NEGATIVE GREENHOUSE GAS EMISSIONS IN FRANCE BY 2050: TECHNO-ECONOMIC POTENTIAL ASSESSMENT

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Abstract

Climate change is one of the biggest challenges humanity faces today. The existing mitigation strategies to reduce greenhouse gas (GHG) emissions are not sufficient to deal with the major negative effects of climate change. The European Union's goal of becoming a net-zero greenhouse gas economy by 2050 represents the cornerstone of the European Green Deal, in conformity with the EU's global commitments under the Paris Agreement. To achieve climate neutrality goal by 2050, the deployment of Negative Emission Technologies (NETs) will be necessary. This paper focuses on one of these technologies, namely Bioenergy with carbon capture and storage (BECCS). In particular, it studies the French potential in terms of negative emissions and shows to what extent BECCS can represent a viable solution for achieving climate neutrality in France by 2050. We estimate the cost and potential of negative emissions for each of the nine BECCS technological options considered. Depending on the types of biomass corresponding to each technology, results show that the cost of a tonne of negative CO_2 (€/tCO_2) varies widely across the technologies: indirect gasification to Substitute Natural Gas (BioSNG) [32.7; 98.7]; gasification to liquid hydrogen [67.1; 96.2]; fast pyrolysis to liquid hydrogen [78.2; 98.5]; anaerobic digestion to biomethane [54,2; 118.9]; anaerobic digestion to electricity [73.9; 125]; gasification to liquid fuels [120.1; 163]; fast pyrolysis to electricity [150.2; 167.4]; hydrothermal liquefaction to liquid fuels [207.1; 314.4] and ethanol fermentation 53.3 €/tCO_2. Our analysis highlights that BECCS plays a key role in achieving the neutrality goal in France by 2050. For a target of 15 million tonnes negative emissions in France in 2050, if we use 50% of the available biomass distributed equally between the nine BECCS technologies studied, it will be necessary to cumulate the potentials of several BECCS technologies at a cost per tonne of CO_2 varying from 32.7 €/tCO_2 to 98.5 €/tCO_2. The marginal cost will increase with the setting of higher targets.

Keywords: *negative emissions, climate change, carbon neutrality, negative emission technologies, carbon dioxide removal.*

1. Introduction

For more than a century, human actions have influenced the Earth's climate. As a result of cumulative anthropogenic greenhouse gas (GHG) emissions and the increase of the global average temperature, following the United Nations Climate Change Conference in Paris, in 2015, no less than 196 countries have agreed on a common objective which consists in limiting global warming to "well below 2°C" and that efforts should be made to limit it below 1.5°C above pre-industrial levels [1],[2]. This ambition of the Paris Agreement on climate cannot be achieved only through a simple transition from fossil fuels to greener energy sources. According to Van Vuuren et al. [3], during the period 2000-2100, it is necessary a significant reduction of cumulative emissions and implicitly, unprecedented rates of decarbonization, both in the long and short term, in order to be able to limit[1] the climate change to 2°C. Pires [4] highlights that the reduction of GHG emissions may not be enough to mitigate climate change.

High greenhouse gas concentrations in the atmosphere can lead to dangerous levels of global warming, which is why the international scientific community puts in discussion the removal of carbon dioxide[2] (CO_2) from the air, through the so-called "*negative emissions*". The concept of negative emissions gained attention since its first inclusion in the 4th IPCC report (AR4), which included the implementation of Negative Emissions Technologies (NETs) and highlighted the essential role that negative emissions could play in the framework of climate goals. According to the IPCC AR5 report [5], most of the 2°C scenarios involve a large-scale implementation of the NETs after 2050, with the main purpose of compensating the residual CO_2 emissions from the sectors where decarbonization is difficult to achieve (for example, the aviation, agriculture, shipping, a part of car transport, cement production, etc.) [6].

NETs can play a significant role in keeping the increase of global temperature below the level of 2˚C, and this with a probability higher than 66% [5],[9],[10],[11]. In this regard, Alcalde et al. [12] highlight the importance of NETs and the insufficiency of just reducing

[1] with a probability of around 66 %.

[2] Most research has focused on 'Carbon Dioxide Removal' (CDR), as CO_2 is the most predominant greenhouse gas [4],[7],[8].

greenhouse gas emissions from human activity. Negative Emission Technologies have the capacity to achieve long-term removal of CO_2 from the atmosphere, unlike conventional methods for reducing GHG emissions [13]. Gasser et al. [14] show that in order to reach the 2°C objective, negative emissions alone are not enough, but they are necessary even if we would dispose of very high mitigation rates. At the same time, Fuss et al. [15] point out that if there is no significant reduction of emissions in the short-term, then negative emissions will also be inefficient for achieving climate goals. To substantially remove CO_2 from the atmosphere, Integrated Assessment Models (IAMs) involve scenarios based on a large-scale implementation of NETs [5],[12],[16], the studies based on these models showing both the long-term and strategic importance of the Carbon Dioxide Removal for achieving a 2˚C target [11],[17]. Fuss et al. [15] highlight that while there are some scenarios to 2°C that are not based on negative emissions, all 1.5°C scenarios are almost inconceivable without them. Mac Dowell et al. [18] also indicated that the ambitions to limit climate change to no more than 1.5°C–2°C by the end of the 21st century rely heavily on the availability of NETs.

