climate and economic point of view; to evaluate what is the best way to use constrained biomass resources by assessing the effects that raw materials types, different processes and end products have on carbon stocks and on the overall GHG mitigation from the global perspective. A concrete example on how more thorough deployment of Bio-CCS could penetrate in near-term markets is given as a Finnish Bio-CCS roadmap with scenarios highlighting the bottlenecks and constrains. The roadmap assessment is based on power plant, industrial plant and emission database calculations with future projections for existing installations.

The technical implementation of Bio-CCS in different industrial sectors goes hand in hand with the development of conventional CCS technology deployment. In general, similar solutions are suitable for capturing $CO_2$ from biomass applications as for fossil fuels. The main differences relate to the size and the location of emission sources (biomass-based installations are often decentralized and of smaller scale compared to fossil-based installations) or to the different kind of impurities in the combustion process, ash and flue gas. However, no principal technical restrictions to the capture of biogenic $CO_2$ exist in energy generation applications or industrial processes. As a consequence, certain Bio-CCS applications are low-hanging fruits for near future deployment of carbon capture assuming that negative emissions are accounted for.

In this paper the potential technologies for Bio-CCS and the feasibility of some solutions are compared both from a sustainability and cost point of view. There are four major biomass conversion routes where Bio-CCS is applicable; biochemical conversion

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(fermentation and hydrolysis), thermo-chemical conversion (e.g. gasification), power production (gasification and combustion) and industrial processes. In addition to ethanol fermentation the thermo-chemical biomass conversion processes are considered the first-phase targets for applying capture of CO2, both from a logistic and cost point of view.

The main Bio-CCS technologies assessed in this study are Fischer-Tropsch diesel production, bio-SNG production, lignocellulosic ethanol production, torrefaction and biomass based power production such as co-firing biomass in a coal-based condensing power plant and biomass-based CHP (combined heat and power) production. The most applicable industry sector for introduction of Bio-CCS is obviously pulp and paper industry but some potential exists also in cement industry, iron and steel industry and oil and gas refineries.

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 can take place in iron and steel industry (~3 Mt/a), pulp and paper industry (~1.3 Mt/a) and in combined heat power (CHP) production (~2.5 Mt/a) as opposed to straw ethanol production of smaller scale (~0.1 Mt/a). However, the $CO_2$ avoidance potential per unit of biomass raw material utilized is highest in co-firing (20t$CO_2$/toe), iron and steel industry (10t$CO_2$/toe) and in CHP production (8t$CO_2$/toe) whereas straw ethanol has lowest potential also in this category (1.5tCO2/toe). The cost estimations show a theoretical economic advantage of Bio-CCS over fossil CCS on carbon prices when the carbon sink effect is accounted for. The total costs for Bio-CCS vary from 35€/ton to 300€/ton $CO_2$ stored depending on the technology.

As the potential of Bio-CCS is bound to the availability and usage of biomass raw materials, the sustainability of the raw materials is of essence. The current biomass flows and potentials set the initial limits for the wider deployment of Bio-CCS. Efficient utilization of constrained resources is an essential question, when the target is to optimize the impact on the system level, from the society point of view. The ultimate objective is to suggest whether deployment of CCS has the desired impact on the atmospheric $CO_2$ concentration. As biomass can be used in many ways, the primary purpose of utilization and products containing biogenic carbon also adds up to this. When biomass is utilized for products other than energy, the impact to environment and economy differs. The opportunities with these solutions, realistic potential and the main threats related to Bio-CCS are discussed in the light of sustainability and economic potential.

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*Keywords:* Bio-CCS; Roadmap; feasibility

## 1. Introduction

The urgency to stabilize the global temperature rise at 2°C as highlighted in the IPCC Fifth Assessment Report calls for solutions that can remove $CO_2$ from the atmosphere. Achieving negative $CO_2$ emissions by removing $CO_2$ from the atmosphere is possible by applying carbon capture in processes using biomass (Bio-CCS). Biomass has the capability of withdrawing and storing atmospheric $CO_2$. As a result, $CO_2$ released during biomass combustion can be captured and stored permanently underground, thus depriving the atmosphere of $CO_2$.

In the Nordic Energy Technology perspectives IEA states the following about Bio-CCS potentials in the Nordic countries alone: “This additional reduction in the CNBS (scenario) is due to an increased use of bioenergy with CCS (BECCS) in the power sector, which results in negative net $CO_2$ emissions. In the CNBS, 7 Mt of CO2 are captured at BECCS plants in the power sector compared with 3 Mt in the CNS.” [1]. European Biofuels Technology platform and Zero Emission Platform Joint Task Force on Bio and CCS produced a background report on Bio-CCS deployment [2]. IEA GHG has ordered a study from Dutch Ecofys to estimate the global potentials for Bio-CCS [3] that also acted as a basis for the JTF background paper. In addition to this VTT has evaluated more in detail what the implications of realizing Bio-CCS could be. As a result, the role of Bio-CCS will be emphasized along the road towards competitive low carbon economy in 2050. [4].

The general alignment in general of the studies published is that significant potential for Bio-CCS can be estimated, as in IEA GHG and JTF reports. Some more detailed studies show much more moderate, yet still significant potential for Bio-CCS. The major difference between these estimations is the estimation of the sustainable biomass raw material potential and the availability and price of biomass on site. The rational for this additional study was to get a good understanding on the potential based on realistic raw material resources and existing energy production infrastructure and its current development on a regional basis.

