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Carbon credits in the aviation sector:

the contribution of biochar to carbon offsetting

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Introduction

Global warming represents one of our time's most urgent and pressing challenges. Over the past few decades, the accumulation of greenhouse gases in the atmosphere, primarily caused by human activities such as fossil fuel use, deforestation, and industrialization, has led to a significant increase in global average temperatures. This phenomenon has triggered a series of devastating impacts on the environment and society, including rising sea levels, ocean acidification, increased extreme heat waves, and destabilization of global climate patterns.

The consequences of global warming manifest in various sectors, including agriculture, biodiversity, food security, and public health, exacerbating socioeconomic disparities and increasing the risk of resource-related conflicts. Addressing this challenge requires a coordinated global commitment and a rapid transition to a low-carbon economy, with concrete policies and actions aimed at reducing greenhouse gas emissions, promoting energy efficiency, protecting natural resources, and adapting to the inevitable impacts of climate change. Only through collective and determined efforts can we hope to mitigate the catastrophic effects of global warming and secure a sustainable future for future generations.

As one of the major contributors to global greenhouse gas emissions, the aviation sector faces a crucial challenge in pursuing environmental sustainability. With the continued growth of air traffic and the expansion of global routes, finding effective solutions to reduce the aviation industry's environmental impact becomes increasingly urgent.

The aviation sector is often referred as "hard-to-abate" because the combination of complex technologies and high costs does not yet allow for a viable, sustainable alternative. Unlike passenger transportation on wheels, which has found possible emission reduction solutions in electric vehicles, the technological limitations of airplanes do not allow for complete electrification. Consequently, aviation must find sustainable solutions with current technology and in a short time frame. Sustainable fuels are now well known and represent the only currently available solution to decarbonize this sector in the short and medium terms.

Biochar has been getting momentum among the potential solutions for creating zero or even negative biofuel value-chains. This work investigates the potential benefit of biochar application for the sustainable aviation fuel sector. The goal is to increase the capacity of sustainable fuels using biochar to reduce greenhouse gas emissions.

The proposed analysis is based on the current legislation, both at the European and global levels, which delineates the context in which fuels can be defined as sustainable and establish decarbonization scenarios to comply with the Paris Agreement. Following these regulations, some possible scenarios are proposed and evaluated in economic terms.

The work begins with an analysis of the aforementioned legislative framework, differentiating between the European environment and the international one. Europe aims to be the first sustainable economic region and has introduced the European Green Deal at the end of 2019 as a set of legislative proposals to lead the continent towards climate neutrality. There are three relevant acts considered for this study. The Renewable Energy Directive II (RED II)(2018) [1] sets the targets for renewable energies and the practical methodologies for calculating them. It is crucial in this case for biofuel techniques, how they should be evaluated, and their impact on climate change. Before this, the Emission Trading System (ETS)(2003) [2] was developed to set a cap on emissions with a cap-and-trade mechanism among various sectors, including civil aviation. Lastly, the ReFuelEU Initiative [3] sets the minimum quantities of biofuels that the aviation sector must progressively use by 2050.

After this initial chapter on the aforementioned legislative framework, biochar is analysed, including its characteristics and slow pyrolysis as its production method. On the one hand, biochar represents a valid solution to combat issues such as climate change, energy generation, and waste management; on the other hand, slow pyrolysis is an important technology for biomass sector development due to its flexibility and product valorisation.

Subsequently, the supply chain of sustainable fuel produced from camelina plants is analysed from both an energy and environmental perspective. The "life cycle assessment" (LCA) analysis is now the basis for all sustainability assessments. In this case, the results obtained from the European Bio4A Horizon 2020 project have been used to feed the model of a generic Sustainable Aviation Fuel (SAF) production chain with biochar use. Using the European directives, the valorisation of biochar as a carbon sequestration technology within the aviation fuel production chain is analysed.

The next step deals with carbon credit markets, their history, the systems prevalent worldwide, and their functioning. The ETS bases its competitiveness on developing a regulated carbon credit market, i.e., the quantities of CO2 removed from the atmosphere that can be sold to those who need or want to reduce their environmental impact.

This is then connected to the methodology that generates carbon credits through biochar placed in the soil. The platform Puro.earth has developed a standard to calculate these types of credits, which can then be sold in the voluntary market or within closed schemes.

The first economic assessment is based on the CORSIA (Carbon Offsetting Reduction Scheme for International Aviation) system [4]+. It compares the costs associated with fossil fuels with the SAF's costs. The CORSIA system, still voluntary, foresees a reduction in required offsets if a company uses sustainable fuels. The analysis, therefore, evaluates whether this reduction covers the added cost represented by using SAF.

The next step takes the perspective of a generic airline operating in Italy and studies its future scenarios up to 2030. The ETS is a European system that sets a cap on emissions allowed for the aviation sector, gradually decreasing this cap to reduce emissions. The system is designed to allow companies to manage their strategies autonomously, aiming to maintain competitiveness within the sector. Therefore, to meet emission reduction targets, airlines can use SAF, which guarantees a certain reduction at the expense of higher fuel costs. For airlines, this means that they must minimize the quantity of SAF used while improving its LCA impact. Depending on production techniques, different emission factors make one fuel more sustainable than another. It is following this reasoning that the use of biochar in the SAF production chain is introduced. In calculating sustainable fuel emissions, the RED II [1] establishes that agronomic practices can sequester carbon in the soil, thereby reducing Greenhouse gas (GHG) emissions. Biochar placed in the soil thus enhances fuel through the "e_{sca}" parameter and reduces its emission value. This solution would enable airlines to reduce their emissions with lower SAF use, thus reducing costs. The cumulative analysis, therefore, compares five different scenarios to provide a general overview of the associated costs of each, evaluating their economic feasibility.