The European Union's goal of becoming a net-zero greenhouse gas economy by 2050 represents the cornerstone of the European Green Deal, in conformity with the EU's global commitments under the Paris Agreement. In the 2030 climate and energy policy framework and the European Green Deal, the European Commission acknowledges that Carbon Dioxide Capture and Geological Storage (CCS) can play a key role in achieving the EU's long-term emissions reduction goal [19],[20].

This article focuses on one of the Negative Emission Technologies (NETs), Bioenergy with carbon capture and storage (BECCS), and aims to study the French potential of negative emissions by 2050 necessary to move towards carbon neutrality. For this technology, we identify the pathways characterized by the lowest costs and the highest productivity in France.

2. France within the European climate objectives

2.1 The French National Low-Carbon Strategy

France strongly supports European objectives, and since 2015 has adopted the National Low-Carbon Strategy (SNBC), which aims to represent France's roadmap to a transition to a low-carbon economy in all sectors of activity. With the adoption of the first National Low-Carbon Strategy in 2015, France had committed itself to reduce GHG emissions by 4 at the 2050 horizon compared to 1990 levels. With the introduction in 2017 of the Climate Plan for France by the Ministry of Ecological Transition and Solidarity, new targets have been set that replaced the initial ones (factor 4), with more ambitious ones that involve achieving carbon neutrality by 2050. This target, enrolled in law in 2019, assumes that GHG emissions in France will have to be reduced by 6.9 compared to 1990 levels.

The latest National Low-Carbon Strategy was published in March 2020, with the main goal of achieving carbon neutrality by 2050. The objectives of reducing French greenhouse gas emissions associated with the National Low-Carbon Strategy are presented under the form of carbon budgets, expressed as an annual average per 5-year period in millions of tonnes of CO_2 equivalent (see the last three carbon budgets in Table 1) [21]. The carbon budgets initiated in 2015, in the French Energy Transition for Green Growth Act by SNBC, were also revised in 2019.

TABLE 1: Carbon budgets according to the French National Low-Carbon Strategy (SNBC). Source: IFPEN based on [21].

Period	2019-2023	2024-2028	2029-2033
Carbon budget (Emissions without LULUCF*)	422 $MtCO_2eq$/year in average	359 $MtCO_2eq$/year in average	300 $MtCO_2eq$/year in average
Carbon budget (Emissions with LULUCF*)	383 $MtCO_2eq$/year in average	320 $MtCO_2eq$/year in average	258 $MtCO_2eq$/year in average

* LULUCF – Land Use, Land-Use Change and Forestry

2.2 Negative emissions from LULUCF sector in France

In 2018, the Land Use, Land-Use Change and Forestry sector in France absorbed 17.26% more CO_2 from the atmosphere than in 1990. The negative emissions from LULUCF come from Forest Land, Grasslands and Harvested wood products. But negative emissions from the LULUCF sector will not be enough. Therefore, it is essential to study the solutions represented by artificial sinks, and implicitly Negative Emission Technologies (NETs), which, together with natural sinks, should be able to allow as much compensation as possible of emissions in the short, medium and long-term.

2.3 France's carbon sink target for 2050

Given that neutrality must be achieved in 2050, the French National Low-Carbon Strategy assesses the residual emissions to 80 $MtCO_2eq$ in 2050 and **-82 $MtCO_2eq$ for sinks** (which would allow a reserve of -2 $MtCO_2eq$) [21],[22],[23]. CITEPA [22] suggests that of the residual[3] emissions in 2050 (80 $MtCO_2$), 60% are assigned to agriculture and 20% to industry.

Regarding the carbon sink of France, for the year 2050, the -82 $MtCO_2$ are attributed:

- **to the LULUCF sector, in a percentage of 82% (soils, biomass forests, etc.)**
- **to CO_2 capture and storage (CCS) (BECCS + DACCS)[4] in a percentage of 18%**

Based on the objectives and data from the National Low-Carbon Strategy [21] and [22], in Figure 1, we illustrate one of the scenarios that would allow obtaining carbon

[3] emissions that cannot be avoided.

[4] BECCS - Bioenergy with carbon capture and storage; DACCS - Direct Air Carbon capture and storage;

neutrality by 2050 in France. This scenario is inspired by the reference scenario of SNBC, called “With Additional Measures Scenario” (in french, scénario “Avec Mesures Supplémentaires” - AMS). Thus, according to this scenario, approximately -67 $MtCO_2$ would come from the LULUCF sector, and -15 $MtCO_2$ would have to be obtained through Negative Emission Technologies.

The interdependence between natural and artificial sinks must be taken into account (the higher the quantity of carbon absorbed by the LULUCF sector, the lower the dependence on NETs), so that achieving the goal is done with the lowest costs, while simultaneously reducing the impact on the environment.