## 2. What is Bio-CCS?

Bio-CCS means capturing and storing of $CO_2$ originating from biogenic sources. As biomass binds $CO_2$ from the atmosphere through photosynthesis during growths it grows it is considered to be renewable and a carbon neutral raw material. When carbon dioxide emitted from conversion of biogenic raw material is permanently stored in a geological formation, the net greenhouse gas impact becomes negative as biomass raw material is renewed, i.e. new biomass grows to replace the biomass utilised in the process. This is the case with carbon neutral sustainable biomass raw material. In principle, if the carbon stock contained by biomass within a boundary over a certain time period remains the same or even grows, the biomass can be considered carbon neutral.

Bio-CCS technologies and application sectors cover all biomass utilising sectors (in contrast to term BECCS, Bio Energy CCS) with installation sizes reaching a $CO_2$ emission level of several hundred kilotons per year. These cover well established industrial sectors with existing large scale biogenic $CO_2$ emission sources such as pulp and paper industry and power sector. Also industrial fields in rapid development phase such as liquid biofuels industry and bio economy in general are in consideration. Figure 1 illustrates the general principle of capturing biogenic carbon. The industry example used in Figure 1 is power generation. It shows the order of magnitude of GHG effects and other major operational parameters of deploying CCS to biomass fired power plant. The order of magnitude of GHG impact is twice as big when compared to conventional CCS or replacing fuel with biomass alone. In case the carbon neutrality of biomass raw material is less than that of e.g. coal the net $CO_2$ impact of such Bio-CCS installation is roughly between one or two times coal-based CCS. In worst case scenario it could be even worse. Therefore, Bio-CCS is not justifying ignoring sustainability questions regarding life cycle $CO_2$ emissions of biomass raw material unnecessary, but even highlights theme with possibilities for increased use of biomass.

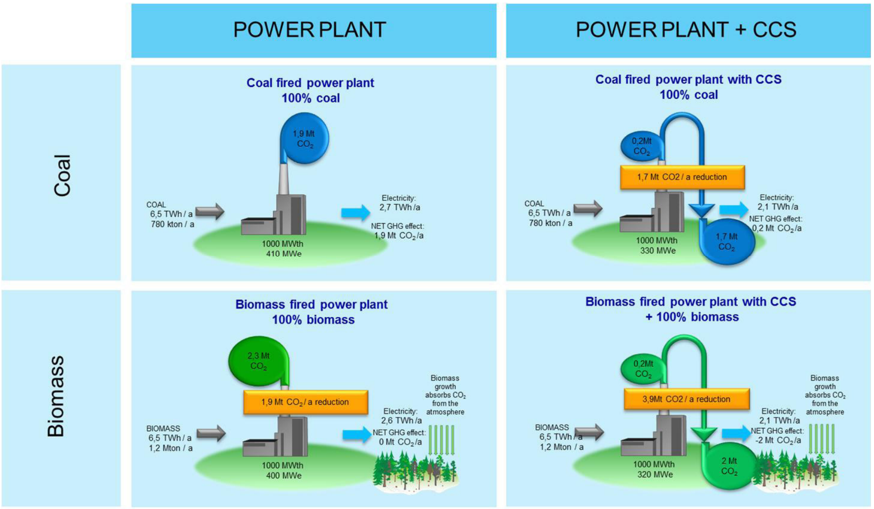

Fig. 1. Principle of carbon balance when applying Bio-CCS [5]

## 3. Technology pathways for Bio-CCS

CCS technologies can technically be applied to any biomass refining or utilizing process emitting $CO_2$. This paper covers potential large scale biomass utilizing processes in the northern coniferous forest belt. The processes are chosen to give a realistic picture of the order of magnitude of GHG impacts related to certain type of processes; e.g. not all product or process variations are presented, as the order of magnitude remains the same. The $CO_2$ footprint of a process can also be diminished by removing carbon from the process in other forms than $CO_2$. This leads to a completely different kind of lifecycle approach for carbon cycles with also aspects related to cascading use of biomass. These novel concepts e.g. in pulp and paper industry are left outside scope of this paper.

For technology comparisons fixed values for production efficiencies, costs for emission reductions etc. have been used. This is not the case in real life. For example, cost of emission reduction can vary significantly depending on integration and assumptions. However, a general interdependencies and orders of magnitude of results have been the objective. For more detailed information and description of the different technologies, references have been provided [5]. Transportation and storage costs are considered according to Kujanpää et al. [6].

Table 1 shows the general assumptions utilized in this study. No additional taxes or financial support means have been included in this assessment in order to make the results more applicable outside Finland. These assumptions can always be discussed and this snapshot with the fixed assumptions is presented here to enable the comparison. The emission reduction of different biomass technologies are considered based on the approach of EU emission trading scheme which considers biomass in power production as carbon neutral. The emission reductions in other products, such as FT diesel are considered according to EC renewable energy directive and guidelines [6, 7]. All installations are considered in Nordic context, and more detailed information on individual technologies in general can be obtained e.g. from existing publications [2, 5].

Table 1. General cost assumptions used as basis in the calculations

| Commodity | Cost | Unit |
|---|---|---|
| Electricity | 50 | €/MWh |
| Biomass | 18 | €/MWh |
| Coal | 12 | €/MWh |
| Diesel | 1,535 | €/l |
| Diesel (taxes removed) | 82,7 | €/MWh |
| Gasoline | 1,665 | €/l |
| Gasoline (taxes removed) | 93 | €/MWh |
| Torrefied biomass | 32 | €/MWh |
| Natural gas Gas | 23,5 | €/MWh |
| Investment period | 20 | years |
| Interest rate | 7 | % |

### *3.1. Bio-CCS in liquid biofuels production, Bio-SNG production and torrefaction*

1st and 2nd generation liquid biofuels production, Bio-SNG production and torrefaction processes producing bio based energy carriers all offer possibilities of capturing carbon dioxide.

