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Life cycle assessment of negative emission technologies for effectiveness in carbon sequestration

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Abstract

As climate change and emissions targets tighten, negative emissions technologies (NETs) will play a crucial role in making sure global temperature rises do not exceed Paris Agreement goals. There are a variety of NETs that can be used to abate greenhouse gas (GHG) emissions, but it is uncertain which are more effective, and by how much, as well as what the net GHG removal is as all NETs will emit GHGs and other pollutants throughout their life cycles. We conducted a life cycle assessment (LCA) to compare four NETs: afforestation/reforestation, enhanced weathering, direct air capture and bioenergy with carbon capture and storage. These are compared on their life cycle impacts to climate change, land use change and toxicity (human and terrestrial). We find that the most effective NET is afforestation/reforestation for the environmental impacts considered while enhanced weathering and direct air capture are less effective. However, when the rate of carbon removal is considered, we find that afforestation/reforestation is much slower than the other NETs. Therefore, while it has the lowest impacts to the environment, either long time frames or large-scale implementation is needed for it to match the capacity of direct air capture or bioenergy with carbon capture and storage.

Keywords: negative emissions technologies; life cycle assessment; afforestation; enhabced weathering; direct air capture; bioenergy with carbon capture

1. Introduction

The reduction of greenhouse gas (GHG) emissions is critical for meeting Paris Agreement targets but the rate of decarbonization is not matching the rate needed to meet 2°C or 1.5°C goals [1]. As fossil fuels are predicted to play an important role in global energy demand up to and beyond 2030 [2, 3], there is a need for negative emissions technologies (NETs) to ensure net-zero emission targets are met.

These NETs are technologies which remove carbon dioxide (CO_2) from the atmosphere and there are a wide variety of options available, ranging from those which increase the size of carbon sinks available, to storing CO_2 in geological storage facilities [4].

Nomenclature

AR	afforestation/reforestation
BECCS	bioenergy with carbon capture and storage
DAC	direct air capture
EW	enhanced weathering
GHG	greenhouse gas
LCA	life cycle assessment
NETs	negative emissions technologies

Previous studies have estimated the life cycle impacts of specific NETs [5-8] or have reviewed the use of life cycle assessment (LCA) for evaluating NETs [9]. However, no

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studies have compared multiple NETs on their effectiveness in removing CO_2 and other impacts to the environment. This is the aim of this work; we present a LCA of four different NETs with the aim of comparing them on their life cycle GHG emissions and other environmental impacts (land use and toxicity). As far as the authors are aware, this is the first study to compare multiple NETs on their life cycle environmental impacts. This is important to study, as emissions from NETs predevelopment and operation could negate or significantly reduce the net GHG removal or result in other adverse impacts to the environment and subsequently result in NET strategies being less effective.

The results of this work would be of interest to policy makers, individuals involved in developing NETs or anyone with an interest in NETs.

2. Methodology

The LCA was conducted in GaBi 10 for the four NETs:

- afforestation/reforestation (AR)- planting of trees for carbon dioxide removal;
- enhanced weathering (EW)- removal of carbon dioxide from the atmosphere via chemical decomposition of rock. Olivine is considered in this work;
- direct air capture (DAC) with carbon storage- separation of carbon dioxide from ambient air which is then stored in geological storage; and
- bioenergy with carbon capture and storage (BECCS)- capturing the carbon dioxide from the flue gas of biomass combustion in a biomass power plant, which is then stored in geological storage.

The functional unit is one tonne of CO_2 (1 t CO_2) sequestered and a cradle to grave system boundary is considered for all the NETs, as shown in Figure 1. End of life activities are not considered in our system boundary because of significant differences and uncertainties in the types of activities carried out per NET.

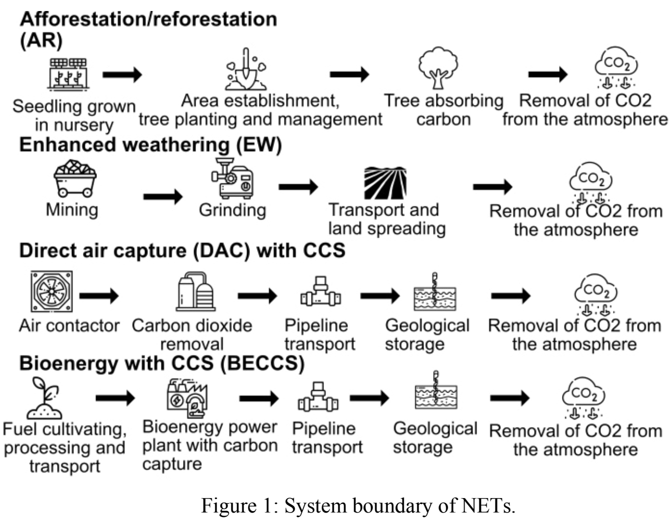

Figure 1: System boundary of NETs.