From the two levers that allow to obtain negative emissions, namely, LULUCF sector and CO_2 capture and storage (CCS), in this paper, we focused our analysis on the second lever that relies on Negative Emission Technologies, by studying the French potential on NETs, and implicitly the 18% (around 15 $MtCO_2$) necessary to obtain carbon neutrality in France by 2050.

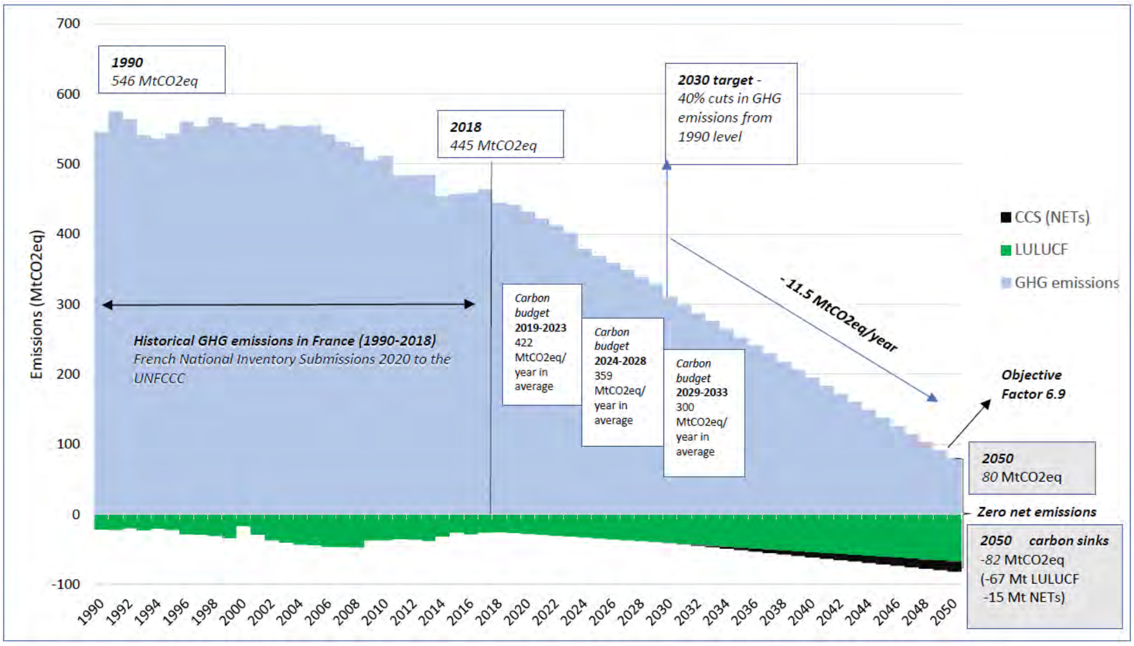

FIGURE 1: Trajectory of GHG emissions in France, in order to achieve the carbon neutrality in 2050. Source: IFPEN based on the objectives and data from the French National Low-Carbon Strategy [21],[22] .

As stated by the French National Low-Carbon Strategy, the BECCS technology is seen as the starting point that would allow obtaining negative emissions in a continuous way on a very long-term, also emphasizing that at the moment, the technology is in a very early stage of development.

3. Methodology - BECCS implementation

In most climate change scenarios that use negative emission technologies, bioenergy and carbon capture and storage (BECCS) is presented as the best option and the most mature technology to decarbonize emission-intensive industries, and to allow negative emissions.

3.1 Biomass resources in France in 2050

We took into account the most important sources of biomass that are adaptable to the implementation of BECCS technologies. The main sources of biomass as raw material that we considered in this paper and that can be widely used in France are agricultural biomass, forest biomass, livestock effluents and waste.

According to the French National Biomass Mobilization Strategy [24], in France, the biomass of agricultural origin that can be used, is very diverse, France being the leading agricultural producer in the European Union. Regarding the forest biomass, it is one of the most important renewable resources in France. Livestock effluents are another important resource, with a significant use for BECCS technology. Waste can also be used for BECCS implementation.

To examine these sources of feedstock, as well as the projected availability in France, at the horizon of 2050, we used previously published studies, in particular, the French National Biomass Mobilization Strategy[5] [24], ADEME [25], FranceAgriMer [26]. Based on the estimates[6] from these studies, the quantity (expressed in million tonnes of dry matter) of mobilizable biomass resources in France in 2050 that we used in this paper, is summarized in Table 2.

The cost of each category of biomass considered were based on [27],[28],[29],[30]. In this paper, costs are

[5] The French National Biomass Mobilization Strategy distinguishes two categories of biomass, without double counting: non-methanized biomass with low moisture and methanized biomass with high moisture.

[6] The estimation of mobilizable biomass resources at the horizon of 2050, is characterized by some uncertainty, in the sense that the publications that estimate them are based on different scenarios, with a predilection for specific uses.

expressed in euro$_{2020}$, and calculated by applying a yearly inflation rate[7].