*Thermo-chemical liquid biofuels production*

Fischer–Tropsch synthesis (FT) and gasification based synthetic diesel production route was chosen as example of thermochemical biomass conversion process for transportation fuels. The FT diesel plants currently under consideration to be invested in Finland are examples of this technology. The process is based on circulating fluidized bed (CFB) gasification of forest residues with low temperature gas cleaning and Fischer–Tropsch synthesis. The cost and performance data utilized in this study are based on the work by Hannula [9], with more specific estimations on the CCS train. The scale of the plant is 300 MW fuel input producing 0.11 Mtoe synthetic diesel per year. As for gasification and synthesis based routes, excess $CO_2$ needs to be removed from the production process in order to adjust the H/CO ratio down to a suitable level for FT synthesis. As a consequence, a pure $CO_2$ stream of 4.1 MtCO2/ Mtoe$_{, \text{product}}$ is readily available. For CCS purposes, this stream needs to be compressed, transported and permanently stored in the underground storage as the actual capture process is already part of the FT diesel process.

*Bio-SNG production*

The concept of Bio-SNG is based on the idea of producing synthetic natural gas from biomass via gasification and feeding supply the fuel gas into the existing natural gas grid. The synthetic natural gas is produced by gasifying forest residues in a CFB gasifier and removing excess $CO_2$ as in the FT diesel process, but in order to obtain a different H/CO ratio to produce natural gas via synthesis. The scale of the plant is 288 MW forest residues input producing 0.14 Mtoe synthetic natural gas per year. As with FT diesel production, a pure stream of 3.9 MtCO2/ Mtoe$_{, \text{product}}$ is available$_,$ and again needs to be compressed, transported and permanently stored in the underground storage.

*Lignocellulosic ethanol production*

As 1st generation ethanol production is not expected to grow significantly in Europe lignocellulosic ethanol production was assessed in this study. Straw ethanol is produced by milling of straw, steam explosion, fermentation and distillation of the produced ethanol. The process in this study is not integrated; however some advantage could be gained via integration to power production or district heating network. The ethanol production of a single site is 0,12Mtoe/a. The $CO_2$ stream from fermentation of sugars in to ethanol is relatively pure, but is assumed to require moderate purification and further compression before transportation to storage. From the stoichiometry of ethanol fermentation approximately 1.64 MtCO2/Mtoe$_{, \text{product}}$ is produced.

*Torrefaction*

The torrefaction process considered in this study is a pre-treatment process of biomass raw material for co-firing in pulverized coal boilers and for replacing coal in steel mill pulverized coal injection. $CO_2$ capture from a torrefaction installation has not been considered as the amount of $CO_2$ emission from a single site is very small. In addition, the flue gas composition is less attractive for $CO_2$ capture compared to other gas streams considered in this paper. The composition resembles conventional power plant flue gas and the needs to be fed into a boiler or treated with other means because of the odorous gases it contains. The size chosen for a typical installation is 200 000 t/a torrefied pellet (TOP) and the feed required is 130 MW forest residues or other biomass.

### *3.2. Biomass utilization in energy production*

Power and heat production is currently the second largest user of biomass in Europe after pulp and paper industry. Two different technologies are considered for the power sector; one representing a more Central European approach for power production by co-firing torrefied biomass in a pulverized coal boiler, and one representing a more Nordic approach by combusting up to 100% biomass in fluidized bed (FB) boilers.

*Biomass co-firing*

Co-firing case in condensing power production is considered to be an advanced peak load power plant producing only electricity with high efficiency. The plant characteristics are chosen to reflect both the effect of co-firing moderate shares of biomass and also the peak load behavior in a power plant, as this has increasingly become the tendency in coal condensing power production in Finland. It is, however, acknowledged that no such advanced high efficiency boilers would currently only to be utilized for peak loads. The power plant considered in this paper is a 1500 MWth pulverized coal plant with 1500 h/a operation and it is producing electricity at a net efficiency of 44% and using up to 20% torrefied pellet.

*Bio CHP*

The typical Nordic example of biomass power production considered in this paper is a medium sized circulating fluidized bed boiler producing both power and heat. The annual operation of this 500 MWth installation is 6500h/a, with an advanced electrical net efficiency of 42% and 50% efficiency for heat production. The boiler is designed to use up to 100% biomass fuel, mainly forest residue and energy wood. Post combustion carbon capture is considered as capture technology here.

### 3.3. Biomass usage in industrial processes

For biomass utilization in industrial processes, the largest and most potential processes have been chosen for this analysis. Biomass based raw materials can also be utilized in other industrial processes, such as in petro-chemistry and cement manufacturing. Oil refineries are very complex installations, with only moderate potential for biomass utilization. For utilization in a refinery, forest biomass could for example be introduced as pyrolysis oil for hydro treatment, or as refinery co-feed. As there is no considerable $CO_2$ stream from hydro-treatment of vegetable oils, this was not considered as an option for Bio-CCS. The approach of this study is also considered to be to general for complex installations such as oil and gas refineries. Cement industry was not seen as a major biomass utilizing sector in the timeframe of this analysis in a Finnish context. For these reasons, both refineries and cement plants were left out of this study. However, in a larger geographical perspective, these sectors can be seen at least as potential utilizers of biomass and CCS.