2.1. Life cycle inventory data and impact assessment method

The NETs were modelled based on existing projects (Table 1 and Table 2) and the ecoinvent v3.4 dataset was used to model the processes. A North American geography is considered for all the NETs; DAC and BECCS are Canadian, and AR and EW are based on being located in the USA. The IPCC AR5 LCIA method was used to calculate the impacts to climate change (global warming potential, GWP) while the ReCiPe was used to estimate the impacts to land use and toxicity (terrestrial and human).

Table 1: Parameters of NETs.

	CO_2 removal capacity	Projects based on	Project lifespan
AR	5 kg CO_2 per year per tree (1.3 to 22)	Panama forestry and UK forestry[1] [10-12]	10 to 100 years
EW	0.4 t CO_2 per t olivine (0.3 to 0.6)	Project Vesta [13]	23 to 62 years[2]
DAC	1 Mt CO_2 per year	Carbon Engineering [14]	25 years
BECCS	4 Mt CO_2 per year	Drax BECCS plant [15]	25 years

[1]for tree density only
[2]time to reach full saturation

2.1.1. Afforestation/reforestation

The amount of CO2 removed by trees is 1.3 to 22 kg CO2 per year per tree (average of 5 kg CO2 per year per tree) [16-18], and the tree density is 333 to 2,500 trees per hectare (average of 1,400) [10-12]. These were used to build the models in GaBi, as they determined how many seedlings, the amount of land preparation and forestry management is needed over the project's lifespan. Energy and material requirements for land preparation and forestry maintenance are adapted from Nicese 2021 [7]. A 100 km distance (round trip) between the nursey and planting site is assumed. A sensitivity analysis was conducted by varying the tree density, CO2 removal rate and project lifespan. Different forestry management practices were not considered.

2.1.2. Enhanced weathering

Ground olivine is spread over land e.g. coastal areas, soil treatment, and any CO_2 in the air will react with it to form carbonate minerals. The carbon absorption capacity of olivine ranges from 1.6 to 3.7 t olivine per t CO_2 (average of 2.7 t olivine per t CO_2) [19, 20]. This impacts the amount of olivine mining and processing required. We consider olivine ground to grains of 10 μm diameter, with 20 t trucks used to transport the olivine 48 km (30 miles) to the site for land spreading. Mining and processing energy requirements are adapted from Hangx and Spiers 2008 [19]. A sensitivity analysis was conducted by varying the trucking distance, energy source to grind the olivine (Table 2) and the purity of the rock (60% and 100%).

2.1.3. Direct air capture with carbon storage

A liquid amine process is considered and our process is based on the pilot plant operated by Carbon Engineering [14]. This facility has a 1 megaton CO_2 (Mt CO_2) per year capacity and all energy and material requirements are adapted from Keith 2018 [14]. Carbon dioxide in ambient air reacts with potassium hydroxide to form potassium carbonate. This is then reacted with calcium hydroxide to form calcium carbonate, which is then decomposed under high temperature to separate out the

CO_2 for storage. Heat and power requirements were met through a variety of methods, including onsite combined heat and power generation, grid electricity and renewable electricity (Table 2). A CCS pipeline distance of 80 km is considered [21], and injection energy is adapted from Koornneef 2008 [22]. A sensitivity analysis was conducted by varying the heat and power source to the DAC process and the carbon capture pipeline distance.

2.1.4. Bioenergy with carbon capture and storage

We consider a biomass power plant (for heat and power generation) with post-combustion carbon capture using an amine solvent (monoethanolamine, MEA). Our power plant is based on the Drax BECCS plant which has a 4 Mt CO_2 per year capacity and uses woodchips as fuel [15]. We also consider miscanthus pellets as an alternative fuel. The heat and power needed in the carbon capture process is met through the heat and power generated by the power plant. As more energy is produced by the power plant (per t CO_2 generated), subdivision was used. A CCS pipeline distance of 80 km is considered [21], and injection energy is adapted from Koornneef 2008 [22]. A sensitivity analysis was conducted by varying the energy source used to produce miscanthus pellets and the carbon capture pipeline distances. Variations in the feedstock production (e.g. agriculture practices) were not considered because of uncertainty and a lack of data available.