TABLE 2: Quantity and cost of biomass considered available in France in 2050. (Costs are expressed in €$_{2020}$). Source: IFPEN based on data provided by [24],[25],[26],[27],[28],[29],[30].

Biomass type	Quantity (million tonnes DM/year)	Biomass cost (€$_{2020}$/tonne DM)
Forest biomass	29.23	69.43
Agricultural biomass	41.74	52.01
Livestock effluents	17.88	32.61
Waste	3.58	25.15

*DM refers to dry matter.

3.2 BECCS – portfolio of technologies

BECCS is characterized by a large portfolio of technologies at different stages of maturity. In our analysis, we consider various BECCS technologies: **Gasification,** with three different options (Gasification with Fischer-Tropsch Synthesis to Liquid Fuels; Gasification with Water-Gas Shift to Hydrogen; Indirect gasification to Substitute Natural Gas (BioSNG), **Fast pyrolysis** with two options (Fast Pyrolysis to Hydrogen; Fast Pyrolysis to Electricity), **Anaerobic digestion** with two options (Anaerobic digestion to bio-methane; Anaerobic digestion to electricity), and **ethanol fermentation** and **hydrothermal liquefaction to liquid fuels**. In addition to the amount of CO_2 that can be captured, through the implementation of these procedures, we can obtain electricity, heat, liquid fuels, hydrogen, biomethane, synthetic natural gas, long-lived carbon products, or combinations thereof.

One of the BECCS technologies analyzed is Gasification, more precisely, Gasification with Fischer-Tropsch Synthesis to Liquid Fuels. The diagram (see Figure 2) shows an example of the circuit of carbon for this technology. To create this diagram, we used data and information from three reports [31],[32],[33]. As we can see, in a typical FT diesel plant, based on oxygen blown Circulating Fluidized Bed (CFB) gasification, 52% of the carbon in the feedstock is released as high-purity CO_2 that can be captured and stored, 37% ends up in Fischer-Tropsch diesel stream, 5% is vented as CO_2 in the flue gas of the combined heat and power unit, 6% is found in the char from the gasifier.

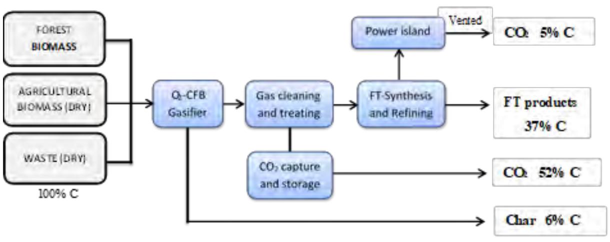

FIGURE 2: Gasification with Fischer-Tropsch Synthesis to liquid fuels. Source: IFPEN based on [31],[32],[33].

By taking into consideration the 52% of the carbon that could be captured and stored, as well as the biomass resources available in France, that are associated to this technology, namely, the forest biomass, the agricultural biomass with low moisture and the dry waste, we calculated the amount of CO_2 equivalent that can be captured and stored through this technology option.

The same principle was used for the other BECCS technologies considered (see other examples of figures in the Annexes).

3.3 BECCS - The calculation of the potential and cost of negative emissions

For each BECCS pathway that leads to negative emissions, as listed in the previous section, we have estimated both the potential and cost of negative emissions.

For the calculation of the cost of negative emissions, we used the equation (1) below, inspired by the analytical framework proposed by Baker, et al. [31]:

$$Negative\ Emissions\ Cost = \frac{TAC-PR}{NEP} \qquad (1)$$

Where:

- *Negative Emissions Cost* refers to the cost of producing negative CO_2 emissions from the biomass conversion technologies studied (expressed in euro per tonne of CO_2 equivalent);
- *TAC* is the *Total Annualized Cost* (expressed in €/year), which includes the annualized capital cost (CAPEX), the fixed and variable operating cost (OPEX). The cost of biomass and the cost of capture, transport and storage are part of OPEX;
- *PR* is the *Product Revenue,* obtained from the sale of products (electricity, heat, hydrogen, liquid fuels, biomethane, BioSNG, digestate, bio-ethanol) resulting from the analyzed BECCS technologies (expressed in €/year);
- *NEP* is the *Negative Emissions Potential,* representing the annual amount of CO_2 removed due to the Negative Emissions Technology (expressed in tonnes of CO_2eq).

To calculate the potential and cost of negative emissions in France in 2050, we created an excel model, that allows us to calculate for all the BECCS technological options studied the parameters listed above.

We first calculated the annual negative CO_2 emissions quantity, for each pathway, by using the following equation:

$$NEP = \left(\sum_i Q_{Bi} \cdot CARB_i \right) \cdot C_{capt} \cdot \frac{44}{12}, \quad i=1,6 \qquad (2)$$

Where:

- Q_{Bi} refers to the amount of biomass of type i in tonnes of dry matter (DM) (Forest biomass, High Moisture Agricultural Biomass, Low Moisture Agricultural Biomass, Dry Waste, Wet Waste, Livestock effluents);

[7] https://www.insee.fr/fr/statistiques/2122401#tableau-figure1

- $CARB_i$ refers to the organic carbon content[8] of biomass i (% mass);
- C_{capt} refers to the percentage of carbon that can be captured and stored in each of the analyzed BECCS technologies (%).
- $\frac{44}{12}$ refers to the conversion of one tonne of carbon equivalent into one tonne of CO_2 equivalent.

