Master Thesis

Carbon Capture Benchmark

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Abstract: Carbon capture will play a key role in achieving the global climate targets set out in the Kyoto Protocol and the Paris Agreement. The aim of this project is to give a global view of the different existing and developing technologies for carbon capture. The current global framework of climate policies and geopolitical and energy crisis is presented, as well as projections for the future of this sector.

Additionally, examples of companies using these technologies are included to show their direct application. Finally, the alignment of carbon capture with the SDGs (Sustainable Development Goals) is analyzed and a practical case for the achievement of the SDGs in Tres Cantos, a municipality in the north of the Community of Madrid is explained.

Keywords: Carbon Capture; Climate Change; Technology; Global Warming, Direct Air Capture, Reforestation, Afforestation, Pyrolysis, Hydrothermal Carbonization.

1. Introduction

Climate change has become a global problem driven primarily by the anthropocentric increase of greenhouse gases in the atmosphere, such as methane (CH_4) or carbon dioxide (CO_2). The Paris Agreement has established a global framework to avoid severe climate change by limiting global warming below 2ºC, preferably 1,5 ºC compared to pre-industrial levels [1] [2]; the European Union has established the European Green Deal, which includes policy initiatives to achieve carbon neutrality by 2050 and the Fit For 55 initiative, which aims to reduce greenhouse gases emissions at least 55% by 2030 compared to 1990 [3] [4] [5].

In this context, carbon capture offers solutions to meet the challenge of the energy transition to a cleaner future, where reduction of emissions is not enough to reach the carbon neutrality target. Residual emissions from industrial processes, transport, or agriculture, will continue for a long time. Although getting to zero emissions is challenging, removing as much CO_2 as possible from the atmosphere is possible.

This study aims to analyse and compare the different technologies available or in development for carbon capture, including options from reforestation to complex technological solutions. The context of the current situation and future projections will also be described. Finally, the alignment of carbon capture with the SDGs (Sustainable Development Goals) is explained and a practical case of measures to reach the SDGs in a municipality is presented.

2. State of the Art

Technologies

Carbon capture refers to the different technologies for the removal of CO_2 from the atmosphere. Three types of solutions can be defined: technological, natural, and hybrid.
In the technological solutions, CO_2 is captured and compressed for transport by pipelines or ships to a geological formation for storage or to an industry for its usage. The main industrial uses of CO_2 today are fertilizer production and enhanced oil recovery (EOR)[1]. It could be used as well in other industries such as the manufacture of chemicals, fuels, or solvents.
In natural solutions, CO_2 is absorbed by trees, and in the case of hybrid solutions, CO_2 is retained in a liquid phase (bio-oil) and a solid phase (biochar) or captured by microalgae.

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[1] Enhanced oil recovery: injection of CO_2 into an oil reservoir to increase production by reducing oil viscosity.

There are currently numerous plans by governments to support the implementation of new carbon capture facilities in the energy sector and heavy industry, such as the €10bn European Innovation Fund. Figure 1 shows the current pipeline of capture technologies in operation, construction, or at different stages of development from 2010 to date [6]. According to the IEA (International Energy Agency), today's power and industrial carbon capture installations can capture around 40 MtCO2 annually [7]. However, the pipeline is still far from reaching the target set for 2030 in the NZE scenario (Net Zero Emissions by 2050 Scenario) of 1.200 Mt CO2 captured per year [8]. NZE scenario involves reaching net-zero emissions only in the global energy sector by 2050.

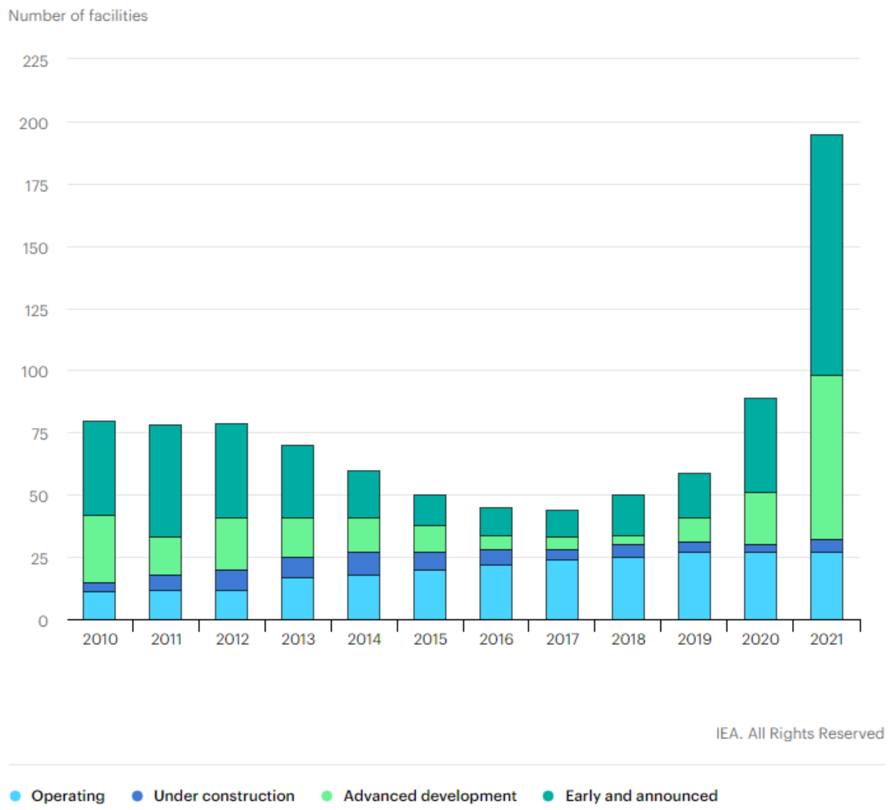

Figure 1. Global pipeline of commercial CCUS facilities operating and in development, 2010-2021 [6].

Technological solutions involve many technologies. Post-combustion carbon capture by absorption with amines is one of the most mature technologies available among the energy sector. This technology allows extending the life of fossil fuel plants through a refitting that allows to capture up to 90-95% of the emissions of CO_2 generated. It is possible to find pre-combustion capture technologies in Integrated Gasification Combined Cycle (IGCC) plants or oxy-combustion technologies, still in development. In addition, many companies and start-ups at an early stage of development are establishing projects around the world to develop and create new technologies for Direct Air Capture (DAC) using different methodologies.

Furthermore, there are natural carbon capture methods such as reforestation, afforestation, or agroforestry. Thanks to these methods it is possible to capture the CO_2 present in the atmosphere by photosynthesis. Likewise, some hybrid methods allow retaining of the CO_2 captured by the trees throughout their life, such as pyrolysis or hydrothermal carbonization. Other types of hybrid solutions involve fixing the CO_2 using microalgae.

These technologies allow companies to obtain carbon credits to compensate for the emissions of those sectors in which it is not possible to reach zero emissions. These credits can be used on regulated and voluntary markets, explained in the next section.

Climate policies

In 1997, the Kyoto Protocol was signed, aligned with the United Nations Framework Convention on Climate Change's objective of reducing global warming. In this protocol, the industrialized countries undertake to reduce their greenhouse gas emissions by at least 5% compared to 1990 levels during the period 2008-2012 (first commitment period). In particular, the European Union is committed to reducing its greenhouse gas emissions by 8%. The Kyoto Protocol enters into force in 2005, establishing for the first time real greenhouse gas emission reduction targets with compliance targets [9] [10] [11].