*Iron and steel industry*

In iron and steel industry, the most common process route is the blast furnace – basic oxygen furnace route. This is also considered in this assessment, as the major iron and steel plants in Nordic countries utilizes this process. For iron and steel industry biomass is considered for the replacement of pulverized coal injection. All of the PC injection is replaced by torrefied pellets resulting up to 36% of the total carbon input to blast furnace process. This is assumed to be a realistic option, despite the problems with additional impurities entering the process. In theory, all carbon introduced to the blast furnace could be replaced with biogenic carbon, but replacing an increased coal injection was considered to be an ambiguous enough medium term target to be combined with CCS. For carbon capture, flue gas recycling considered as the route for CCS. Besides enabling the capture of $CO_2$, the oxygen blast furnace (OBF) also reduces coke consumption.

*Pulp and paper industry*

The pulp and paper industry represents one of the major emission sources of biogenic $CO_2$ in Finland. Major emission sources from a pulp mill are recovery boilers, bark/power boilers and lime kilns. For several reasons only emissions from the recovery boiler were considered in this study. The power boiler sizes vary significantly depending on installation and integration of the plant. The size of the lime kiln being only some tens of megawatts. $CO_2$ capture is done with post combustion technology, and the effects to the mill site are considered accordingly. A 2000 adt/d kraft mill was considered as a basis for the estimation.

## 4. Costs and related emission reduction potential of different technologies

Based on the aforementioned assumptions on site emission reduction potential for different installations were calculated based on modeling and cost estimation. In general, the CCS and Bio-CCS potentials are directly related to the thermal power of installation. The results in Figure 2 shows that the highest total $CO_2$ emission reduction potential is assumed to be in iron and steel industry and CHP power plant. The emission reduction from a co-firing condensing plant is rather small, due to the low annual operational hours. If the operational hours would be higher (e.g. 6500 h as with CHP), the reduction potential would be 3.7 Mt/a. The biggest on-site emission reduction based on biomass use is also associated with iron and steel industry and CHP production. This is due to the fact that these installations are capable of utilizing large amounts of biomass annually, and as a consequence, the emission reduction potential is higher. Likewise, the small emission reduction potential of ethanol production is due to smaller scale installations.

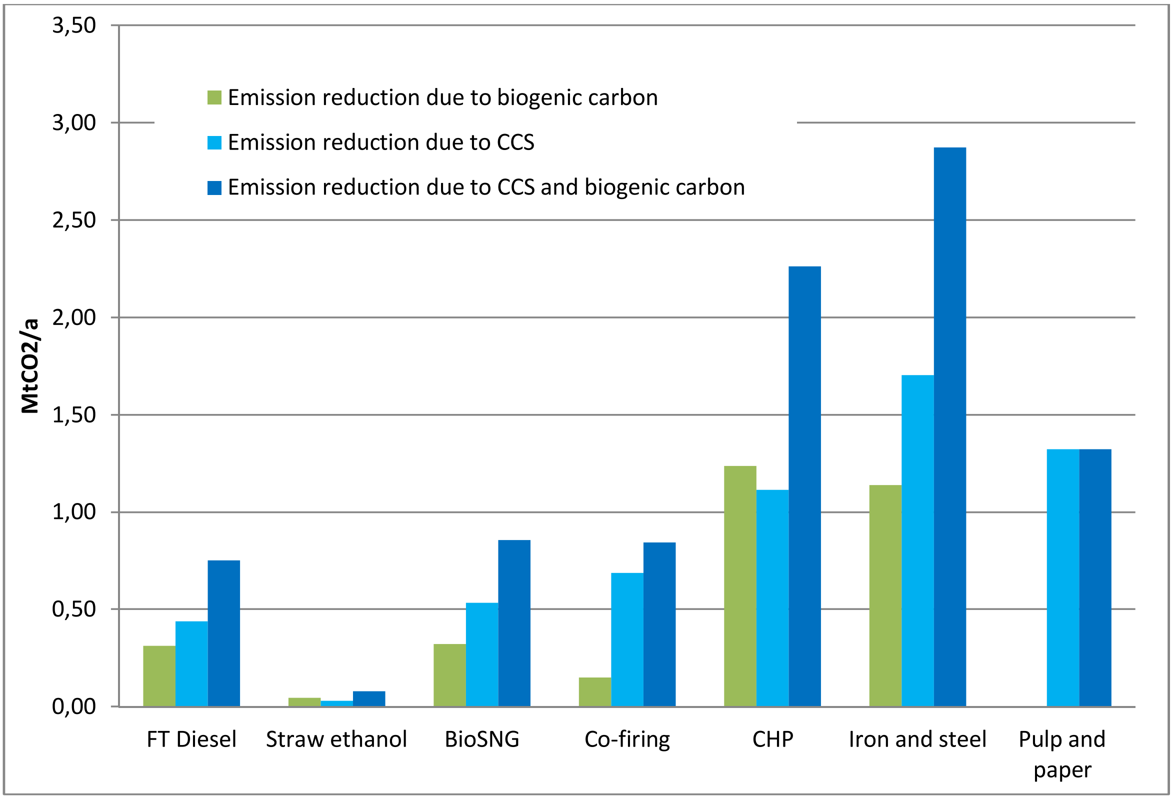

Fig. 2. Emission reductions of different Bio-CCS applications related to additional biomass use from operator perspective. [5]

Figure 3 shows that when considering the climate impact per amount of biomass co-firing power production, CHP production and iron and steel industry will have the largest effect. This is because the biomass directly replaces fossil fuels like coal, peat or coke and the fuel stream is fully converted into $CO_2$ in flue gas on site. In case part of the carbon in the process is converted to a product, it leads to more complex replacement chain and broader assessment boundaries, as in case of production of liquid biofuels. When more conversion steps are added to a process, the overall efficiency of the total chain from raw material to end product typically lowers. However, it is important to keep in mind that different end-products cannot always be utilized for all purposes (such as transportation fuels) and thus cannot directly be compared based entirely on this aspect. Co-firing power production and iron and steel production have the largest overall effects due to the large amounts of coal used in addition to biomass. Consequently, in this comparison they benefit from also from capturing fossil carbon. As the capture rate considered is 90% of the total emissions of the installation the total capture volumes will be significant.