We start from the categories of biomass resources available in France in 2050, and depending on the carbon content of each category of biomass, we calculate the amount of carbon captured and stored, as well as the amount of carbon contained in the products resulting from each BECCS technology. Then, we converted the quantity of carbon captured by each process in quantity of negative bio CO_2eq.

Through the excel model created, we then determined the cost of one tonne of negative CO_2 by each BECCS technology. Thus, we considered a single facility for each of these technological paths, in which we introduced a quantity of biomass (in tonnes of dry matter) adapted to the capacity of the facility according to the data taken from various reports [34],[35],[36],[37],[38],[39]. We mention that the data taken from these differentiated plants for each technology, refer especially to CAPEX, OPEX, energy, heat and biomass consumption, which allowed us to calculate the total annualized cost, as well as the revenues obtained, according to the equation 1. The plants are assumed to be operational 8000 hours/year, with a lifetime of 15 or 20 years depending on the technology. We also mention that the role of the plants to which the reports used refer, was not to capture CO_2, but to produce various products for sale (electricity, heat, hydrogen, etc.). For the capture, transport and storage of CO_2, we considered as a hypothesis, a capture and compression cost of 40 €/tCO_2 captured, a transport cost of 20 €/tCO_2 transported and a storage cost of 30 €/tCO_2 stored. We consider the cost of transport and storage are paid as services performed by specialized companies. For technologies that allow to obtain hydrogen as a final product, we added a cost of hydrogen liquefaction of 0.5 €/kg H_2 [40].

In our analysis, we consider that in general, the CO_2 captured and stored is of high-purity. We also mention that in the case of the fast pyrolysis, the biochar obtained was not accounted in negative emissions potential calculation, although it is assumed that 80% of its carbon remains sequestered in the soil for 100 years.

For product revenues calculation, we multiplied the amount of final product that we can obtain from each BECCS technology and its wholesale price that is taken from the literature[9] (electricity – 0.16 or 0.067 €/kWh depending on the plant size, heat – 0.054 €/kWh, digestate – 0.72 €/kg N, biomethane – 90.75 €/MWh, hydrogen – 2.74 €/kg, BioSNG – 91.44 €/MWh, Bio-ethanol – 0.74 €/litre, liquid fuels – 684.75 €/t).

All costs are calculated and reported in $euro_{2020}$, applying a yearly inflation rate.

4. Results

One of the main objectives of this model was the use of biomass resources and BECCS associated technologies in order to show to what extent BECCS can represent a viable solution for obtaining negative emissions and implicitly, for achieving climate neutrality in France by 2050.

The cost of negative CO_2 emissions is strongly influenced by various factors such as the type and cost of biomass, the electricity price, the selling price of the resulted final products, as well as the percentage of CO_2 captured corresponding to each BECCS technology analyzed. We performed an analysis of the sensitivity of the nine BECCS technologies to the cost of biomass, with the mention that each technology is characterized by certain types of biomass. For this, we varied only the cost of agricultural biomass (around the price used in the paper of 52.01 $€_{2020}$/t dry matter), keeping constant the cost of the other parameters (see Figure 3). Results show that the cost of negative emissions through the technologies of ethanol fermentation, anaerobic digestion to biomethane and hydrothermal liquefaction to liquid fuels, is highly sensitive to the cost of biomass due to the fact that these technologies have a lower negative emissions potential per tonne of dry biomass (0.22 tCO_2/tDM, 0.30 tCO_2/tDM and respectively, 0.35 tCO_2/tDM). In contrast, gasification to liquid hydrogen and gasification to liquid fuels have the highest negative emissions potential per tonne of dry biomass (1.63 and 0.94, respectively), reason why they are less sensitive to the cost of biomass.

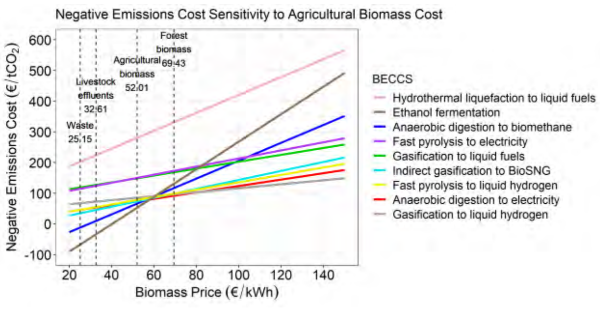

FIGURE 3: Variation of the negative emissions cost to the cost of biomass. Dashed vertical lines indicate the cost of biomass ($€_{2020}$/tDM) used in the paper (agricultural biomass: 52.01; forest biomass: 69.43; livestock effluents: 32.61; waste: 25.15).