Subsequently, The Paris Agreement appeared in 2015. It is an international treaty aligned with the United Nations Framework Convention on Climate Change. It aims to limit global warming below 2ºC, preferably 1.5ºC, compared to pre-industrial levels. Therefore, it establishes 5-year cycles of climate measures, increasingly ambitious. Every 5 years, countries must declare their plans (NDC: Nationally Determined Contributions) for reducing emissions and adapting to climate change, as well as carry out measures to achieve these objectives [12] [13] [14] [15].

A global commitment and transition are necessary to face climate change since the increase in the concentration of greenhouse gases in the atmosphere is affected by worldwide emissions (Gaia Hypoyhesis [16] [17] [18]).

In line with the Paris agreement, the European Union establishes in 2019 the ***European Green Deal***, which includes a series of socio-economic measures aimed at achieving climate neutrality by 2050. The European Union also sets an intermediate target for reducing emissions by 2030 in the de-nominated Fit For 55 initiative. It aims to achieve a 55% greenhouse gases reduction by 2030 compared to 1990 [4].

Particular importance is attached to the proposed measures in the energy sector since it is responsible for 75% of the greenhouse emissions of the European Union [19]. In this sector, the use of renewable energies continues to gain importance, as well as the improvement of energy efficiency. Industrial processes and product use (e.g. Cement or steel production) account for 10% of EU emissions [20]. In this case, measures are proposed to encourage a circular economy and reduce emissions.

To help decarbonize these sectors (energy, heavy industry, and aviation), the European Union launched the EU ETS (Emissions Trading System) in 2005. The EU ETS is a regulated and mandatory emissions market for the most carbon-intensive sectors. This market operates with a cap-and-trade system, where companies receive free allowances[2] (carbon credits) based on a sector-specific benchmark. These companies can obtain additional emission allowances by auction if needed. Companies in the power sector don´t receive any free allowances, having to obtain all allowances by auction. At the end of the year, all companies must have enough emission allowances to compensate for their emissions or they will have to pay a penalty. In addition, each year the absolute emission cap for EU ETS is reduced to meet carbon neutrality by 2050 [21].

In addition to regulated markets, there are voluntary carbon markets as well. These allow companies in non-regulated sectors to offset their emissions by developing sustainable projects (reforestation, afforestation, etc). It is common to develop carbon capture projects in developing countries or transition economies because trees, surface (m^2) and labour cost are much lower [22]. It is very likely that in the future these markets will end up being regulated by international policies and laws, which limit activity in these sectors.

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[2] Countries carry out the distribution of free allowances (1 carbon credit = 1 t CO_2), following the regulation established by the European Commission.

It is essential that the lesser developed countries also adopt this type of carbon emissions regulation. Otherwise, there can be a migration of technologies from rich countries to the poorest, ending in these being polluted so that the rich can be net-zero.

Figure 2 shows historical emissions reduction in the European Union, as well as future trends. In this way, it can be observed that stricter measures will be necessary to achieve the stated targets.

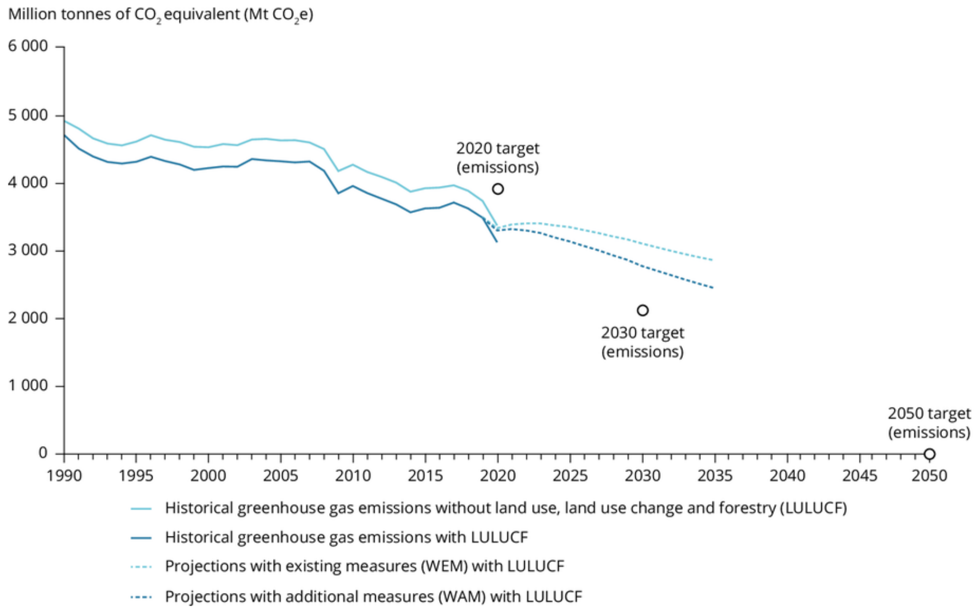

Figure 2. Historical trends and future projections of greenhouse gas emissions in EU.

Despite the European Union's efforts to achieve climate neutrality, some controversial actions related to the conflict in Ukraine are emerging. The gas price increase from the sanctions imposed and the threat of a cut-off from Russia has led countries like Germany to rethink their energy strategy. Due to the risk of gas supply, Germany has decided to temporarily reopen idle carbon power plants. Italy has also rethought the reopening of closed carbon plants to reduce dependence on Russia. In fact, the Vice-President of the European Commission and responsible for the Green Deal, Frans Timmermans, declared that the use of carbon as an alternative to Russian gas does not pose a problem to achieve the climate objectives of the European Union. He also stated that the security of supply takes precedence over all other considerations [23] [24].

In a context of a climate emergency, these measures and statements can be highly controversial because it seems that the priorities are not yet clear: the climate or the economy.

The following section describes the technologies available for carbon capture, as well as examples of companies using or developing such technologies.

3. Carbon Capture Technologies

NATURAL SOLUTIONS

Natural solutions offer options to offset emissions in the short term. Different types of projects are presented below:

Reforestation

One of the simplest methods for carbon capture is the reforestation of previously deforested or cleared areas in the past 50 years. Vegetation allows carbon in the atmosphere to be sequestered through photosynthesis, helping to achieve decarbonization targets. However, it should be considered that the foliage would emit the CO_2 captured throughout its life in case of decomposition or burning, so it is crucial to correctly manage the reforestation spaces. The ability to capture carbon depends considerably on tree species and area. Typically, a carbon capture range can go between 1-35 t CO2/ha.yr [25] [26].

In its Special Report on climate change and land management, published in 2019, the IPCC (Intergovernmental Panel on Climate Change) already noted that reforestation actions (recovery of degraded forests) and afforestation (planting forests where previously there were none) could remove up to 10,1 gigatons of greenhouse gases per year globally [27]. However, implementing this method requires a high initial investment (3000 €/ha [28]) and takes years to reach economic profitability. The legislation requires the maintenance of these forests for long periods of time to be considered carbon capture projects. In the case of Spain, the minimum period is 30 years [29].

The IPCC stresses the importance of carrying out planned reforestation, considering all the impacts that can originate in the short, medium, and long term. The socioeconomic implications for the populations near the reforested area should also be considered [30].

Reforestation is one of the most widely used methods for offsetting emissions and obtaining carbon credits for voluntary markets. These projects can generate controversy since they are usually carried out in developing countries, rather than where emissions are generated. This is mainly due to the lower cost of carrying out reforestation projects in these geographies (lower trees and labour costs, etc).