3. Results

3.1. Impacts to climate change

All of the NETs considered have a net carbon removal, with the exception of DAC when grid electricity is used for onsite power and natural gas used to meet heat needs (Figure 2, upper limit of error bar). The most carbon effective NET is AR (GWP of 36 kg $CO_{2eq.}$/t CO_2 removed) followed by BECCS (GWP of 51 to 201 kg $CO_{2eq.}$/t CO_2 removed) and consequentially these have high net CO_2 removal (net removal of 799 to 964 kg $CO_{2eq.}$). In BECCS, the biomass production and processing are the main hotspots while in AR it is the forestry management. EW and DAC have lower carbon removal (GWP of 62 to 636 kg $CO_{2eq.}$/t CO_2 and 205 to 964 kg $CO_{2eq.}$/t CO_2, respectively) but when energy and heat needs are decarbonized, the net carbon removal significantly improves (GWP of 62 kg $CO_{2eq.}$/t CO_2 removed and 205 kg $CO_{2eq.}$/t CO_2 removed, respectively). The reason why AR is the most effective NET is because it has the lowest energy and materials inputs; most of the energy and materials are used in the forestry management and planting (tree protector and truck to transport the saplings), and little is needed during site preparation per tree. The GWP is correlated with the lifespan of the project and tree density; under a 10-year lifespan and low tree density, the GWP is significantly higher in comparison to the baseline (up to 636 kg $CO_{2eq.}$/t CO_2 removed, Figure 2).

However, while AR has high net carbon removal, the rate of removal is low (Table 3). When comparing the NETs on rate of CO_2 removal, DAC and BECCS have much higher rates and subsequently fewer units are needed per t CO_2 removed.

Table 2: Data inputs used to model the NETs.

AR
Tree density: 1,400 (333 to 2,500) per hectare [10-12]
1.2 seedlings per mature tree [23]
100 km distance round trip from nursery to planting [7]
Tree protector used (2 kg in weight)
Energy requirements for ploughing, excavation, tilling, harrowing and forest maintenance taken from Nicese et al., [7]
Diesel is used in machinery during ploughing, excavation, tilling and harrowing
Petrol is used to power machinery used in forestry management e.g. power saws, chainsaws
Fuel and equipment needs were calculated per hectare (for ploughing, excavation, tilling and harrowing) and per tree (forestry management)
EW
Crushing and grinding is carried out in the quarry
20 t trucks travel 30 miles for land spreading
Olivine ground to 10 μm diameter grains
Mining energy: 2 kWh/t rock [19]
Crushing energy: 2 kWh/t rock [19]
Transport to grinding energy: 3.5 kWh/t rock [19]
Griding energy: 172 kWh/t rock [19]
Electricity and diesel used to meet energy demand
USA grid electricity and renewable (wind and hydro) electricity for grinding considered
DAC
DAC energy requirements [14]:
Contactor: 82 kWh/t CO_2
Causticer: 27 kWh/t CO_2
Slaker: 3,584 kWh/t CO_2
Calciner: 1,458 kWh/t CO_2
Auxiliary: 213 kWh/t CO_2
Onsite heat and power generation (natural gas, biogas, woodchips), Canadian grid electricity only, Canadian renewable (wind) electricity, grid electricity and natural gas and renewable electricity and biogas considered for DAC heat and power
80 km CCS pipeline is baseline and 1.9 to 500 km considered in sensitivity analysis [21]
Air flow into DAC process is 251,000 t/h which results in 112 t/h CO_2 produced [14]
CO_2 transport and injection process same as in BECCS
BECCS
0.9 kg miscanthus pellets and woodchips per 1.6 kg CO_2 [24]
Canadian grid and renewable (wind) electricity to produce miscanthus pellets considered
Carbon capture energy consumption is met through energy generated by biomass power plant [22]:
Scrubber energy: 24 kWh/t CO_2
Stripper energy: 1,390 kWh/t CO_2
CO_2 compression energy: 111 kWh/t CO_2
MEA consumption: 2.34 kg/t CO_2
80 km CCS pipeline is baseline and 1.9 to 500 km considered in sensitivity analysis [21]
CO_2 injection energy: 7 kWh/t CO_2 [22]