We also performed an analysis of the sensitivity of the BECCS technologies studied to the electricity selling price. The cost of a tonne of negative CO_2 from the

[8] The mass organic carbon content (% mass) in biomass, considered in this paper is: 0.504 for forest biomass, 0.4688 for agricultural biomass [41]; 0.346 for livestock effluents [42] and 0.45 for waste [43].

[9] https://selectra.info/energie/guides/environnement/rachat-electricite-gaz-edf#biogaz
https://eplagro55.fr/fileadmin/user_upload/pdf/Innovations/Biogaz/Rapport_gnv.pdf
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technologies that produce and sell electricity (fast pyrolysis to electricity and anaerobic digestion to electricity) is extremely sensitive to the selling price of electricity (see Figure 4). The cost of negative emissions from the other technologies does not depend on the selling price of electricity, as they do not produce saleable electricity.

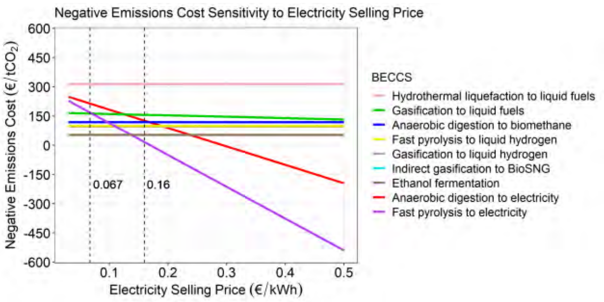

FIGURE 4: Variation of the negative emissions cost to the selling price of electricity. Dashed vertical lines indicate the electricity selling prices used in this paper: 0.067 $€_{2020}$/kWh (installed power > 1 MW) and 0.16 $€_{2020}$/kWh (installed power < 200 kW), depending on the power of the facility.

Among the technologies analyzed in the paper, the results show that indirect gasification to BioSNG, gasification to liquid hydrogen, fast pyrolysis to liquid hydrogen and ethanol fermentation, have the negative emissions cost below 100 €/tCO_2, regardless of the type of biomass used. In contrast, fast pyrolysis to electricity and hydrothermal liquefaction to liquid fuels, have the highest negative emissions costs, exceeding 150 €/tCO_2 (see Figure 5). An analysis of these technologies in terms of cost and potential will be presented below.

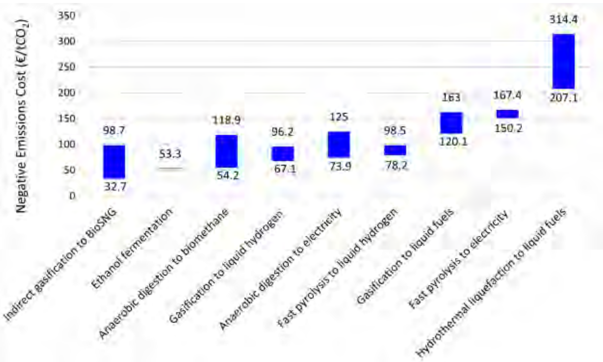

FIGURE 5: Variation of the negative emissions cost (€/tCO_2) for each BECCS technology analyzed, depending on the type of biomass used.

All these technologies require a consumption of electricity and heat that differs significantly from one technology to another. For calculating the cost and energy consumption, we used for each technology a plant of different powers, capacities, lifetime (15 or 20 years), locations[10], depending on the data found in the literature, as we mentioned in the previous section. Hydrothermal liquefaction to liquid fuels and indirect gasification to BioSNG are high consumers of electricity and heat, reported to tonnes of dry biomass, while the anaerobic digestion to electricity and biomethane are small consumers. If we refer to the tonne of negative CO_2, the technologies the most consuming of electricity and heat are gasification to liquid fuels, hydrothermal liquefaction to liquid fuels and anaerobic digestion to biomethane.

If the total available biomass in France that can be mobilized in 2050 would be distributed equally between the BECCS technologies associated to the same type of biomass[11], a cumulative amount of negative emissions of 62.2 $MtCO_2eq$ would be obtained by using these nine BECCS technologies. However, this is a theoretical case, as not all the available biomass could be used for the BECCS technology in the future.

Therefore, given the fact that biomass will always be a resource for which there is competition and for a better mobilization of the types of biomass available by 2050, we decided to take in the first instance 50% of each biomass category available distributed equally between the BECCS technologies (see Figure 6 and Table 3). The results show that reaching the target of 15 Mt negative emissions in 2050, with the lowest costs, would require the implementation of all the technologies on the left of the first dashed vertical line in Figure 6 below, up to including fast pyrolysis to liquid hydrogen from forest biomass, technology with the cost of 98.5 €/tCO_2.

The estimated total electricity consumption necessary to reach this target of 15 million tonnes of negative emissions in 2050, in France, using 50% of the available biomass distributed equally, is approximately 6.08 million MWh/year (6.08 TWh/year). Compared to the electricity final consumption[12] in 2019 in France, which was 473 TWh, this estimated consumption would represent only 1.3%.