CO_2 Revolution

CO_2 Revolution is a Spanish start-up that is dedicated to reforestation and CO_2 compensation projects, taking into account the biodiversity of the ecosystems. CO_2 Revolution has carried out projects throughout Spain, especially in areas where fires have deforested.

Afforestation

Afforestation consists of planting trees to generate new areas of forest where historically there have not been (for more than 50 years). This process can be carried out for commercial or environmental purposes. The benefits include reducing soil erosion, lowering the impact of run-off, and improving air and water quality in the area. It also allows carbon sequestration of the atmosphere in the same way as reforestation.

Usually, afforestation´s purpose has been to commercialize the wood or fibers obtained from the trees. However, with increased policy and awareness toward a carbon-neutral economy, carbon capture projects are rising to obtain carbon credits for the voluntary markets. Fast-growing species are usually used, adversely affecting native species in the area.

Agroforestry

Agroforestry consists of introducing trees into agricultural areas (crop fields, farms, etc.). There are some negative aspects, such as competition for water and nutrients with the crop or pest hosting. Therefore, it is essential to define the trees' species to be implemented and their distribution in the area [31].

Agriculture, forestry, and other land use account for 23% of total anthropogenic emissions [32]. Therefore, this carbon capture method makes it possible to carry out sustainable agriculture, tackling the problems of deforestation associated with intensive agriculture [33] [34].

Forest Conservation

Deforestation is responsible for 17% of global CO_2 emissions, therefore, it is a crucial factor to consider when reaching decarbonization targets. One of this method´s main advantages is that large forest areas can be conserved with a meager capital investment [35].

This method gains particular relevance in tropical forests since they present a high risk of illegal timber harvesting and change in land use from forest to agriculture or stockbreeding [36].

HYBRID SOLUTIONS

Carbon capture is also possible through the transformation of biomass by chemical reactions. Different hybrid solutions are presented below:

Pyrolysis

As discussed in the previous section, trees return almost all of the CO_2 they have absorbed during their lifetime when decomposing. Thanks to biochar, it is possible to intercept this process capturing part of the carbon before it reaches the atmosphere. Biochar is a residue obtained from the decomposition of biomass at high temperatures in an inert atmosphere (absence of oxygen). This production process is called pyrolysis and can be divided into three main stages, as shown in figure 3 [37].

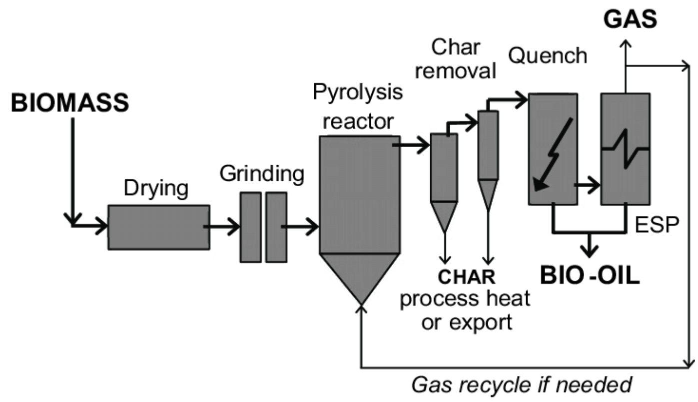

Figure 3. *Simplified biomass pyrolysis process* [37].

Firstly, the biomass is fed into the process, where it is dried to avoid water content in the bio-oil product and ground into small particles before reaching the reactor [37].

Secondly, the biomass decomposes in the pyrolysis reactor. The leading reactor technologies include, but are not limited to, fluidized beds, transported beds, rotating cones [38] . Usually, biomass pyrolysis is performed in a temperature range between 450-500ºC to maximize the generation of biochar, although operating conditions may vary depending on the feedstock and desired biochar properties. Pyrolysis is an endothermic process, so it requires energy contribution to maintain the reaction temperature. It is common to burn the product gases to obtain power, even to get a sustainable thermal process. As shown by a large number of studies, the biochar yield decreases with the increase of the temperature and heating rate, resulting in around 20 % weight (wt.) of the raw material [39] [40] [41] [42] [43]. This is because a higher temperature favors the generation of gases and a very reactive carbon, which evolves towards the formation of volatile compounds [44]. The effect of pyrolysis temperature on biochar yield is depicted in figure 4 for different biomass residues. Lower vapor residence times[3] are desired because it minimizes vapor cracking reactions and reduces process heat requirements [43].

In addition, biochar yield is affected by the proportion of biomass components: hemicellulose, cellulose, and lignin. Biochar yield is lower in biomass with high cellulose content. However, the higher the lignin content in the initial biomass, the higher the biochar yield due to its high thermal stability. Therefore, low process temperatures, slow heating rate, and higher lignin content are the key factors that favor biochar production in a biomass pyrolysis process [44].

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[3] Vapor residence time: time vapor fraction remains inside the pyrolysis reactor.

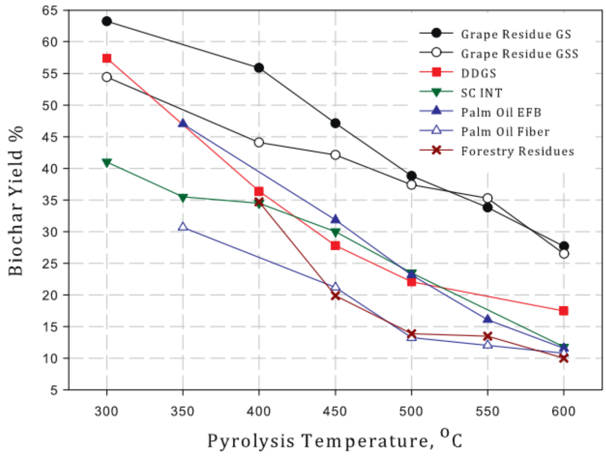

Figure 4. *Effects of pyrolysis temperature on the biochar yield from various biomass residues, wt. % feed, at 5s vapor residence time* [43]. *GS (Grape Skins), GSS (Grape Skin and Seeds), DDGS (Dried Distiller´s Grains), SC INT (Sugar Cane Internal Bagasse), EFB (Empty Fruit Bunches).*

Finally, the main products are separated: solid biochar, liquid bio-oil, and gas. One of the critical requirements in the design of a pyrolysis process is biochar removal because it can act as an effective vapor cracking catalyst. The solid fraction is usually separated in one or more cyclones. [37]. In the end, the gas is separated from the bio-oil by a fast-cooling process to maximize bio-oil recovery.

Plant-based biochar (PBC) can be used as a soil additive since it has a high carbon content and porosity. In this way, it improves the capacities of water retention, nutrients, and fixing of atmospheric carbon in the soil, but with little fertilizer effect on the ground. In addition, it is possible to consider it a method of carbon sequestration of the atmosphere due to its high stability, which allows it to stay in soil over the years [45].

However, the use of biochar is still a minority practice despite its advantages [46] [47]. Nevertheless, with the change of mentality towards climate change by companies and governments towards net-zero, it is beginning to gain importance as it is one of the few technologies already available to scale although there is room for improvement.

There is also criticism of biomass production because, as with biodiesel, conflicts could arise if land used for food generation is used for biochar production. Therefore, it is essential to emphasize that not every kind of biomass can be used for biochar generation. In addition, it is necessary that the source of biomass is close to the pyrolysis plant to avoid emissions in the transport to the plant.

The other by-product, bio-oil, can be used directly as fuel in boilers and furnaces. It can also be used for chemicals such as resorcinol-formaldehyde (wood adhesive) or to produce slow-release fertilizers. Furthermore, it can be injected into geological storage as a carbon capture method when it is not used for other commercial purposes [48] [49].