An effort has been made to provide the most updated data, but it has to be noted that the evolution of prices and costs is extremely rapid in this period. Especially regarding fuel prices, in the coming years, there are expected variations that will modify the scenario. Also, the price of carbon credits is volatile, both over time and depending on the systems. Developing a more regulated and unified system that can equate all technologies is still uncertain. Wider collaboration among the states in this area could greatly help boost this market, which is still characterized by uncertainty in its effectiveness.

The results of this work provide an opportunity to assess the status of the initiatives within the existing legislative framework. Besides setting more or less stringent targets, clear and effective methods are needed to accelerate decarbonization, by specifying the path to be followed, especially through incentives that guarantee companies remain competitive in the market. As stated in the 17 Sustainable Development Goals, energy must be clean but also accessible to all: the transition must be sustainable both economically and climatically.

Legislative framework

The aviation sector is undoubtedly one of the most challenging to address in the process of decarbonization that the entire world is trying to implement. For this sector, technological and cost limitations still hinder a transition towards a renewable and sustainable resource.

Nevertheless, according to various directives and laws aimed at decarbonizing this sector, a gradual reduction in emissions is expected year after year. Speaking of regulations, two macro-systems have dealt with this matter so far.

On the one hand, there is the European scope and the Green Deal, which includes, among others, the Renewable Energy Directive II [1], the Emission Trading System [2], and specific directives for fuels such as ReFuelEU [3].

On the other hand, concerning the aviation sector, the International Civil Aviation Organization (ICAO) has developed a system to reduce emissions called CORSIA (Carbon Offsetting and Reduction Scheme for International Aviation) [4].

European Green Deal

The European Union launched the European Green Deal in December 2019, containing a series of proposals, incentives, and regulations aimed at a green transition towards climate neutrality by 2050 [5].

This collection of initiatives aims to decrease greenhouse gas emissions to the point of eliminating them, making the continent the first 'climate-neutral' bloc. The main objective is then broken down across the numerous different sectors involved. It starts with the energy sector but also encompasses the industrial sector, construction, transportation, food, and biodiversity preservation. However, all this must be ensured without compromising the ongoing economic growth while pursuing a goal of social sustainability in which no one is left behind.

All the directives related to the Green Deal are grouped under a comprehensive new package known as 'Fit for 55' [6]. This plan was developed by the European Union to reduce the continent's emissions by 55% by 2030 compared to 1990 levels, ultimately achieving climate neutrality by 2050.

This set of proposals includes:

- EU Emission Trading System (EU ETS)
- Social climate fund
- Carbon border adjustment mechanism (CBAM)
- ReFuelEU Aviation
- Fuel EU maritime initiative
- Renewable Energy Directive (RED II)
- States' emissions reduction targets
- Land use, land use change and forestry (LULUCF) regulation
- Energy efficiency directive

The proposals range across all sectors; those involved in the aviation sector are mainly: EU ETS [2], RED II [1] and ReFuelEU Aviation [3]. Instead, LULUCF is more focused on biochar and agricultural practices.

European Union Emission Trading System

This is a tool adopted by the European Union to limit greenhouse gas emissions and establish a system for trading emission allowances [2]. The system annually determines the allowed emissions, which are provided as allowances. Most of these allowances are given for free, a portion is auctioned among companies, and a final portion is reserved for special cases that require additional allowances, such as new companies.

This mechanism, known as 'cap-and-trade,' sets a maximum cap on permissible emissions, with corresponding distributed allowances (1 allowance = 1 ton of CO_2). These allowances can then be traded and bought on a dedicated market among companies, ensuring the flexibility to reduce emissions most cost-effectively. Hence, when a company reaches its maximum permitted emissions level, it has to buy new allowances on the carbon market. Year after year, these free allowances decrease linearly, driving companies to gradually reduce and eventually eliminate their emissions.

The Emissions Trading System (ETS) was launched in 2005 and is now in its 4th phase. In the initial pilot phase (2005-2007), during which nearly all allowances were granted for free, a foundation was established for carbon pricing and the necessary infrastructure for monitoring and verifying emissions. The second phase (2008-2012) expanded the scope by adding the aviation sector (since January 1, 2012), reduced the percentage of free allowances to 90%, and increased fines for violations.

The third phase (2013-2020) brought a significant change by modifying the maximum cap. Previously, each state determined its cap individually; now, a single cap is set at the European level. Additionally, other industrial sectors and emissions from other gases were included (previously, only CO_2 and N_2O emissions were considered). In this phase, as shown in Figure (1) below, the total CO_2 emissions from the aviation sector covered by the ETS system increased from 53.5 Mt in 2013 to 68.2 Mt in 2019, before the collapse caused by the Covid-19 pandemic [7]. Despite the increase in total emissions, the allowances allocated for free remained nearly unchanged over the years, while the purchase of European Union Allowances (EUAs)