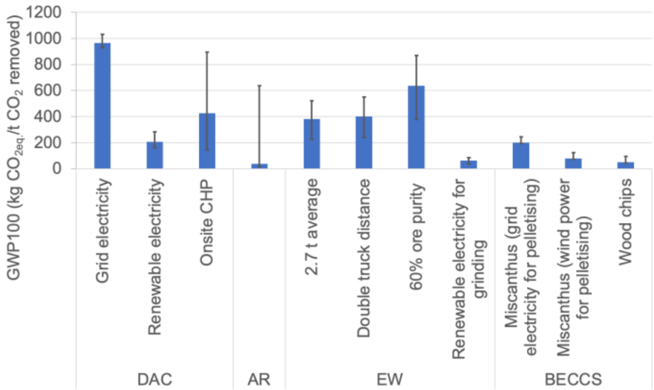

Figure 2: GWP results (excluding biogenic CO_2); bar shows the baseline and the error bars show the range in values under various scenarios: energy mix, tree density, truck transport distance, CCS pipeline distance etc.

Table 3: Time to sequester and the number of units needed to sequester 1 t CO_2. The values shown are for amount of CO_2 removed only and are not based on the life cycle GWP results.

	Time to sequester 1 t CO_2	Number of units to sequester 1 t CO_2 in one year
AR	10 to 100 years[1]	46 to 735 trees
EW	23 to 62 years[2]	37 to 229 t olivine
DAC	32 seconds[3]	1×10^{-6} DAC plants
BECCS	8 seconds[3]	2.5×10^{-7} BECCS plants

[1]per AR project
[2]per 1.6 to 3.7 t olivine
[3]per plant

3.2. Impacts to land use

When impacts due to land use (species loss caused by land use change, relative to crop production) are considered, AR has the lowest impact (8 annual crop$_{eq.}$ y/t CO_2 removed) followed by DAC (2 to 15 annual crop$_{eq.}$ y/t CO_2 removed) and EW (20 to 33 annual crop$_{eq.}$ y/t CO_2 removed) as can be seen in Figure 3. BECCS has much higher impacts (253 to 281 annual crop$_{eq.}$ y/t CO_2 removed) in comparison to the other NETs. This is primarily caused by biomass production, as large quantities of miscanthus and woodchips are needed to sequester 1 t CO_2 and consequentially the impacts to land use are large. As different agricultural practices were not considered in this work, there is little difference between the BECCS scenarios shown in Figure 3- different length of the CCS pipelines is only considered in the error bars and this has little effect on the impacts to land use change. Had this been assessed in the sensitivity analysis it is likely the error bars would be more significant in BECCS, as the biomass production and processing are the main emission hotspots.

The impact of BECCS reduces when woodchips are used instead of miscanthus, but the impacts are still much larger than the other NETs. Only AR under the scenario of lowest tree density and 10-year project life span has impacts comparable to BECCS. Impacts are high under this scenario as large areas of land are needed to sequester 1 t CO_2 (because more trees are needed), which results in more forestry management needs. In DAC the heat and power needs of the process are the main hotspots for this indicator. The impacts greatly reduce when heat and power are met through onsite generation instead of grid electricity. In EW, the olivine mining is the main impact hotspot and the impacts greatly increase when the ore purity is lower (60% instead of 100%) and when the absorption capacity is lower (3.7 t olivine per t CO_2 instead of 1.6 or 2.7 t olivine per t CO_2).

3.3. Impacts to toxicity

When comparing the NETs in their impacts to terrestrial and human ecotoxicity, AR has the lowest impacts overall (187 and 24 kg 1,4-dichlorobenzene$_{eq.}$/t CO_2 removed (kg 1,4-DCB$_{eq.}$/t CO_2 removed)), as shown in Figure 4, with impacts caused mostly by the plastic tree protector, truck transporting the sapling for planting and metals used in the machinery used in forestry management (e.g. power saw). EW has the highest impacts (546 to 1,166 kg 1,4-DCB$_{eq.}$/t CO_2 removed), mostly due to the electricity used to grind the olivine (human ecotoxicity) and the transport and spreading of olivine in land spreading (terrestrial ecotoxicity). In both human and terrestrial ecotoxicity, the electricity source and consumption in EW is important as impacts are much higher when grid electricity is used (in comparison to renewable electricity) and when the ore is 60% pure.