Living Char

Spanish company dedicated to the production and commercialization of biochar, developed by three non-profit cooperatives (Carbón Vivo, Idària "Empresa d'inserció" and TEB Verd). They also develop studies for the generation of knowledge about biochar since it is not yet known by many farmers [50].

Charm Industrial

American company dedicated to collecting residual biomass of crops and forests for its transformation into bio-oil by pyrolysis. It then transports the bio-oil for injection into deep geological storage for carbon capture [51].

Hydrothermal Carbonization (HTC)

Hydrothermal carbonization is an alternative method to pyrolysis. The main difference is that hydrothermal carbonization allows treating biomass regardless of its moisture level efficiently and at relatively low temperatures. In addition, it enables working with waste from different sectors, such as agriculture, solid municipal waste, or sludge, obtaining a homogeneous and easily storable product, which can be used for carbon capture or energy recovery [52] [53].

The process consists of a liquid phase chemical reaction in a pressure vessel (10-15 bar) with a temperature range between 180 to 220 ºC [54]. Unlike pyrolysis, it is an exothermic process, so the energy consumption to maintain the reaction temperature is much lower. [54]The reaction´s yields correspond to 75-80% solid fraction (similar to biochar), 15-20% liquid fraction, and 5% gas fraction (mainly CO2). In this process, 90% of carbon is captured [54]. Temperature is the key parameter of the reaction, so it must be correctly adjusted for each type of biomass to reduce ash production and change product yields.

The solid fraction can be recovered energetically in combustion boilers or be applied as a soil additive thanks to its properties, similar to biochar. Thanks to its high porosity structure it can retain water and nutrients, slowly releasing them to the soil. Its application to the soil presents the same qualities as in the case of biochar. The liquid-phase byproduct can be treated to eliminate the organic compounds to obtain water suitable for irrigation. It can also be used for energy recovery (anaerobic digestion) or to produce chemicals (fertilizers, bio-fuel, etc).

Ingelia

Spanish company dedicated to the development of hydrothermal carbonization technology. Since 2010, they have had an industrial "biochar" production plant in Valencia to demonstrate the viability of this technology and intend to expand this concept in other countries (figure 5).

Ingelia has developed a modular design, which provides net-zero "biochar" suitable for its energy recovery and a liquid phase, ideal for irrigation of dams or crops after eliminating the organic compounds. The modular design allows them to adapt to the availability of existing raw materials as well as seasonal variations. In addition, the same reactor can be used for several raw materials by varying the reaction parameters: P, t, or catalysts [55].

Figure 5. Ingelia´s Hydrothermal carbonization plant *[55]*.

Microalgae

Oceans, along with forests or forest areas, are considered the main natural carbon sinks. They can capture around 30% of all anthropocentric CO_2 emissions, presenting a higher carbon capture efficiency than terrestrial plants [56]. Part of the CO_2 dissolves in the surface layers of the water, while another part is captured through the photosynthesis carried out by photosynthetic microorganisms (algae or cyanobacteria) [57] [58].

One of the direct consequences of climate change is ocean acidification due to increased absorbed CO_2 in the oceans. Acidification reduces the ability of the oceans to capture CO_2, making it stay in the atmosphere for longer. Acidification, together with the pollution and overexploitation of the ocean, endangers the survival of marine ecosystems.

Artificial capture of CO_2 by algae reproduces the process that occurs naturally in the ocean but intensively (facilitating contact between microalgae and CO_2). Like all photosynthetic organisms, algae need solar radiation, CO_2, and nutrients (N, P, K) to generate biomass. Preferably, the source of CO_2 should be the exhaust gases from the chimney of some industry or power plant [59]. The ability to capture carbon depends on the choice of the species of microalgae. Some of the desired parameters are high growth rates, minimum nutrient requirements, resistance to adverse weather conditions, and resistance to pollution.

One of the main advantages of this carbon capture method is that microalgae cultivation does not affect land-use change because it is done in soils with no agricultural value. In addition, it requires a minor land extension than forests to capture the same amount of CO_2.

We can find two main methods to grow microalgae [60]:

- ***Open cultivation systems***: the easiest method corresponds to open ponds, presenting surfaces of up to 250ha. We can also find tanks or raceway ponds. CO_2 is injected and dissolved in the water, obtaining low yields per ha. It is necessary to maintain a level of agitation employing some mechanical element to avoid the sedimentation of the algae and to facilitate the diffusion of nutrients. Also, the injection of CO_2 itself provides part of the necessary agitation.
  Minimal capital and operating costs are some of the key advantages of this methodology. The biggest issue these systems present is the difficulty of controlling the temperature, a fundamental factor for the growth of the algae [59]. Another disadvantage is that this methodology is vulnerable to contamination and lousy weather conditions.

Brilliant Planet

This British startup is an excellent example of using this methodology. Its objective is to implement micro-algae carbon sequestration plants in coastal desert lands without needing fresh water. In this way, it aims to capture large quantities of CO_2 while contributing positively to ocean acidification and climate change reduction. Brilliant Planet plans to operate with open ponds, using seawater and replicating the perfect growing conditions for algae to proliferate. In this way, Brilliant Planet wants to achieve carbon capture at a low cost [61].

Figure 6. Morocco´s plant project by Brilliant Planet *[61]*.

- ***Closed cultivation systems***: These photobioreactors (PBRs) allow a high control of parameters, facilitating temperature and gas exchange control. In addition, it significantly reduces contamination concerns and leads to a significant reduction of space. The main drawback of this system is that it requires periodic cleaning [59]. Furthermore, this methodology involves high capital expenses in infrastructure and operation of the plants.

AlgaEnergy

The Spanish company AlgaEnergy uses this technology in one of its plants (figure 7). This plant uses CO_2 from the flue gases from Spain's largest combined cycle power plant (owned by Iberdrola) for the industrial production of microalgae [62]. The plant´s primary purpose is to commercialize biomass obtained from microalgae [63]. Microalgae biomass can be used to generate biofuels and bio-products for the pharmaceutical and cosmetic sectors.

Figure 7. AlgaEnergy Plant *[62]*.

TECHNOLOGICAL SOLUTIONS

The climate change regulatory framework has led the most carbon-intensive emission industries to develop carbon capture systems within their own processes. These technologies consist of the capture of CO_2 before it reaches the atmosphere. This results in a concentrated CO_2 stream that can be transported and stored. BECCS[4] (Bioenergy with Carbon Capture and Storage) projects use the same kind of technologies as fossil fuels in their processes.

Depending on how the capture of CO_2 is made, three methods are distinguished: post-combustion, pre-combustion, and oxy-combustion.

Post-combustion [64] [65] [66]

In this case, CO_2 is captured from the flue gas after the combustion of the fuel (coal, natural gas, or biomass) with air taken directly from the atmosphere (21% O_2, 79% N_2). Therefore, the concentration of CO_2 in the flue gas is low (10-15% [67]), requiring voluminous and expensive equipment to treat the entire flow of combustion gases.

The most used and mature post-combustion method is chemical absorption[5]. Firstly, flue gases enter the absorption column, where CO_2 reacts with a liquid solvent that retains it. Solvents are commonly amines (MEA) or ammonia. Subsequently, the CO_2-rich solvent stream is carried to a stripper column in which the reverse reaction takes place. In this way, the solvent is regenerated and taken back to the absorption column and a gaseous stream rich in CO_2 is obtained. However,

[4] BECCS: processes by which bioenergy is obtained from biomass, with a carbon capture stage.