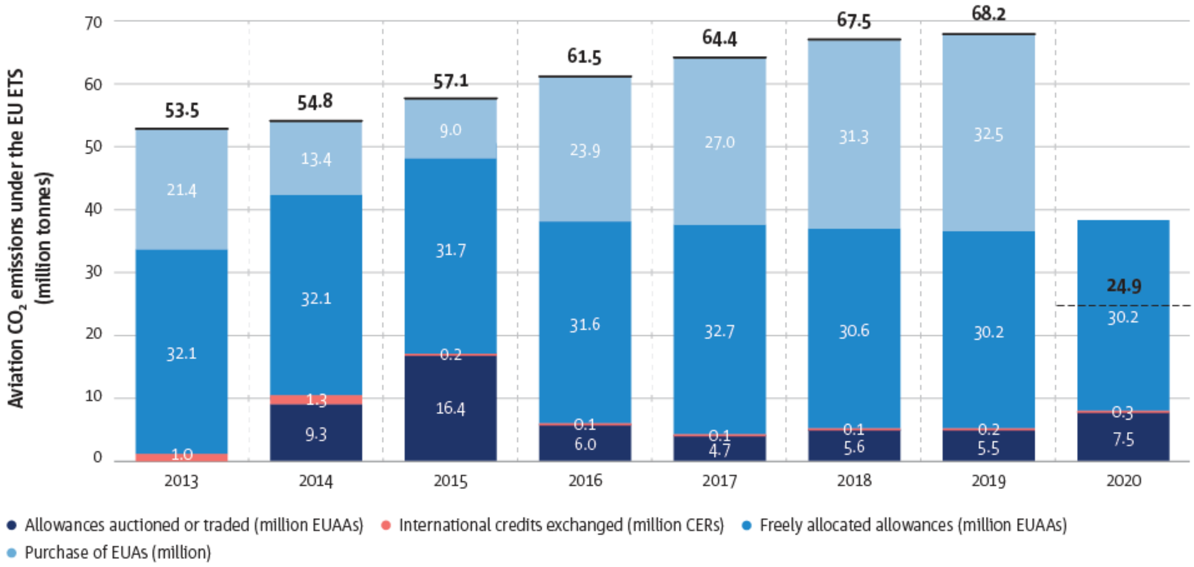


Figure 1: Aviation CO2 emissions under EU ETS in 2013-2020 where 1 EUAs = 1 tonCO2 [7]

on the market grew, contributing to a reduction of around 159 Mt of CO_2 in other sectors [7].

The fourth phase (2021-2030), which we are currently in, has been revised to align it with the goals of the new Green Deal and the "Fit for 55%" package. In this final phase, a linear reduction in permitted emissions of 4.3% from 2024-2027 and then 4,4% per year from 2028 is planned, with the flexibility to make adjustments under certain conditions.

Regarding the aviation sector, the European ETS system regulates and considers emissions produced only from flights within the European Economic Area (EEA) [2].International flights to other continents fall under the CORSIA system (Carbon

Offsetting and Reduction Scheme for International Aviation) [4], developed by the International Civil Aviation Organization (ICAO), which will be discussed later.

An important element to be considered in this Directive concerns the emission factors considered. The monitoring and reporting of emissions from air transport in Annex IV Part B, specifies that values are taken from the 2006 IPCC guidelines. However, the emission factor for biomass that meets the sustainability criteria defined by RED II can be considered as zero. This will, therefore, be a parameter that must be taken into account when assessing the fuel emissions.

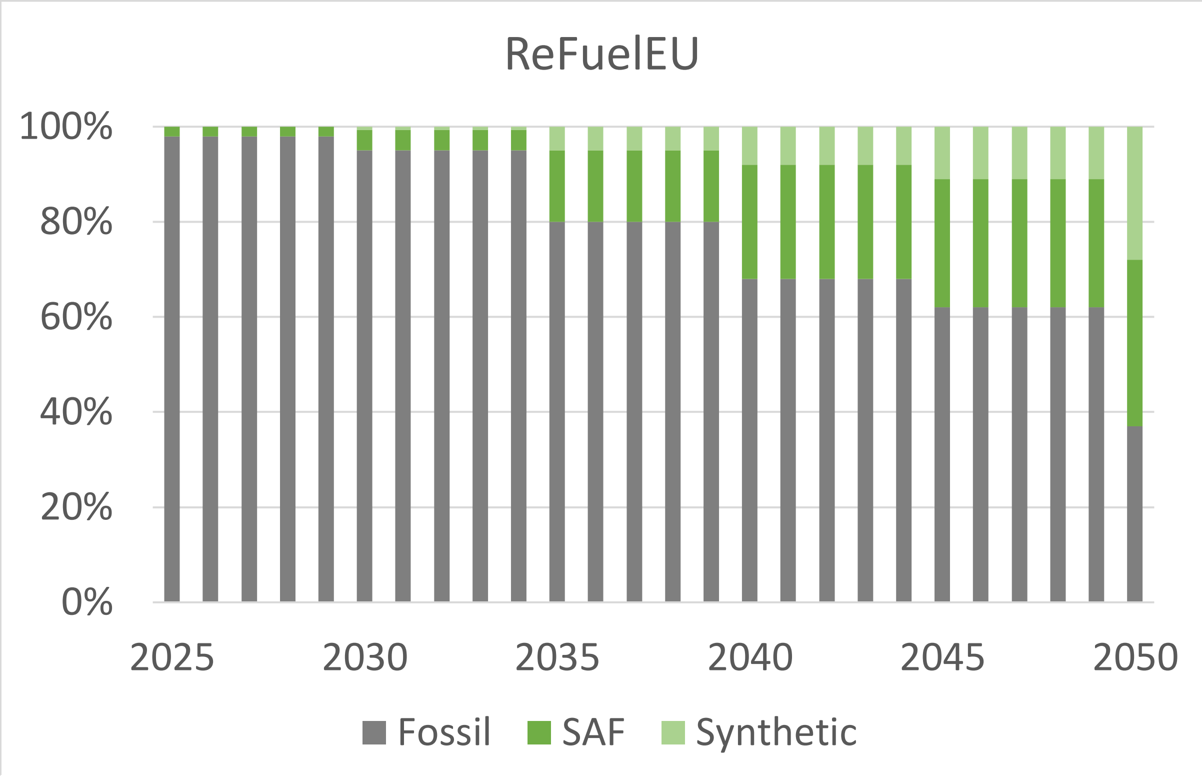
Renewable Fuel EU

The ReFuelEU regulation was introduced on January 1, 2023, to further incentivize sustainable transition in the aviation sector. This regulation aims to promote the adoption and diffusion of Sustainable Aviation Fuels (SAFs) in a crucial industry like aviation [3]. These are fuels with a lower impact on greenhouse gas emissions that must comply with sustainable criteria defined by the Renewable Energy Directive and CORSIA.