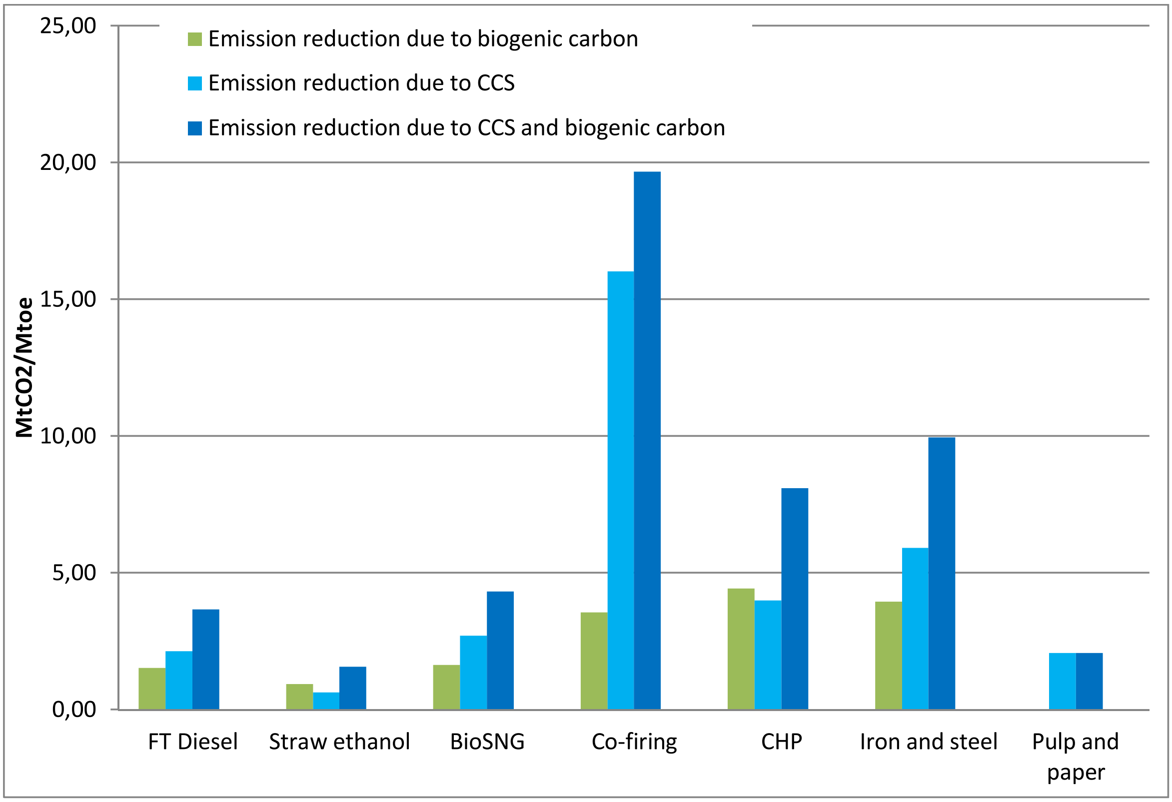

Fig. 3. On-site emission reduction Mt $CO_2$/Mtoe from additional biomass utilised from operator perspective. [5]

The costs of emission reduction on site are considered from the site owner's point of view [Figure 4]. Biogenic $CO_2$ emissions are accounted as fossil emissions. The lowest costs are associated with FT diesel production, CHP power production and iron and steel production. The low cost in FT diesel production is due to a concentrated $CO_2$ stream already available in the process. CHP production capture costs are lower compared to co-firing power production due to the low operational hours of co-firing. It is also affected by better integration opportunities and better recovery of low quality heat in CHP production, something that is reflected in the costs. Considering higher operational hours for condensing power production the capture cost would decrease to 56€/ton. High capture costs of straw ethanol are due to the small process scale. CHP production is also associated with lowest $CO_2$ emission reduction costs in relation to utilization of biomass. This is because CFB boiler is the only technology (besides FT-diesel production) considered capable of using cheaper biomass fractions and does not require heavy pre-processing of raw material. Costs of CCS in iron and steel industry are relatively low because application of an oxygen blast furnace reduces the coke consumption of the process and makes the process more efficient. However, the costs associated with an oxygen blast furnace are most sensitive to assumptions about operational environment, such as the price of electricity, coke and LPG. The cost of emission reduction from straw ethanol production is high because the reduction potential is a lot smaller than for example with FT diesel.