BECCS has high impacts in terrestrial ecotoxicity (1,300 kg 1,4-DCB$_{eq.}$/t CO_2 removed), which are mostly caused by emissions from the bioenergy power plant but the feedstock also has a small effect as impacts are slightly lower when woodchips are used instead of miscanthus. However, it has the lowest impacts in human ecotoxicity (-663 to 82 kg 1,4-DCB$_{eq.}$/t CO_2 removed); negative for the miscanthus scenarios because of net removal of substances harmful to human health during feedstock cultivation/production. Like in Section 3.2 the error bars are not significant in both terrestrial and human toxicity because only increasing/decreasing the CCS pipeline length was considered in the sensitivity analysis and as can be seen, this has minimal impact. Had other variables such as the operating conditions of the biomass power plant e.g. flue gas treatments or other biomass fuels, been assessed it is likely the error bars would be more significant.

DAC has high impacts in both terrestrial and human ecotoxicity which are caused by the heat and power needs of the process, as well as calcium carbonate consumed in the process. The impacts to terrestrial ecotoxicity are high when grid electricity is used, as well as when woodchips are used to fuel onsite heat and power generation. Grid electricity is also the main emission source in human toxicity, as the grid electricity scenarios have higher impacts than when renewable electricity and onsite heat and power are used to meet heat and power needs.

4. Conclusions

There is a net carbon removal for all the NET options considered with AR being the most effective as it has the lowest GWP. AR is also the most effective across the other environmental impacts considered. However, it has a low carbon removal rate which means that while it has the lowest GWP, large quantities of CO_2 can only be removed either over long timespans or when large numbers of trees are planted.

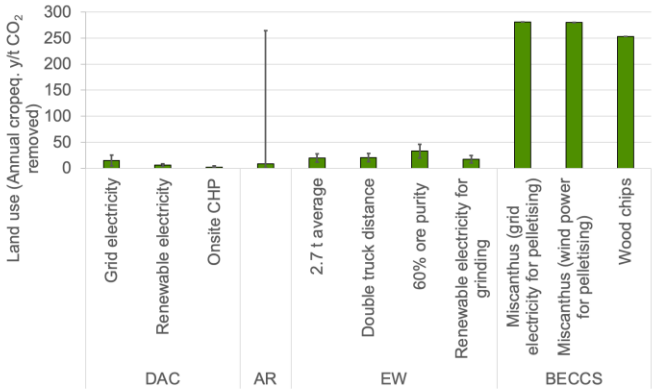

Figure 3: Land use impacts; bar shows the baseline and the error bars show the range in values under various scenarios: energy mix, tree density, truck transport distance, CCS pipeline distance etc.

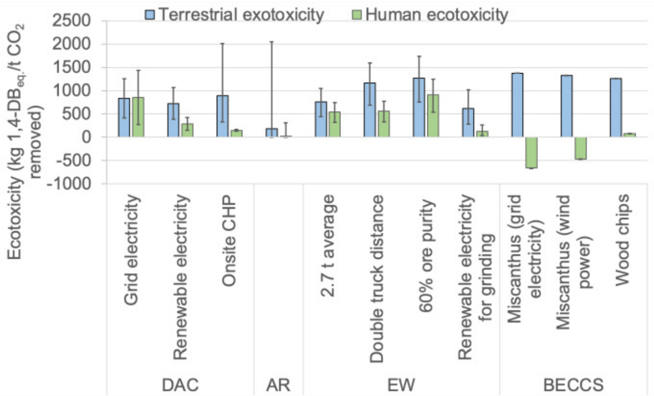

Figure 4: Terrestrial and human ecotoxicity impacts; bar shows the baseline and the error bars show the range in values under various scenarios: energy mix, tree density, truck transport distance, CCS pipeline distance etc.

Of the other NETs, EW and DAC are the least effective in terms of impacts to climate change and toxicity but have much lower impact for land use in comparison to BECCS. It is clear that the different NETs have varying effectiveness in terms of carbon removal and other environmental impacts. While AR appears to be the most carbon effective, large quantities of it would be needed to remove significant amounts of CO_2 from the atmosphere. BECCS and DAC, while being less effective, are capable of removing large quantities of CO_2 from the atmosphere much more quickly and require fewer units. Future work should focus on NETs not considered in this work, such as soil carbon and alternative DAC and BECCS configurations. Future work could also consider using the results of LCA studies of NETs in energy and climate models.