Starting from 2025, mandatory minimum quotas for SAF are established, which must be utilized both by airlines and supplied by airport refuelling facilities. The initial percentage of SAF usage is set at 2% in 2025, gradually increasing to a minimum quota of 63% sustainable aviation fuels by 2050, including a minimum of 28% synthetic aviation fuels, as shown in the following table 1.

Table 1: ReFuelEU minimum value of SAF requested [3]

	2025	2030	2035	2040	2045	2050
Percentage of SAF used in aviation	2%	5%	20%	32%	38%	63%
Of which: sub-mandate Synthetic fuels	-	0.7%	5%	8%	11%	28%



Graph 1: Share evolution of SAF according to ReFuelEU [3]

Additionally, the regulation includes provisions to prevent "tankering" practices, seeking to ensure fair market conditions among different states [3]. Practices like "tankering" occur when airlines load more fuel than necessary at a given airport to avoid refuelling partially or completely at a destination airport where fuel is more expensive [3].

Renewable Energy Directive II

The cornerstone decree of the European Green Deal is undoubtedly the Renewable Energy Directive, which is now almost in its III revision [8]. Initially amended in 2009 and further updated in 2018, it is currently undergoing a revision process since 2021 in response to the increased sustainable targets for 2030 under the "fit for 55%" package [6].

The co-legislators have reached an agreement to revise the directive and increase the share of renewable energy in the EU's gross final energy consumption to 42.5% from the current 32% [8]. This directive aims to promote energy use from renewable sources and sets targets for the minimum shares of these at the European level. It also establishes rules for financial systems supporting this transition, outlines how states can collaborate and sets sustainability criteria and greenhouse gas reduction requirements for biofuels, bioliquids, and biomass fuels [1].

Precisely, article 29 paragraph 10 of the directive establishes a minimum value of emission savings from the use of biofuels in order to be considered sustainable which is 65 [1]. This is crucial, because it must be taken into account when considering the emissions in the aviation sector regulated by ETS, as several biofuels do not reach the threshold value.

While the aviation sector is not directly mentioned in this directive, it falls under the transport sector's directives in Article 25. This article stipulates that the minimum share of sustainable fuels or electricity used in the transport sector must be at least 14%, but with the revision of the legislation, this threshold will be raised to 29% [8]. The directive does not differentiate emissions for various transport modes (maritime, aviation, road, etc.) but requires a cumulative sum.

However, there is a clarification on calculating the minimum share [1]. It is done as a fraction, where the numerator is the quantity of energy from renewable sources, and the denominator is the total amount consumed by the sector. It is a ratio of energies calculated as the product of the fuel's calorific value and the quantity used. In the calculation of the numerator, for aviation fuels, if advanced biofuels or biogas are used from raw materials listed in Annex IX Part A [1] of this directive, their energy content is considered 1.2 times higher; for non-biological renewable fuels, it is considered 1.5 times higher. Therefore, more importance is given to these types of fuels.

This directive establishes a methodology and practical values for calculating greenhouse gas emissions from the production and use of a fuel. Annex V [1] contains typical and default greenhouse gas (GHG) emission values for biofuels and bioliquids that can be used to calculate emissions in the aviation sector. Specifically, Annex V Part C [1] outlines a technique for calculating individual greenhouse gas emissions, as shown in the following equation:

Eq. 1

$$E = e_{ec} + e_l + e_p + e_{td} + e_u - e_{sca} - e_{ccs} - e_{ccr}$$

Where:

Table 2: Emission value for each process step [1]

$\boldsymbol{E}$	total emissions from the use of the fuel;
$\boldsymbol{e_{ec}}$	emissions from the extraction or cultivation of raw material;
$\boldsymbol{e_{l}}$	annualized emissions from carbon stock changes caused by land-use change;
$\boldsymbol{e_{p}}$	emissions from processing;
$\boldsymbol{e_{td}}$	emissions from transport and distribution;
$\boldsymbol{e_{u}}$	emissions from the fuel in use;
$\boldsymbol{e_{sca}}$	emission savings from soil carbon accumulation via improved agricultural management;
$\boldsymbol{e_{ccs}}$	emission savings from CO2 capture and geological storage;
$\boldsymbol{e_{ccr}}$	emission savings from CO_2 capture and replacement.

All these parameters are reported for different value chains and different feedstocks in the same Annex.