If the LULUCF sector cannot reach the target of 67 Mt negative emissions in France in 2050, then Negative Emissions Technologies will need to capture more than 15 $MtCO_2$. Thus, if we set a 30 Mt target for negative emissions obtained through BECCS, in 2050, it would be necessary to implement almost all BECCS options studied using all categories of biomass as input. For 30 Mt of negative emissions, using 50% of the biomass, the cost per tonne of negative CO_2 varies from 32.7 €/tCO_2 to 280.6 €/tCO_2.

If instead of using 50% of the biomass available in 2050, we only use 30% of the biomass, then reaching a target of 15 Mt negative emissions would be done at a marginal cost of 163 €/tCO_2. For a 30 Mt negative emissions target, the quantity of biomass would not be sufficient.

[10] from France, United Kingdom, Switzerland, Denmark, Finland.

[11] BECCS technologies use different types of biomass. Biomass is distributed according to the characteristics of each technology. For example, forest biomass was divided into six parts because there are six technological options that use this type of biomass.

[12] https://www.edf.fr/groupe-edf/espaces-dedies/l-energie-de-a-a-z/tout-sur-l-energie/le-developpement-durable/la-consommation-d-electricite-en-chiffres
https://www.iea.org/countries/france

Assuming that the total amount of dry biomass in France in 2050 will be 92.4 million tonnes, then to obtain 15 Mt negative emissions it would be necessary to use 24% of the available biomass in 2050 (22.3 Mt dry matter), distributed proportionally between the BECCS technologies associated with the characteristic biomass types: Forest biomass - 7 Mt DM; Agricultural Biomass (dry) - 1.9 Mt DM; Agricultural Biomass (wet) - 8.2 Mt DM; Livestock effluents - 4.3 Mt DM; Waste (dry) - 0.34 Mt DM; Waste (wet) - 0.53 Mt DM.

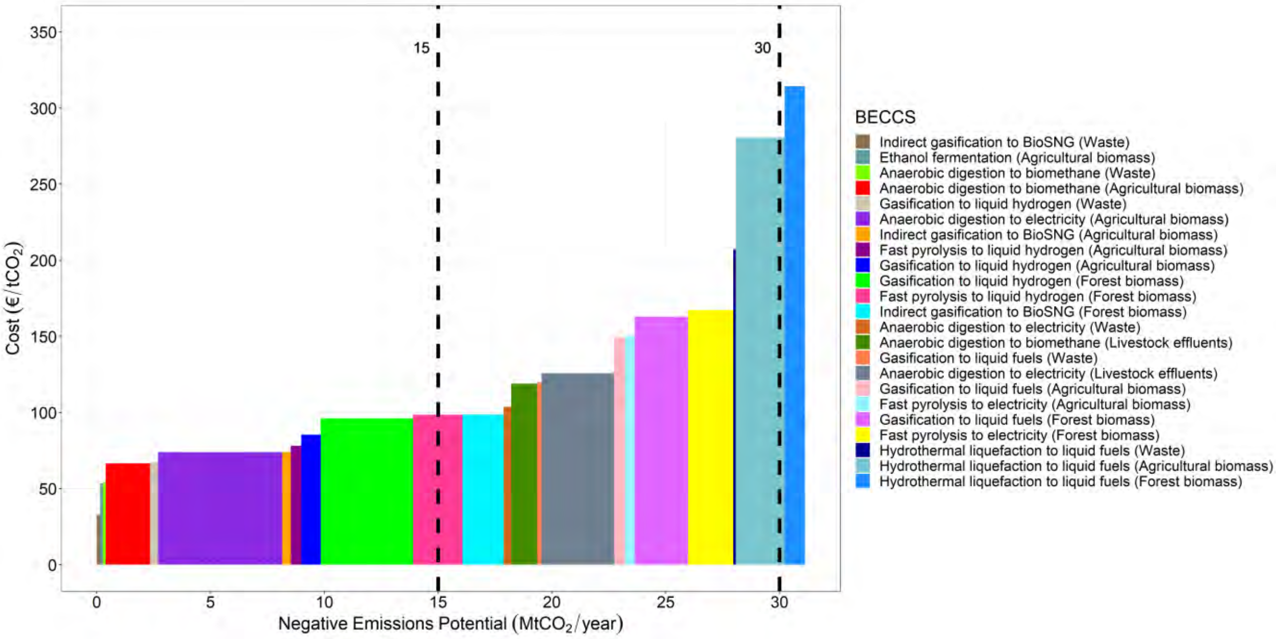

FIGURE 6: 2050 potential of negative emissions in France, when 50% of biomass is distributed equally between BECCS technologies. Biomass is distributed according to the characteristics of each technology.

TABLE 3: Negative emissions potential and cost for each BECCS technology, by using 50% of the biomass in France, in 2050. (Costs are expressed in €2020).