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References

[1] UNEP, *Emissions Gap Report 2019*. 2019, United Nations Environment Programme (UNEP): Nairobi, KE.
[2] IEA, *World Energy Outlook 2020*. 2020, International Energy Agency (IEA): Paris, FR.
[3] BP, *Energy Outlook 2020*. 2020, British Petroluem (BP): London, UK.
[4] EASAC, *Negative emission technologies: What role in meeting Paris Agreement targets?* 2018, European Academies Science Advisory Council (EASAC): Halle, DE.
[5] Lefebvre, D., et al., *Assessing the potential of soil carbonation and enhanced weathering through Life Cycle Assessment: A case study for Sao Paulo State, Brazil.* Journal of Cleaner Production, 2019. **233**: p. 468-481.
[6] Lefebvre, D., et al., *An anticipatory life cycle assessment of the use of biochar from sugarcane residues as a greenhouse gas removal technology.* Journal of Cleaner Production, 2021. **312**: p. 127764.
[7] Nicese, F.P., et al., *Estimating CO2 balance through the Life Cycle Assessment prism: A case – Study in an urban park.* Urban Forestry & Urban Greening, 2021. **57**: p. 126869.
[8] Deutz, S. and A. Bardow, *Life-cycle assessment of an industrial direct air capture process based on temperature–vacuum swing adsorption.* Nature Energy, 2021. **6**(2): p. 203-213.
[9] Goglio, P., et al., *Advances and challenges of life cycle assessment (LCA) of greenhouse gas removal technologies to fight climate changes.* Journal of Cleaner Production, 2020. **244**: p. 118896.
[10] Carbonfund.org. *Panama Reforestation Project – Reforesting a Lost Tropical Rainforest*. 2020 [cited 2020 December]; Available from: https://carbonfund.org/project/panama-reforestation-project-reforesting-a-lost-tropical-rainforest/.
[11] CCC, *Net Zero – The UK's contribution to stopping global warming*. 2019, Committee on Climate Change (CCC): London, UK.
[12] Forest Carbon. *Available projects* 2020 [cited 2020 December]; Available from: https://www.forestcarbon.co.uk/our-woodlands-and-peatlands/available-projects.
[13] Project Vesta. *FAQ/The Science*. 2020 [cited 2020 December]; Available from: https://www.projectvesta.org/faq.
[14] Keith, D.W., et al., *A Process for Capturing CO2 from the Atmosphere.* Joule, 2018. **2**(8): p. 1573-1594.
[15] Drax. *Drax to pilot Europe's first carbon capture storage project*. 2018 [cited 2020 December]; Available from: https://www.drax.com/press_release/drax-to-pilot-europes-first-carbon-capture-storage-project-beccs/.
[16] Forestry Research, *Forestry Statistics 2018- Chapter 4: UK Forests and Climate Chnage* 2018, Forestry Commission, Forest Research Edinburgh, UK.
[17] Toochi EC, *Carbon sequestration: how much can forestry sequester CO2?* Forestry Research and Engineering: International Journal, 2018. **2**(3): p. 148-150.
[18] Urban Forestry Network. *Trees improve our air quality*. 2020 [cited 2020 December]; Available from: http://urbanforestrynetwork.org/benefits/air%20quality.htm.
[19] Hangx, S.J.T. and C.J. Spiers, *Coastal spreading of olivine to reduce atmospheric CO2 concentrations: a preliminary evaluation*. 2008, Utrecht University, CO2 Capture, transport and storage (CATO): Utrecht, NL.
[20] Mazzotti, M., et al., *Mineral carbonation and industrial uses of carbon dioxide*, in *Carbon Dioxide Capture and Storage*, B. Eliasson and R.T.M. Sutamihardja, Editors. 2008, Cambridge university Press: Cambridge, UK.
[21] Global CCS Institute, *Carbon dioxide (CO2) distribution infrastructure: The opportunities and challenges confronting CO2 transport for the purposes of carbon capture and storage (CCS)*. 2012, Global CCS Institute: Canberra AU.
[22] Koornneef, J., et al., *Life cycle assessment of a pulverized coal power plant with post-combustion capture, transport and storage of CO2.* International Journal of Greenhouse Gas Control, 2008. **2**(4): p. 448-467.
[23] Cambria, D. and D. Pierangeli, *Application of a life cycle assessment to walnut tree (Juglans regia L.) high quality wood production: a case study in southern Italy.* Journal of Cleaner Production, 2012. **23**(1): p. 37-46.
[24] ecoinvent, *ecoinvent 3.4*, ecoinvent, Editor. 2017: Zurich, CH.

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