[5] Chemical absorption: separation of one of the components of a gas phase by its solubility in a liquid solvent.

if done with absorption, CO_2-rich solvents can cause corrosion problems and the desorption stage requires high energy consumption. Subsequently, CO_2 is compressed for its transport for use in an industry or storage in a deep geological formation.

CO_2 post-combustion capture could be also done with membranes, adsorption[6], etc. In the case of adsorption, solids with a high specific surface are usually used (active carbon, zeolites, functionalized amines). Membrane separation is commonly used to capture CO_2 from natural gas combustion. Ideally, a membrane with high CO_2 selectivity[7] and high permeability should be selected.

The main advantages of this process are high efficiency and selectivity to CO_2 for low concentrations of it. In addition, this process can be implemented in existing plants as an end-pipe solution, without needing to make major changes in the plant. In addition, a plant that has been refitted will have a higher operating cost than the original plant.

A diagram of the process is shown in Figure 8.

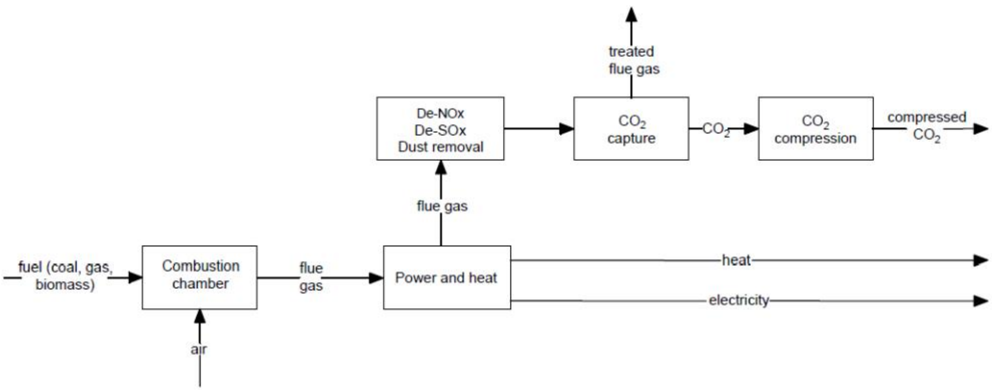

Figure 8. *Post-combustion CO2 capture process* [68].

Boundary Dam Carbon Capture Project (Canada)

In 2014, the 120 MW Boundary Dam coal plant was refitted with the installation of a carbon capture system. The installation of the equipment and modernization of the plant cost $1.24 billion. Thanks to this, the plant can continue providing coal energy, avoiding 90% of the emissions it emitted previously (~1 Mt CO2 per year). The captured CO_2 is then transported for its storage in geological formations [69] [70] [71].

This project demonstrates the feasibility of using carbon capture technologies in large coal-fired power plants as it remains one of the most widely used fuels worldwide. The technology can be installed in almost any existing coal power plant, allowing the continued use of coal as a fuel sustainably.

Pre-combustion [72] [73] [74]

This capture technology is normally used at Integrated Gasification Combined Cycle (IGCC) plants, which produce heat and electricity from syngas (CO + H_2).

In this process, the solid fuel (coal or biomass) is gasified instead of burned entirely as in the post-combustion process. Incomplete combustion occurs in the presence of pure oxygen and

[6] Adsorption: separation of a dissolved solid, liquid or gaseous component by its adhesion to a solid surface.

[7] A membrane is a selective barrier, which allows the passage of some compounds or others depending on its pore size.

steam to produce syngas. It is possible to obtain the syngas from methane steam reforming as well.

The syngas, a mixture of CO and H_2, is purified and fed to the Water Gas Shift Reactor, where steam is added to convert the CO into CO_2 and H_2. Then, CO_2 is captured prior to combustion, and H_2 is burned in a gas turbine to produce heat and electricity. A heat transfer system can recover the heat produced during H_2 combustion to produce steam, which is used in a turbine to complement the electric generation of the gas turbine. Usually, the CO_2 separation in pre-combustion methods is done by physical absorption[8] or using a membrane. Some of the compounds used for physical absorption are selexol, rectisol, or fluorine.

Typical gas composition before the separation is around 40% CO_2 and 55% H_2. Therefore, the main advantage of this configuration is that CO_2 capture is favoured due to the high CO_2 concentration. However, the main disadvantage of this process is that it is only applicable to new construction plants, so its implementation at the industrial level is currently minimal.

A diagram of the process is shown in Figure 9.

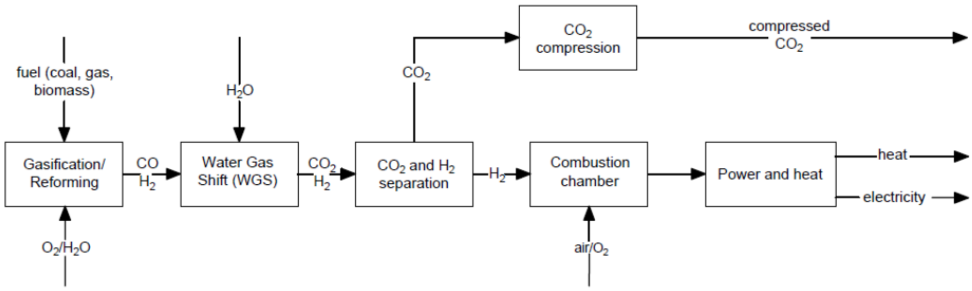

Figure 9. Pre-combustion CO2 capture process [68].

This technology is used to obtain blue H_2 (obtained from fossil fuels, including a CO_2 capture stage). It is low-emission hydrogen and is the most viable way to reduce emissions in the short and medium-term in hydrogen production. Hydrogen can be used as a fuel in a combustion chamber, as a raw material in industry or as a fuel. Therefore, it can be an alternative option until green hydrogen (generated from renewable energies) is available at an industrial level.

GreenGen Project

Project carried out by China Huaneng Group intending to demonstrate the feasibility of operating an IGCC carbon plant along with hydrogen production and carbon capture. The project corresponds to a 250 MW IGCC coal plant for generating electricity from syngas with a pre-combustion system carbon capture. In this case, the capture is made by absorption with amines. The project is already operating and has involved an investment of $360 million [75] [76] [77].

Oxy-combustion [78] [79]

The oxy-combustion process involves introducing pure oxygen to burn the fuel (coal, natural gas or biomass) rather than introducing air as in post-combustion processes. The elimination of N_2 from the combustion gas means a reduction in NOx formation, obtaining a rich stream in H_2O and CO_2 (85-90%). The heat generated is used to produce high-pressure steam that moves a steam turbine to generate electricity. Part of the flue gas is recirculated to the boiler to control its temperature. Subsequently, the stream is cooled to condense the water, obtaining a rich CO_2 stream.

[8] Physical absorption: separation of one of the components of a gas phase by reaction with a liquid solvent.

The main advantage of this technology is that the equipment is much smaller because N_2 is not going through the process, so the volume of the flue gases is much lower. This also facilitates the separation stage to obtain the CO_2-rich stream because the CO_2 concentration is higher. In addition, the gas treatment system is simplified due to the reduction of formation of NOx.

The oxy-combustion process is shown in Figure 10.