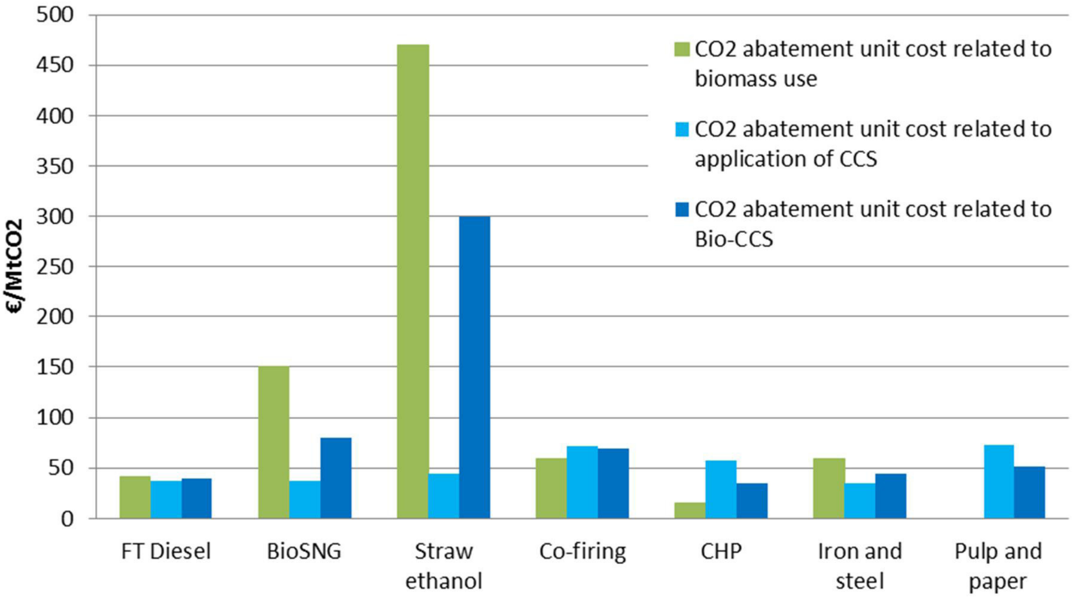

Fig. 4. Unit costs of on-site $CO_2$ emission reduction from the operator perspective. [5]

## 5. Availability of biomass raw material

The energy use of solid biomass in EU28 is 945 TWh [10] of which roughly 70% is woody biomass and 170 TWh is related to direct fuel use of total round wood harvest. The majority of the wood consumed is currently not imported. The round wood use in the European forest industry in 2012 was 343 million $m^3$ which roughly equals 680 TWh in energy terms [11]. 50% of this is consumed in three countries; Sweden, Finland and Germany. 3326 TWh of coal was utilized in EU28 in 2011 [12]. 20% of this would theoretically correspond to the entire round wood use of European forest industry. To put this in to a perspective to Finnish Bio-CCS roadmap, the total commercial round wood removals in Finland were 52 million $m^3$ in 2012 [12] with annual growth of forest biomass being in the range of 100 million $m^3$/a.

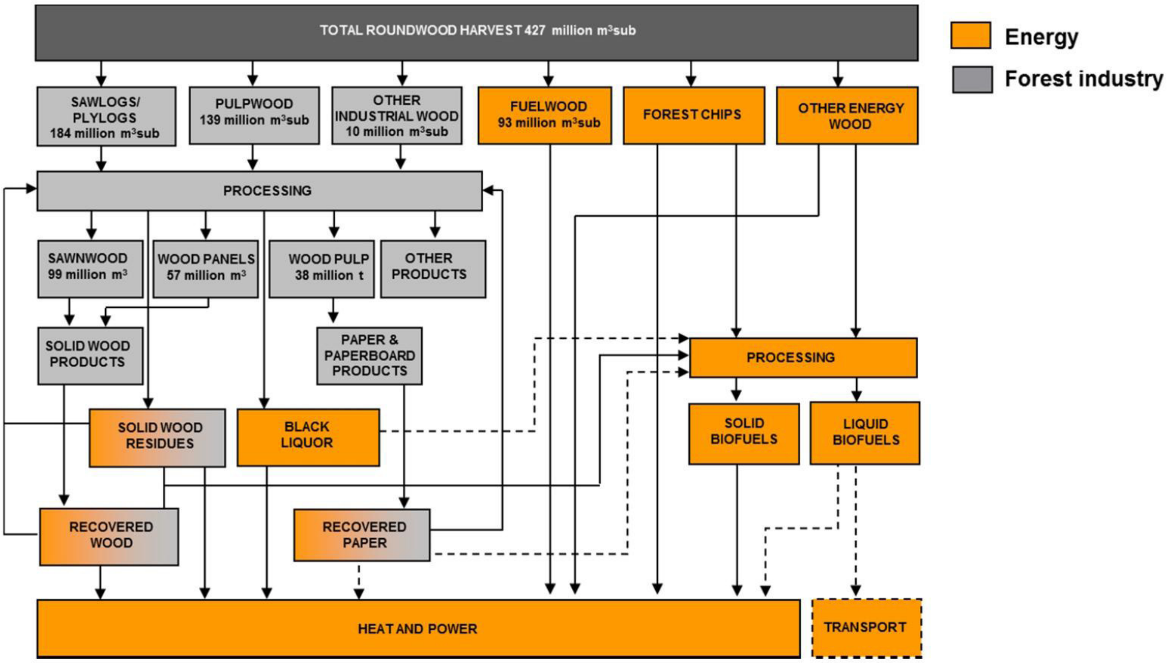

Fig.5. Wood harvest and utilization flows in EU 2012 (Pöyry) [11]