For this study, an important parameter is "e_{sca} "; it's specified that within the context of "improved agricultural management", is included using organic materials, among other things. The calculation of this parameter is then explicitly detailed in Implementing Act 2022/996 [9], which asses the rules to verify sustainability and GHG emissions saving criteria. “Implementing Act” is a term used in the European Union to refer to an act that aims to implement or put into practice a previously adopted regulation (RED II) [1]. In other words, it is a measure that provides specific details or instructions on how to apply and enforce the provisions of a law or regulation. The computation for the e_{sca} parameter is outline in Annex V [9] and reported below:

Eq. 2

$$e_{sca} = (CS_A - CS_R) \times 3.664 \times 10^6 \times \frac{1}{n} \times \frac{1}{p} + e_f$$

Where:

- CS_R is the mass of soil carbon stock per unit area associated with the reference crop management practice in Mg of C per ha.
- CS_A is the estimated mass of soil carbon stock per unit area associated with the actual crop management practices after at least 10 years of application in Mg of C per ha.
- 3.664 is the quotient obtained by dividing the molecular weight of CO_2 (44.010g/mol) by the molecular weight of carbon (12.011g/mol) in g CO_{2eq}/g C.
- n is the period (in years) of the cultivation of the crop considered.
- p is the productivity of the crop (measured as MJ biofuel or bioliquid energy per ha per year).
- e_f emissions from the increased fertilizers or herbicide use.

The act then reports the methodology to calculate the actual values of CS_R and CS_A. As described in this Annex, the maximum total value of annual emission savings resulting from improved agricultural management's soil carbon accumulation is capped at 45 g CO_{2eq}/MJ biofuel or bioliquid for the entire application period [1]. This cap applies when biochar is utilized as the sole organic soil improver or combined with other eligible e_{sca} practices.

To summarize, the European Union is striving to steer the continent toward a sustainable transition through these directives. These directives have imposed binding and ambitious objectives; however, the specific route to achieve these goals is not specified yet due to the various valid solutions. The most binding European regulations for the aviation sector are the ETS mechanism, which sets an emission cap while allowing companies to manage carbon credits freely, and ReFuelEU, which will obligate airlines and airports to implement shares of sustainable fuel as the years progress.

International Civil Aviation Organization

Moving on to the international level, we refer to the International Civil Aviation Organization (ICAO). It is an autonomous agency within the United Nations, founded in 1947 in Montreal. Besides developing standards and technical regulations for international aviation, in 2016, ICAO adopted the CORSIA system to reduce CO_2 emissions from international flights [4] [10]. As shown in the following figure 2 [11], to maintain a carbon neutral growth at 85% of 2019 level, besides improving aircraft efficiency and transport organization, the most important reduction will come from CORSIA, including the development of Sustainable Aviation Fuels.

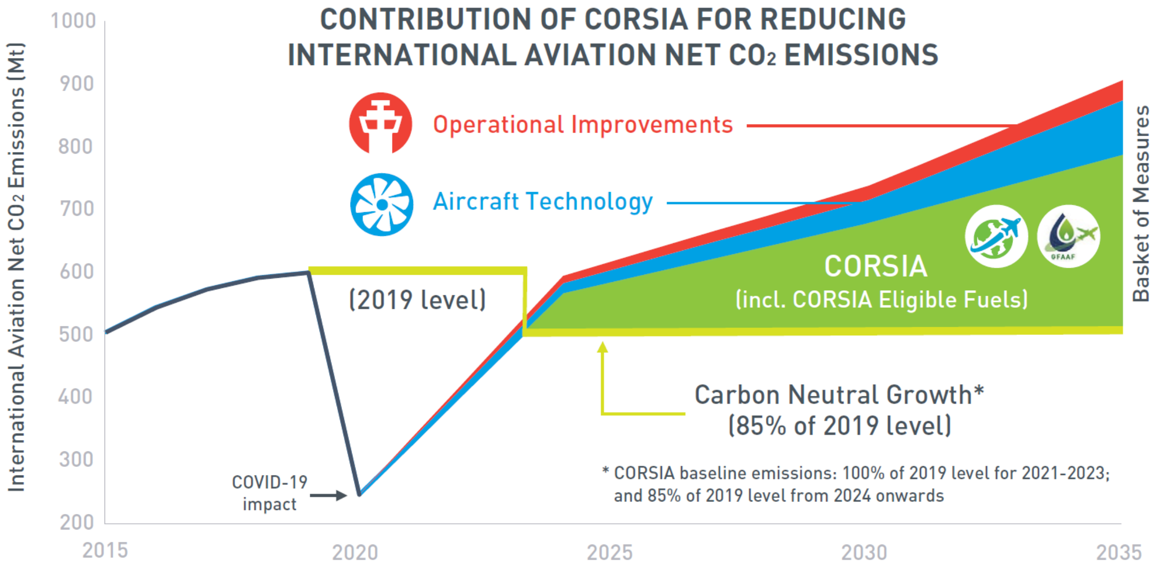


Figure 2: COSRIA forecast emission for aviation until 2035 [11]

Carbon Offsetting and Reduction Scheme for International Aviation

As the acronym suggests, the CORSIA system (Carbon Offsetting and Reduction Scheme for International Aviation) is a carbon offsetting and reduction scheme. In contrast to the ETS system, which creates a market for carbon emission allowances, the CORSIA system is a Market-Based Measure (MBM). Once a predefined emissions threshold is exceeded, airlines are obligated to purchase offset credits from projects that reduce emissions in other sectors [7]. In the CORSIA system, the incentive to reduce emissions is driven by the cost companies must bear to purchase offset credits; furthermore, these credits help fund emission reduction projects [7].

CORSIA is implemented in phases to accommodate the varying needs of different states at their own economic and social development levels. The system is structured in three phases:

- Pilot phase (2021-2023)
- First phase (2024-2026)
- Second phase (2027-2035)

While the first two phases have the same requirements and are voluntary, the last phase applies to all Member States with minor exceptions.