BECCS technology	Agricultural biomass		Forest biomass		Livestock effluents		Waste	
	Potential ($MtCO_2$/y)	Cost (€/tCO_2)	Potential ($MtCO_2$/y)	Cost (€/tCO_2)	Potential ($MtCO_2$/y)	Cost (€/tCO_2)	Potential ($MtCO_2$/y)	Cost (€/tCO_2)
Gasification to liquid fuels	0.49	149.0	2.34	163.0			0.20	120.1
Gasification to liquid hydrogen	0.86	85.4	4.05	96.2			0.35	67.1
Indirect gasification to BioSNG	0.38	74	1.80	98.7			0.15	32.7
Fast pyrolysis to liquid hydrogen	0.46	78.2	2.18	98.5				
Fast pyrolysis to electricity	0.42	150.2	1.99	167.4				
Hydrothermal liquefaction to liquid fuels	2.14	280.6	0.90	314.4			0.12	207.1
Ethanol fermentation	0.12	53.3						
Anaerobic digestion to electricity	5.45	73.9			3.18	125	0.34	103.7
Anaerobic digestion to biomethane	1.95	66.6			1.13	118.9	0.12	54.2
Total potential 50% biomass	**31.1 $MtCO_2eq$**							

5. Conclusions

To achieve the climate neutrality goal by 2050, the deployment of Negative Emission Technologies (NETs) will be essential. In this paper, we focused on Bioenergy with carbon capture and storage (BECCS), considered the most mature technology among NETs.

In our analysis, we studied nine BECCS technological options and identified the pathways characterized by the lowest costs and the highest productivity in France, which would allow to meet the state's goal of being carbon neutral by 2050.

The paper highlights that BECCS presents a high potential in obtaining negative emissions in France. If all the biomass estimated that can be mobilized in 2050 would be used, results showed a total potential of CO_2 negative emissions of 62.2 million tonnes of CO_2 in 2050. Given that biomass is a resource with many uses, for which there is competition, in our analysis, we focused on 50% of all biomass categories available (which would give a potential of 31.1 million tonnes negative emissions). We have estimated the cost and potential of negative emissions for each of the nine BECCS options considered. Depending on the types of biomass corresponding to each technology, results showed that the cost of a tonne of negative CO_2 (€/tCO_2) varies as follows: indirect gasification to BioSNG [32.7; 98.7]; gasification to liquid hydrogen [67.1; 96.2]; fast pyrolysis to liquid hydrogen [78.2; 98.5]; anaerobic digestion to biomethane [54,2; 118.9]; anaerobic digestion to electricity [73.9; 125]; gasification to liquid fuels [120.1; 163]; fast pyrolysis to electricity [150.2;167.4]; hydrothermal liquefaction to liquid fuels [207.1; 314.4] and ethanol fermentation with the cost of negative emissions of 53.3 €/tCO_2. Regarding the potential of negative emissions, gasification to liquid hydrogen and anaerobic digestion to electricity are the technologies with the highest potentials.

Based on the objectives and information from the French National Low-Carbon Strategy [21] and [22], in this paper, we focused on a target of 15 Mt negative emissions by 2050, necessary to achieve the climate neutrality.

Our analysis shows that the target of 15 million tonnes negative emissions in 2050 can be obtained through BECCS implementation. If we use 50% of the biomass distributed equally between the nine BECCS technologies, it will be necessary to cumulate the potentials of certain BECCS technologies at a cost per tonne of CO_2 between 32.7 €/tCO_2 and 98.5 €/tCO_2. Results show that the quantity of 15 million tonnes of negative emissions could be obtained by using only 24% of the total available biomass in 2050.

If a higher amount of negative emissions would be needed to achieve neutrality, we also considered a target of 30 Mt. In this case, the analysis shows that it is necessary to implement all the BECCS technologies analyzed, by cumulating their CO_2 potentials using 50% of the biomass available in 2050, at a cost per tonne of negative CO_2 starting from 32.7 €/tCO_2 and reaching 280.6 €/tCO_2.

BECCS owns a portfolio of technologies with different maturity levels, which allows finding multiple ways to obtain negative emissions, playing a key role in achieving neutrality goal in France by 2050.

6. Annexes

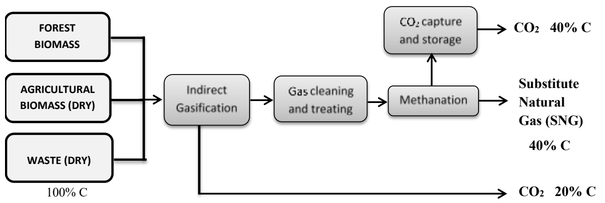

FIGURE 7: Indirect gasification to Substitute Natural Gas (BioSNG). Source: IFPEN based on [31],[32],[33].

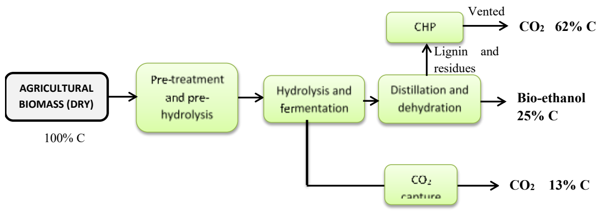

FIGURE 8: Ethanol fermentation. Source: IFPEN based on [31],[32][33]

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