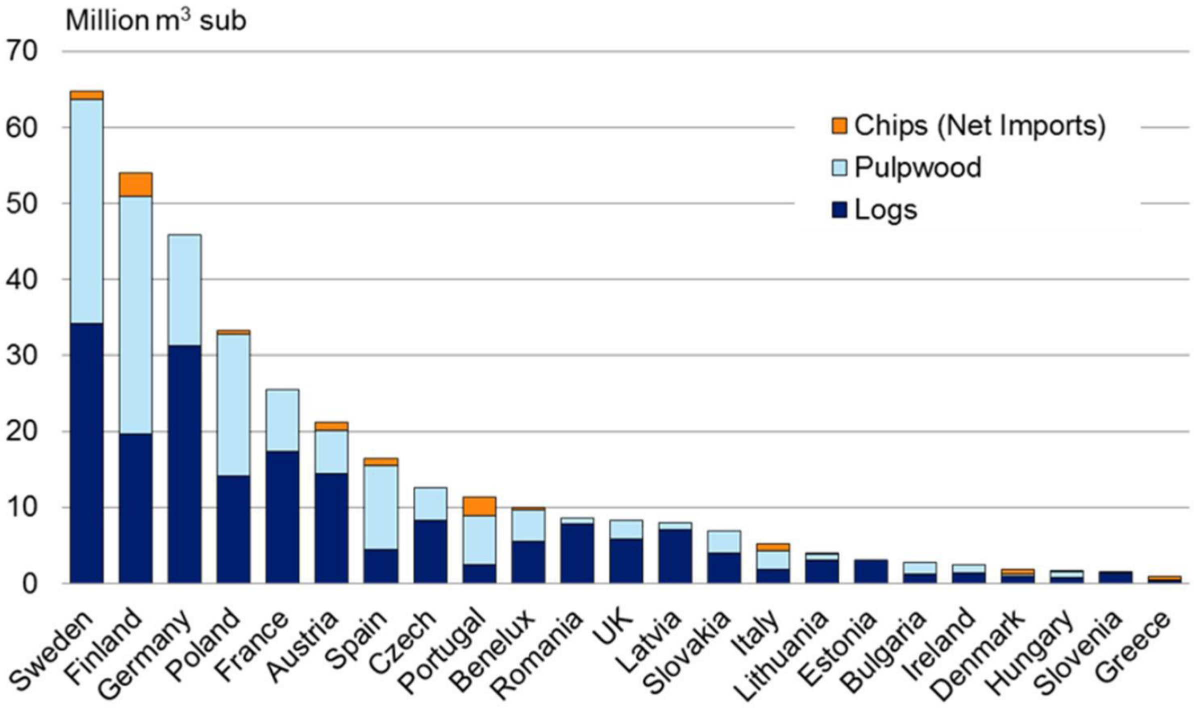

Fig.6. Industrial round wood consumption in EU countries in 2011(Pöyry) [11]

## 6. Finnish Bio-CCS roadmap

In order to understand the potential of different technologies and sectors, a scenario approach was taken. This analysis was conducted for Finland, to represent the Nordic approach for the biomass use in Europe. The Bio-CCS potential was estimated from several viewpoints, trying to assess the realistic maximum potential with each technology and/or sector based on technical deployment potential, existing sites and policies. The technologies and their key figures are compared based on different scenarios. Different sectors utilizing biomass as raw material are separately investigated and the most relevant approach for the development of each sector has been set as a basis for potential estimation. The estimations are based on the projected utilization of biomass, infrastructure potential, sustainable biomass resources, existing and future infrastructure, etc. In each sector, the most relevant basis for limiting factor of deployment potential is considered.

The time perspective of the scenarios is up to year 2030. The $CO_2$ emissions, $CO_2$ emission reduction potential and costs of $CO_2$ emission reductions are estimated for different scenarios as well as preconditions and consequences of the scenarios. Also investments needed to realize the potential are calculated. Six scenarios based on different relevant sectorial limitations were selected for further evaluation:

- prospects for liquid biofuels and Bio-SNG production
- biomass utilization in energy production in existing infrastructure
- biomass co-firing in existing coal based energy production
- biomass co-firing in peat fired power plants
- biomass usage in forestry
- biomass use in iron and steel industry

The scenario results with related costs are presented in Figure 5. The vertical line in the figure differentiates measures already undertaken and future measures. E.g. the biomass utilized in pulp and paper sector is already being exploited, and the negative cost associated to the fact that black liquor in the process needs to be treated in recovery boiler. The impact of increased biomass use is represented by green bars and the impact of deploying CCS is represented with blue bars. The numbers associated with the green bars show the annual biomass amount to be utilized in the sector. Based on this approach, the techno-political maximum potential of Bio-CCS in Finland is estimated to be ~44 Mt/a while the overall $CO_2$ emissions from Finland have recently been in the range of 70 Mt/a. This is a techno-political maximum and not a result of cost optimization. Cost optimization scenarios for Finland have shown results in the range of 8-12Mt/a in 2050 when the overall emission reduction target is set to 80% [4].