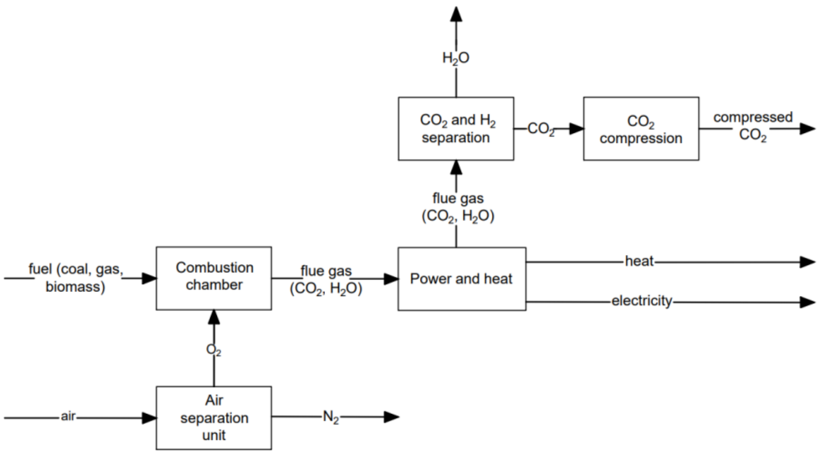

Figure 10. *Oxy*-combustion *CO2 capture process* [68].

Large-scale studies are currently underway, but the technology is still under development. Some pilot plants are Fortum Meri-Pori in Finland and Total Lacq in France [80] [81].

The methods seen above are useful to capture CO_2, but they are not enough to achieve decarbonization targets. Therefore, different technologies for direct air capture (DAC) to store CO_2 or for its commercial use (fertilizers, synthetic polymers, etc) appear. Today's direct air capture solutions are very energy-intensive and require plentiful zero-carbon energy to achieve net negativity (removing more carbon from the atmosphere than is emitted).

Different technologies under development by start-ups and companies are presented below.

Electrochemical carbon removal

This technology pulls the air through electrochemical cells[9] on which a certain voltage is applied, activating the electrodes and adding electrons to the system. In this way, the electrodes can bind the CO_2 and the rest of the air stream is returned to the atmosphere. Finally, a different voltage is applied, releasing and obtaining a CO_2 concentrated stream [82].

This technology is under development by the American start-ups Holy Grail and Verdox. Both are designing modular devices to scale technology according to capture needs [83] [84] [85]. The modular design will allow for more competitive costs, even on a small scale.

Chemical Carbon removal

The technology is based on pulling air from the atmosphere through an air contactor, where it is absorbed in a chemical KOH (potassium hydroxide) and water solution, obtaining a liquid-rich CO_2 stream. Different processes are then carried out to concentrate CO_2. In the pellet reactor $Ca(OH)_2$ (calcium hydroxide) is added to the solution, obtaining small pellets of $CaCO_3$ (calcium carbonate) with the captured CO_2. Pellets are separated from the refreshed KOH solution in a centrifuge. The refreshed liquid solution is recirculated to the air contactor to start the process again, while the pellets are taken to a calciner. High temperatures are applied in the calciner to

[9] Electrochemical cells are capable of generating chemical reactions when a voltage is applied.

obtain CaO (calcium oxide) pellets and a gaseous stream of CO_2, ready to be compressed and transported for use or storage. Calcium oxide pellets are recirculated to the pellet reactor after adding water to form calcium hydroxide again [86]. Figure 11 shows a simplified scheme of this process.

This technology is under development by the Canadian company Carbon Engineering and is being commercialized at industrial-scale by 1PointFive. Carbon Engineering has a pilot plant capable of capturing 1tCO_2 per day when in operation, and a pilot plant for transforming CO_2 into clean fuels [86]. 1PointFive currently has a commercial industrial-scale carbon capture project that is expected to be in operation by 2024 [87].

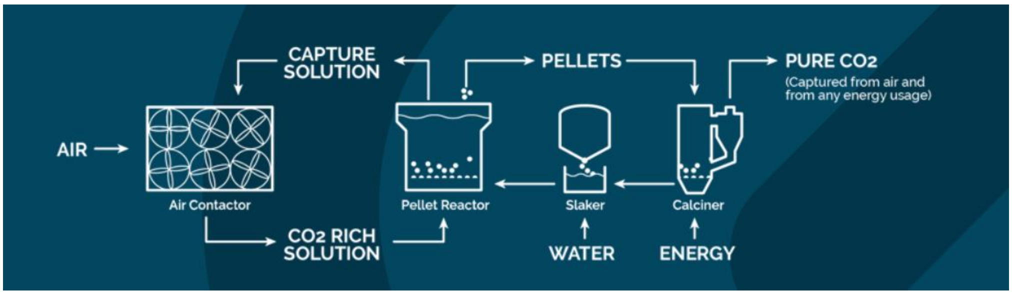

Figure 11. Chemical carbon removal process [86].

Filter Carbon removal

This technology is based on pulling air through a filter with a highly selective filter material that retains CO_2 and allows the rest of the air stream to return to the atmosphere. Once the filter has reached its maximum retention capacity, it is heated up to 100ºC, releasing CO_2 for injection into deep geological storage mixed with water [88].

This technology is under development by Swiss company Climeworks. Currently, it has 15 machines in operation powered by renewable sources (renewable energy or energy from waste). In addition, it has announced the construction of a second large-scale facility with the capacity to capture 36000 tCO2 per year [89].

Other technologies can be found, such as the one developed by the American start-up Heirloom. Heirloom aims to eliminate 1 billion tons of CO_2 by 2035 [90]. Its technology is based on the ability of minerals (one of the most important carbon sinks on earth) to chemically bond to the CO_2 present in air or water over long periods.

4. Future Projections

After analyzing the current situation and the technology benchmark, it can be concluded that carbon capture will play a key role in achieving the decarbonization targets. Its role is crucial in hard-to-abate sectors (heavy industry and long-distance transport) since they are the ones that will take the longest to reach net-zero targets. Figure 12 shows the Levelized cost of production for certain sectors with and without carbon capture technologies. The biggest challenges are faced by the cement industry and long-distance transport, especially aviation. The emissions produced in the clinker´s reaction in the cement industry make decarbonization very difficult. In the case of aviation, there are practically no alternatives to petroleum-derived fuels (kerosene), so high-cost synthetic fuels must be used [91].

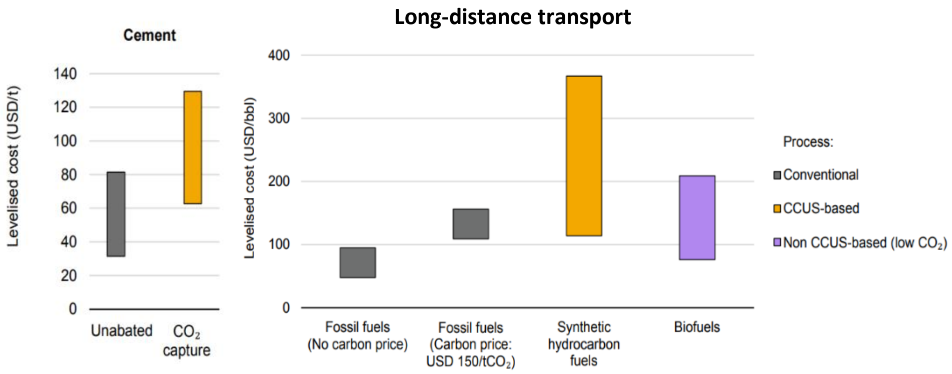

Figure 12. Simplified levelized cost of producing low-carbon cement and long-distance transport [91].