Most developed countries decide to participate voluntarily; however, developed States like Brazil, Russia, India, China, and South Africa (known as BRICS) still do not join the program.

As previously introduced, with this system, the aeroplane operator has to offset all their CO_2 emissions, and it has two ways to do it. On one side, it can reduce its impact by claiming an emission reduction due to the use of Sustainable Aviation Fuel (SAF) or Low Carbon Aviation Fuel (LCAF) that must comply with the CORSIA sustainability criteria (CORSIA eligible fuels) [12]. Conversely, since these fuels still emit GHG, the aeroplane operator must purchase CORSIA Eligible Emission Units [13] to cancel all the remaining offsetting requirements.

CORSIA scheme is applied only on international flights and evaluates the emissions of CO_2 for each one according to this formula [4]:

Eq. 3

$$CO_2 = \sum_f M_f * FCF_f$$

Where:

- CO_2 = CO_2 emissions (in tonnes)
- M_f = Mass of fuel f used (in tonnes)
- FCF_f =Fuel conversion factor of given fuel f, equal to 3.16 (in kg CO_2/kg fuel) for Jet-A fuel/Jet-A1 fuel and 3.10 (in kg CO_2/kg fuel) for Aviation Gasoline or Jet-B fuel.

So, after evaluating the total amount of CO_2 for each flight, the aeroplane operator has to compute the offsetting requirements for the considered year before considering the CORSIA-eligible fuels.

For the period from 2024 to 2035, the amount of CO_2 emissions required to be offset in a given year "y" is computed according to this formula [4]:

Eq. 4

$$OR_y = \%S_y * (OE_y * SGF_y) + \%O_y * (OE_y * OGF_y)$$

Where:

- OR_y = Aeroplane operator's offsetting requirements in the given year y.
- OE_y = Aeroplane operator's CO_2 emissions covered according to the rules in the given year.
- $\%S_y$ = Per cent Sectoral in the given year y.
- $\%O_y$ = Per cent Individual in the given year y where $\%O_y = (100\% - \%S_y)$.
- SGF_y = Sector's Growth Factor.
- OGF_y = Aeroplane operator's Growth Factor.

This gives the quantity of emissions the operator is required to offset. If it uses a CORSIA-eligible fuel, it can claim an emission reduction according to this formula [4]:

Eq. 5

$$ER_y = FCF * \left[\sum_f MS_{f,y} * \left(1 - \frac{LS_f}{LC}\right)\right]$$

Where:

- ER_y = Emission reductions from the use of CORSIA eligible fuels in the given year y (in tons);
- FCF = Fuel conversion factor, equal to 3.16 kgCO_2/kg fuel for Jet-A fuel / Jet-A1 fuel and 3.10 kgCO_2/kg fuel for AvGas or Jet-B fuel.
- $MS_{f,y}$ = Total mass of a neat CORSIA-eligible fuel claimed in the given year y (in tons);
- LS_f = Life cycle emissions value for a CORSIA-eligible fuel (in gCO_2e/MJ) [14];
- LC = Baseline life-cycle emissions values for aviation fuel, equal to 89 gCO_2e/MJ for jet fuel and 95 gCO_2e/MJ for Aviation Gasoline.

Then this parameter is used to compute the Final Offsetting Requirements (FOR) for a compliance period according to the following formula. This period considers the company's behaviour during the previous three years, taking into account the offsetting requirements and the emissions reductions [4].

Eq. 6

$$FOR_c = (OR_{1,c} + OR_{2,c} + OR_{3,c}) - (ER_{1,c} + ER_{2,c} + ER_{3,c})$$

Where:

- FOR_c = Aeroplane operator's total final offsetting requirements in the given compliance period *c*;
- $OR_{y,c}$ = Aeroplane operator's offsetting requirements in the given year *y* (where *y* = 1, 2 or 3) of the compliance period *c*;
- $ER_{y,c}$ = Emissions reductions from the use of CORSIA-eligible fuels in the given year *y* (where *y* = 1, 2 or 3) of the compliance period *c*.

So, this gives the remaining part of the offsetting requirement that the operator must cancel through the CORSIA-eligible emission units. For the first phase (2024-2027) we are about to enter, the Eligible Emissions Units [13] by Programme are:

- American Carbon Registry (ACR)
- Architecture for REDD+ Transactions (ART)

So, aeroplane's operator will have to purchase carbon credits from these verification bodies to offset their emissions. These carbon credits will come from activities that relies on the CORSIA Emission Unit Criteria (EUCs) [15] to be sure that they are obtained following the sustainability goals. This process is put together by the Technical Advisory Body (TAB) which assesses emissions unit programmes and makes recommendations to Council (ICAO) on the programmes whose emissions unit should be eligible.

Hence, the CORSIA system for biochar applications presents two viable options to take it into account.

On the one hand, biochar could be considered an additional carbon sequestration during the cultivation phase of crops that will be converted into biofuel. This will result in a lower Life Cycle emissions of the fuel used and will reduce the offsetting requirement the company has to purchase.

On the other hand, stand-alone carbon credit cand be considered to be produced from a separate program and sold as a CORSIA emission unit according to the programmes above.

Unlocking the potential of biochar: slow pyrolysis and carbon sequestration

In the last years, biochar has gained the attention of agriculture and energy sector as a possible negative-emission technology to fight climate change. However, biochar is known from quite a long time. There have been trails along human history since its beginning with multiple uses, from mixing with clay or using it as a preserver in tombs of the Chinese dynasty, to soil improvement found in the Amazon Basin of South America [16].