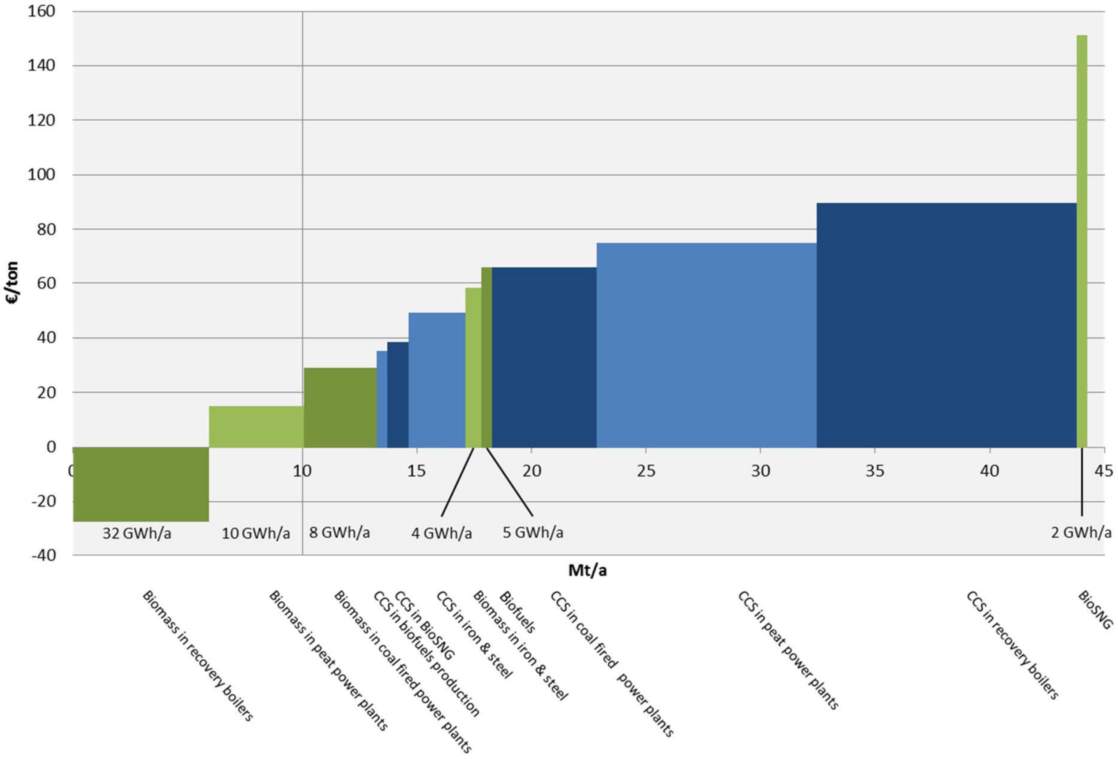

Fig. 7. Techno-political maximum for Bio-CCS potential in Finland 2030. [5]

The potential of Bio-CCS is in the same range as the potential of fossil CCS in Finland. Total technical potential of Bio-CCS in Finland in 2030 is estimated to be 45 Mt $CO_2$/a with the sustainable biomass availability in addition to costs optimization being the limiting factors. Reaching these magnitudes of emission reduction stated above would require use of nearly all sustainable forest growth in addition to all forest residues available in Finland. The raw material availability in relation to cost of raw material will most likely limit the exploited potential to the range of 10 Mt$CO_2$/a.

## 7. Conclusion

Capturing and storing $CO_2$ from biomass utilizing processes (Bio-CCS) binds $CO_2$ from the atmosphere. The net $CO_2$ reduction impact of Bio-CCS per unit energy produced can be multifold in comparison to fossil CCS or 2nd generation biofuels alone. If biogenic $CO_2$ emissions are accounted for, Bio-CCS can be economically feasible compared to fossil CCS. This however depends strongly on the availability and price of the biomass raw material. The potential impact of emission reductions in Finland, in Europe and globally can be significant; In Finland alone in the range could be tens of Mtons yearly if the potential is fully exploited. In principal, the same technologies are suitable for capturing $CO_2$ from biomass applications as for fossil fuel applications. The technical implementation of Bio-CCS to different industrial sectors goes hand in hand with the development of conventional CCS technology. Typically, biomass installations are of smaller scale in comparison to their fossil fuel based counterparts due to the smaller amount of raw material available, the geographical locations related to the raw material availability and due to product demand.

Both from logistics and cost point of view thermochemical biomass conversion processes, such as biodiesel production based on gasification Fischer–Tropsch synthesis or second generation ethanol production are considered as first phase targets for applying capture of $CO_2$. The potential for Bio-CCS in co-firing power production in European is considered to be large whereas combined heat and power production enables superior overall efficiencies also when deploying CCS. Non-traditional biomass processes, such as algae, can open up new opportunities for capturing and storing biogenic $CO_2$. The underlying question is the most efficient utilization of biomass; what would be the overall efficiency in the sustainable biomass value chains.

Bio-CCS and negative emissions can make a significant contribution to climate change mitigation and it is the only large-scale technology that can remove $CO_2$ from the atmosphere. The profound Energy Roadmap 2050 emission reduction targets for greenhouse gases cannot be met without deployment of CCS and rationally reasoned Bio-CCS. However, as biomass is a constrained resource, special attention should be paid to the direction of these raw material streams only to most efficient utilisation with high overall efficiencies. To make Bio-CCS deployment happen in Europe and globally, biogenic $CO_2$ -emissions must be acknowledged, and there must be developed incentives to become carbon negative.

## 8. Discussion

Forest biomass is the biggest biomass raw material stream in Europe. As one sixth of European forest biomass is utilised in Finland and the maximum Bio-CCS potential is 45 Mtons/a it is difficult to imagine the European potential for Bio-CCS would be proportionally a lot higher. 45Mt/a is a large amount, but this highlights the need of revising some of the Bio-CCS potential estimates presented in the public. The question is related to the availability of low cost biomass raw material and woody biomass supply chains. Current woody biomass supply chain is based on utilising all different fractions and side streams of forest biomass, of which the energy fraction is the cheapest. In order to get the wood out of the forests, higher priced fractions need to bring income to forest owners to get the wood moving and this enables moving of cheap fractions at the same time as well. It is not economically feasible to harvest the cheapest fractions alone and therefore they alone do not enable current utilisation of forests. The question of Bio-CCS potential is also related to the current use of wood. The pulp and paper industry currently accounts for the majority of wood energy use in Europe. If ETS and carbon prices enable power producers to pay more from the carbon neutral wood fuel, this might naturally pose pressures for rising prices of energy wood. On the other hand, this puts pressure on fibre wood prices and therefore also on the largest bioenergy producing sector in Europe, making it unclear what the total impact e.g. on $CO_2$ emissions would be and leading to perverse incentives. However, this complexity is to some extent addressed in the latest EC proposal for reducing GHG emission by 40% by 2030 [12] aiming at removing overlapping policy targets with the setting of only a single target for emissions.

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