Carbon capture also offers technological solutions to reduce emissions from existing facilities in the power sector, as they will need to continue operating for years. In addition, natural solutions (reforestation, agroforestry, etc.) and innovative technological solutions (DAC) allow to capture CO_2 directly from the atmosphere, a fundamental requirement to achieve climate objectives.

Due to climate concern and increasing policies, the number of new carbon sequestration projects is on the rise. In addition, there is a shift in mentality from viewing carbon capture as a method of obtaining CO_2 for enhanced oil recovery to seeing it as a method with much greater potential.

According to the IEA, innovation in new technologies will be necessary to achieve the objectives in the Sustainable Development Scenario (SDS). The SDS presents an integrated vision of climate change, enhancing renewable energy services and reducing air pollution. In the SDS all current net-zero pledges are achieved by 2070 [92].
The development and commercialization of new technologies on a large scale could take decades, so a great effort and investment will be needed to develop the technologies in time. Figure 13 shows how technologies increase their contribution as cost reduces over time in the SDS.

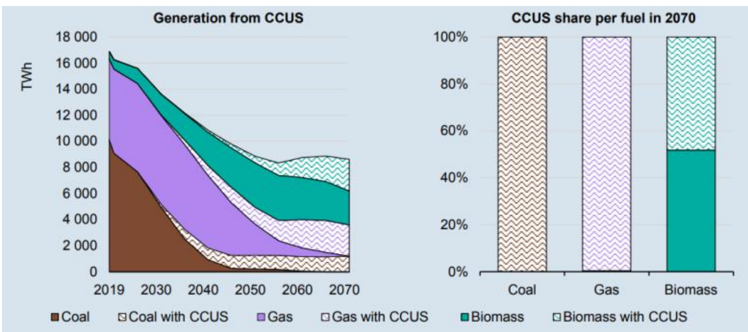

Figure 13. Global Electricity Generation from plants equipped with carbon capture by fuel type [91].

One of the trends is the emergence of industrial hubs, in which different CO_2 emitters share the transport and storage infrastructure. This reduces costs and encourages investment. It also offers an affordable transport and storage solution for smaller facilities. The Porthos Project is the largest CO_2 transport and storage project in Europe. It is made up of 4 companies (Air Liquide, Air Products, ExxonMobil and Shell) that plan to store captured CO_2 in an old gas well in the North Sea, which is currently empty. The Project has the capacity to store 2.5 Mt CO2 per year for 15 years and has involved an investment of 400-500 million euros [93].Other projects include the Nothern Lights in Norway or the Net Zero Teeside in the UK [94].

Another trend is the use of carbon capture for low-emission hydrogen production, as explained in the previous section. The implementation of these technologies can allow the development of hydrogen as an energy vector at a lower cost in the short-medium term. This makes it an ideal alternative until green hydrogen is economically viable. Figure 14 shows the levelized cost of hydrogen production by energy source and technology in 2019 vs 2050.

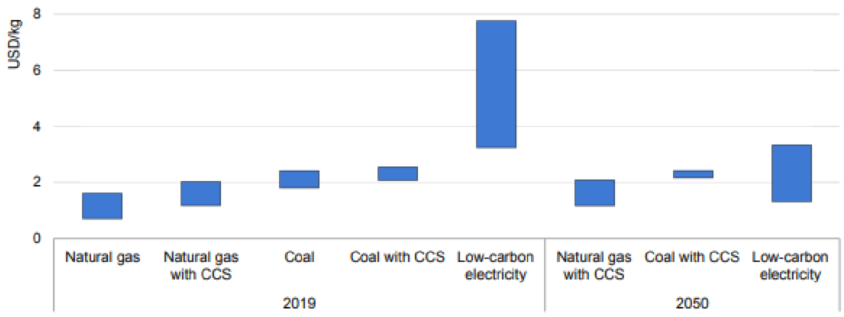

Figure 14. Global average levelized cost of hydrogen production by energy source and technology [91].

In the SDS, low-carbon hydrogen is crucial in the energy transition. Low-carbon hydrogen´s role will be crucial as fuel or raw material in sectors such as industry, power and transport. Figure 15 shows the evolution of hydrogen generation types in the SDS.

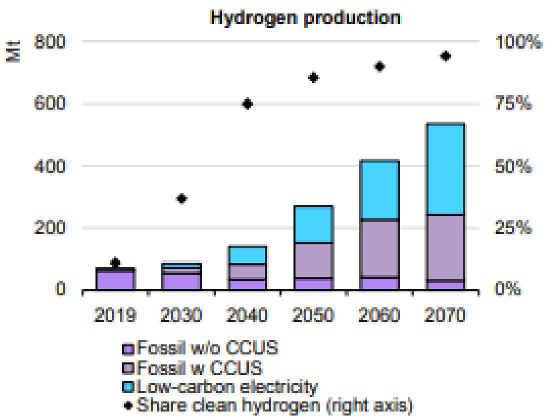

Figure 15. Hydrogen production evolution in the Sustainable Development Scenario [91].

The removal of CO_2 from the atmosphere, directly or indirectly, is gaining more importance. Different technologies can be used: natural solutions (reforestation, afforestation, etc.) and technological solutions (DACs). Currently, DAC technologies present a high operating cost and high energy consumption. In addition, DACs are still in early stages of development, therefore it is not possible to know exactly the cost of commercializing these technologies at a large-scale will be.

These solutions will play an important role from 2050 as a method to generate net-negative emissions, offsetting excess emissions that may have occurred in the first half of the century. Depending on the scenario, these technologies have a greater or lesser impact in the following years as shown in figure 16. One of the challenges is that it is not possible to know exactly how much these technologies will be able to contribute to achieving climate objectives, due to uncertainties in the development and deployment of these technologies.

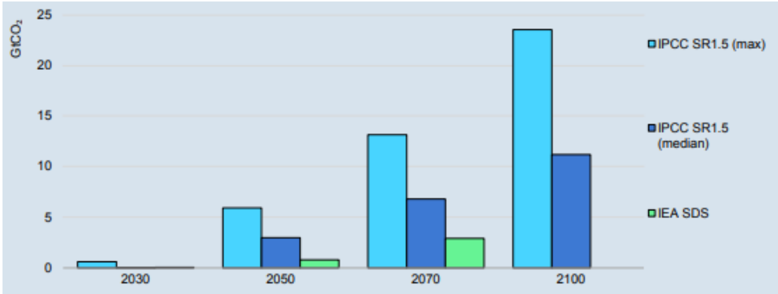

Figure 16. Carbon removal through BECCS and DACS in the Sustainable Development Scenario and IPCC SR1.5 Scenarios [10] [91].

5. Sustainable Development Goals´ Alignment [95] [96]

This paper is aligned with many Sustainable Development Goals (SDG). It is directly related with SDG 13 (***Climate Action***). This goal defines the importance of curbing global warming since it is a worldwide problem that will have serious consequences on population (migrations, urban and rural changes, etc.), biodiversity, the level of the oceans, etc. Aligned with the Paris agreement, SDG 13 defines the need for measures to limit global warming to 2ºC (preferably 1,5ºC) compared to pre-industrial levels. Among the proposed solutions are an investment in climate change adaptation measures, the use of renewable energy, improvement of energy efficiency, and the issuance of green bonds to finance sustainable projects. SDG 13 also mentions carbon capture measures such as emissions compensation with reforestation projects and investment in carbon capture and storage technologies.

Due to its direct relationship with climate change, carbon capture is highly related to SDG 3 (***Good Health and Well-being***), SDG 14 (***Life Below Water***), and SDG 15 (***Life on Land***). If global warming continues to increase, it will have serious consequences for people's health. Therefore, it is essential to act as soon as possible to reduce mortality related to this problem, as well as to ensure a healthy life for the entire population.