Properties and production

Biochar is defined by Lehmann [16] and reported by Chen [17], as "carbon-rich product of biomass produced by the so-called thermal decomposition of organic materials under conditions of anoxia or limited oxygen supply, and at relatively low temperatures". This definition identified the pyrolysis process as the main route to obtain biochar from biomass. Pyrolysis is a thermochemical process in which biomass is decomposed by heating in the absence of oxygen (or limited presence) [18]. The scarcity of oxygen prevents the material from completely combusting and instead leads to the breakdown of complex organic compounds into simpler molecules.

Pyrolysis always generates three products:

- Mix of condensable vapours that is converted into liquid generating pyrolysis oil.
- Mix of permanent gases that can be exploited as syngas.
- A solid carbonaceous material used as charcoal.

The share of these three products varies with the process parameters like process temperature, moisture content, heating rate (HR), and hot vapour residence time (HVRT). They identified three possible modes for pyrolysis.

- Fast pyrolysis: The residence time is really short (from hundreds up to 2 seconds), and the temperatures achieved are quite high (500°C). The heating rate is high to quickly break the biomass and enhance the yield of volatiles [18]. These represent the main product that, once recovered in the liquid phase, generates the pyrolysis oil.

- Intermediate pyrolysis: operates still at high temperatures but with a longer residence time and it gives a balanced output of the three products.
- Slow pyrolysis is characterized by a very long residence time (minutes up to days) and low heating-rate (max 2 degrees per second). This method maximizes solid char yield even if there are also relevant amounts of gas and liquid produced [19] [20].

Since this study focuses on decarbonization and the impact of biochar in this regard, let us further analyse its production process, also in terms of sustainability.

In slow pyrolysis, solid charcoal (biochar) usually represents around one third of the products [21] [22], which means also vapour and gasses needed to be exploited accordingly. Before pyrolysis, biomass needs to undergo a preprocessing step that depends on the type of feedstock. Usually, it is always present a drying stage to reduce the moisture content to around 10% [19], which can be energy-intensive for herbaceous biomass or sludge. Instead, woody waste from forest residue needs to be chopped to obtain a suitable size for heat transfer in pyrolysis unit. During slow pyrolysis, roughly 70% of the mass and half of its energy content, originating from the woody raw material, is transformed into pyrogas [23] [20]. This can be seen as a mixture of condensable hydrocarbons, water vapour and non-condensable gasses. Syngas and bio-oil must be utilized to reduce the impact of GHG emission as much as possible. The most widely used solution [22] combined the production of biochar with the heat generation. In this case, the heat source for pyrolysis and drying steps are supplied by the combustion of bio-oil and bio-syngas obtained from the process [24].

According to the study performed by Cheng [18] this solution also produces extra-heat that can be exploited for domestic heating, substituting fossil sources and thus further reducing the GHG impact. The overall global warming potential obtained states the biochar capacity as a negative emission technology. Nevertheless, the potential varies depending on the feedstock and process temperature. As previously said, sludge has a significant preprocessing energy need that cannot be fulfilled by co-product combustion leading to a positive global warming potential [22].

Some studies were also carried out to apply slow pyrolysis to a steel plant [25]. MUSIC project analysed the possibility to implement biochar production through slow pyrolysis with the steel making process in Arcelor Mittal plant in Taranto. Besides the steel plant and its integration system, it is interesting to look through the biochar production process and its energy balance reported below.

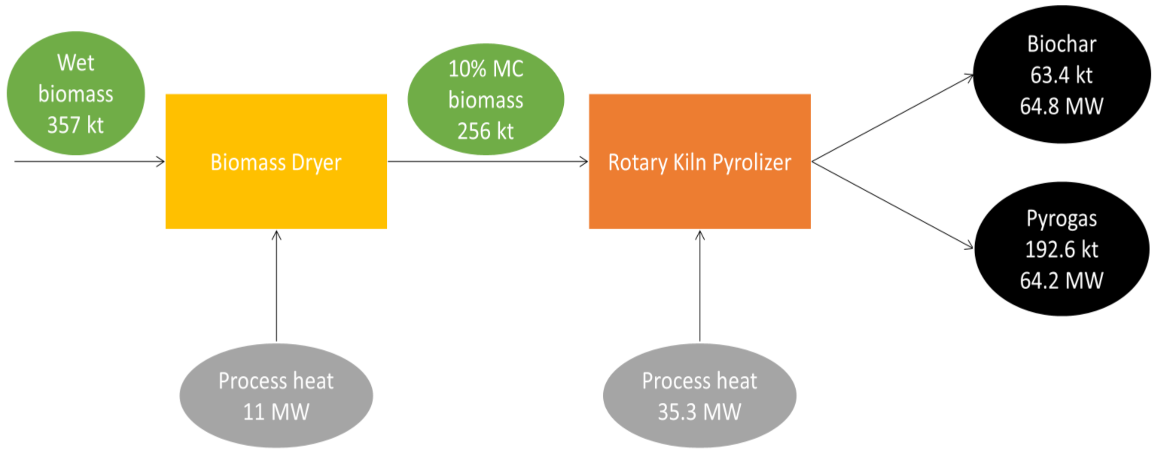


Figure 3: Plant investigated by MUSIC

The plant investigated in this study [25] is composed of a dryer and a rotary kiln pyrolizer chosen for its flexibility in terms of feedstock dimensions and low investment cost. Biomass dryers require about 11 MW, which varies during the year due to different moisture content. Kiln pyrolizer receives 256 kt per year (≈34 t/h) with 10% remaining moisture content. In the table below the mass and energy balance of the reactor conventionally taking the outputs with positive sign are presented.