Moreover, the rise of greenhouse gases in the atmosphere has contributed to an increase in ocean acidification, leading to a negative impact on the marine biosphere. Likewise, it reduces the capacity of oceans to capture carbon as a carbon sink. In addition, climate change contributes to a temperature and level rise of the oceans.

Carbon capture is also closely related to projects that improve life on land. Natural projects such as reforestation, afforestation or agroforestry can tackle problems like deforestation and soil depletion. In addition, these projects contribute to the conservation of ecosystems and the fight against intensive agriculture.

Furthermore, carbon capture will play a critical role throughout the energy transition to a decarbonized economy. In line with SDG 7 (***Affordable and Clean Energy***), carbon capture can significantly reduce emissions from the power sector, or capture those that have not been abated yet.

Finally, a large investment by the public and private sector will be needed to develop technically and economically viable carbon capture technologies. Therefore, innovation for this sector is key, which is an objective included in SDG 9 (***Industry, Innovation, and infrastructure***).

[10] Scenarios´ description can be found in [91].

6. Practical Example SDGs: Tres Cantos

The municipality of Tres Cantos is proposed as an example of applying measures to reach the SDGs. This section has been carried out with the collaboration of the mayor of this town, Jesus Moreno. Through a personal interview the major recounted the following data:

Tres Cantos was conceived as an innovative city of advanced urban design in its time, seeking the optimal integration of man, nature and economy (industry). Planned with great ambitions: green spaces, avenues, etc, the city was designed in phases and sectors (e.g., Calle Mar Adriatico street corresponds to the Mares sector, seas sector, of the 2nd phase).

The town is currently organized in 3 residential phases and 2 industrial estates. The residential sectors can be divided into 2: the consolidated phases, and the North Zone or Nuevo Tres Cantos (New Tres Cantos), in development. The developed industries are mostly around aerospace technology, chemical and pharmaceutical, and food sectors. The presence of industrial polygons has allowed Tres Cantos to grow from being a dormitory town to become an innovation center.

The urban project for the North Zone is defined in the 2006 Partial Plan [97]. It lays the foundations for modern urbanism, more modern than the consolidated Tres Cantos. In the 2006 Partial Plan, an urban planning was carried out more doors inwards, in which each community of neighbors has its own green areas, swimming pool, sports facility etc. Despite the paradigm shift, the goal is still to provide the locality with as many natural spaces as possible.

Currently Tres Cantos has about 51,000 neighbors and has about 60,000 trees. This is a high population/trees ratio compared with other cities. Reforestation and afforestation are carried out through an adequate selection of species and with a correct maintenance of the green areas (pruning, irrigation, etc.). In addition, the Metropolitan Park project aims to connect the northern zone with the southern zone. Existing green spaces and new reforested spaces will be connected, carrying out a non-invasive recovery of the environment. The idea of the project is the integration of green areas, with streams, where nature is the protagonist. Tres Cantos has a local association of ARBA ("Asociación para la Recuperación del Bosque Autóctono", Association for the Recovery of the Native Forest), which promotes reforestation projects with the collaboration of neighbors and the involvement of many young people and children. In this way, the population is made aware of the importance of trees in fighting climate change from an early age. The presence of many green spaces and their proper maintenance contribute to achieve SDGs 11, 13 and 15, and is directly related to carbon capture.

The municipality also contributes to the reduction of greenhouse gas emissions through different forms. Street lighting and public buildings are being replaced by LED lighting, which is cheaper and more environmentally friendly. This has saved almost EUR 1 million per year in energy consumption. The intensity of the street lamps reduces automatically depending on the hour helping to achieve energy efficiency. Replacement of fluorescent lights at schools and institutes by LED lighting, which has a longer lifespan and lower energy consumption, is also under way. In public buildings, sensors have been installed so that lights go out when there is no human presence. These changes contribute to the achievement of SDGs 11 and 13.

Tres Cantos seeks to achieve recognition as a clean electricity generator (SDGs 7, 11 and 13). For this, there are different projects under development for the installation of solar panels on the roof of public buildings (athletics track, nursery schools, cultural center, etc.) to reduce their consumption or achieve energy self-sufficiency. The mentioned projects have not started due to lack of raw materials and components. There are grants for those neighbors with renewable energy auto consumption as well.

There are two urbanizations that use geothermal energy for the climatization (SDGs 7 and 13). One of these urbanizations has obtained the highest energy rating: A. Geothermal energy, together with the use of sustainable design and construction techniques (materials, insulation, façade orientation, collection, and use of rainwater, etc.) reduce the energy consumption of the buildings. The main disadvantage of this technology is a high initial investment. However, the amortization of the investment is guaranteed in the short to medium term, especially in view of the current situation of the energy markets.

The municipality promotes sustainable mobility (SDGs 11 and 13). Tres Cantos plans the installation of more charging points for electric vehicles, and the subsidiaries for the purchase of electric scooters and bicycles. The cycle path is also being renovated and extended, improving mobility through this means of transportation. 45% of the bus fleet, is hybrid, and Tres Cantos has been the first municipality in Spain with a 100% electric interurban bus from the company ALSA connecting the city with the capital [98]. Another means of low-emission transport is the railway. A second Cercanías stop is planned in the north (Nuevo Tres Cantos). These measures will encourage the use of sustainable transport and reduce the consumption of fossil fuels.

Another key objective of the SDGs is water (SDG 6). Having a large number of green areas leads to high water consumption. To reduce water stress in the municipality. 95% of green areas are irrigated with regenerated water using drip irrigation techniques.

The city council has a direct communication channel with the neighborhood via WhatsApp. In this way, neighbors can report incidents in real time and are involved in the care of the municipality (e.g. warning of areas at risk of fire, water leaks, etc). In this line of communication with citizens, awareness workshops are held in schools for recycling, electricity consumption, etc.

7. Conclusions

Once the different technologies for carbon capture have been studied, as well as the global framework has been analyzed, the following conclusions can be drawn:

- Carbon capture technologies can be divided in three types: technological, natural and hybrid solutions.
- Natural solutions offer options to offset emissions in the short term.
- Temperature and type of residue are key parameters when producing biochar by pyrolysis.
- Pyrolysis and hydrothermal carbonization make it possible to obtain a solid compound (biochar), which can be used as a soil additive for carbon capture due to its chemical properties.
- Carbon capture with microalgae is an innovative hybrid solution with a great potential for the future.
- Post-combustion carbon capture by absorption with amines is currently a mature technology, available for its use at large scale.
- DACs technologies are currently expensive and energy-intensive, so their development will take time until they are technically and economically viable.
- Companies, governments and citizens around the world are increasingly aware of sustainability and the impact their carbon footprint has on the planet.
- Climate change solutions cannot be local; they must be having a global vision (The Gaia Hypothesis).
- Regulated and voluntary carbon markets are a useful tool in the decarbonization pathway.
- Carbon capture is crucial in hard-to-abate sectors (heavy industry and long-distance transport) since they are the ones that will take the longest to reach net-zero targets.
- The use of carbon capture technologies will be key in achieving climate targets in the coming years. This will require a major investment in the development of new and improved technologies.

- Due to climate concern and increasing policies, the number of new carbon sequestration projects is on the rise. However, the pipeline is still far from reaching climate targets.
- Carbon capture is an essential factor for the development of hydrogen as an energy vector in the short to medium term.

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