Table 3: Mass and energy balance of the plant

Rotary Kiln Pyrolizer	INLET		OUTLET	
	Biomass	Process heat	Biochar	Pyrogas
Mass balance [kt]	-256		+63.4	+192.6
Power balance [MW]	-93.7	-35.3	+64.8	+64.2

Obviously, mass is conserved with a char yield of ≈25% and a huge amount of exploitable pyrogas. Assuming, as planned, to use the pyrogas for both process heat of dryer and pyrolizer (11MW and 35.3MW) there will still be 17.9 MW that can be utilize. Besides the singular application to the steel industry with biochar as bio-coke, this gives an idea of the exciting feature of slow pyrolysis due to its flexible technology adaptable for several applications and key for decarbonization.

Environmental management technique: the biochar case

Besides this solution with a potential fossil substitution, biochar can be exploited as carbon sequestration technology [21]. Mainly composed by organic carbon (above 60 %), biochar is still used in some countries as fuel for heating and cooking [16]. However, the most interesting exploitation is in the agriculture as a soil amendment. Several studies have pointed out the positive impact on soil constraint on improving crop growth [26]. The increase water holding capacity gives the main advantage due to its high porosity which can be extremely useful in dry-arid area and used also to overcome flooding damage. Many studies also call attention to the correlated ability to hold nutrients [26] [27]. This is a great opportunity in the agriculture sector. Fertilizers are largely used around the world as they are mainly based on nitrogen that comes from ammonia through Harber-Bosh process. This has a negative impact on GHG emissions because it starts from gaseous hydrogen (H_2), which is still obtained by steam reforming of methane. Circling back to biochar, an accurate use can reduce the need for fertilizers and, consequently the GHG emissions.

Besides soil enhancing, the main point of biochar lies on the carbon dioxide sequestration, and conversion into solid carbon. Transforming biomass into biochar before adding it to the soil extends the duration that carbon remains in the soil compared to adding the raw biomass directly [16] [21]. Consequently, over specific periods, this process can be seen as actively removing carbon dioxide from the atmosphere. Biomass, through photosynthesis absorbs CO_2 and fixes the carbon in its structure of cellulose, hemicellulose, and lignin. In the natural cycle, the biomass dies, and decomposing emits back the CO_2 previously absorbed, balancing the cycle. However, when biomass is transformed into biochar, the carbon is fixed as solid carbon and buried underground. Biochar, due to its incredible chemical stability, has a really slow decomposition rate, when put into the soil it can remain for thousands of years under natural conditions [28]. With this method, the CO_2

previously absorbed during the biomass growth is safely stored into the soil, creating a removal credit of CO_2 from the atmosphere.

To summarise what said before, Lehmann [16] [29] identifies four complementary objectives that stimulate biochar application for general environmental management:

- Soil improvement: as previously said, biochar has this incredible capacity to improve soil fertility, and this is crucial in some areas of the world where there is a necessity to fight malnutrition and guarantee food security.
- Energy production: capturing some of the energy developed during the biochar transformation is crucial to reducing overall emissions. Adding biochar to the soil instead of using as fuels, reduces the energy efficiency of the pyrolysis; however, the emission reduction associated with the additions to soil appears to be greater than the usage of biochar as fuels. For this reason, the best use of biochar is as a soil additive rather than as a fuel.
- Waste management: this is a very important issue to assess these days, since giving a second life to all the kinds of waste is critical to enforce a sustainable development and a circular economy. Not only can energy be gained in the process, but volume and weight are also significantly reduced, which simplifies practical management. An important point is also the emission from livestock and industrial wastes, which offers economic opportunities with a reliable source of feedstock generated at a single point location. It should be noticed that, in this case, the costs associated with these by-products are market-dependent and challenging to predict.
- Mitigation of climate change: Carbon sequestration through biochar has emerged as an interesting aspect in recent years. Biochar can be incorporated into soil to remove carbon from the atmosphere. Through photosynthesis, CO_2 is converted into solid carbon within the plant, fixed as biochar via slow pyrolysis, and then buried underground as a safe carbon stock.

Sustainable Aviation Fuels

Sustainable aviation fuels represent a critical innovation in the aviation industry, offering a promising solution to reduce carbon emissions and mitigate environmental impact [30]. Sustainable aviation fuels, derived from renewable resources such as biomass, algae, and waste oils, hold immense potential to revolutionize air travel by significantly reducing its carbon footprint. According to ReFuelEU [3], they are defined as "drop-in" aviation fuels, meaning that they can be safely blended with fossil-based fuels due to their almost identical characteristics and that do not require any change of the fuel infrastructure.

Technology and process

There are various possible pathways to obtain a fuel suitable for the aviation industries, but not everyone has been approved, and only one has reached the Technology Readiness Level (TRL) of the actual proven system and commercialization level (9). Between the several possible routes, here are reported the four main ones that are expected to play a significant role in the near future:

- Hydroprocessed Esters and Fatty Acids (HEFA): HEFA fuels are produced from feedstocks such as vegetable oils, animal fats, and greases through hydroprocessing. This process involves hydrogenation and refining to convert triglycerides into hydrocarbons suitable for use in aviation. This process is currently the only one at a commercial level, even if the availability of feedstock limits the scale-up of its capacity.
- Alcohol-to-Jet (ATJ): At this time, it is at TRL 7-8; SAF is produced through the fermentation of lignocellulosic feedstock or sugar crops into alcohols that undergo three additional steps to become suitable for jet turbine engine (Dehydration – oligomerization – hydrogenation). Its versatility as a feedstock source made it particularly advantageous due to its outstanding sustainability and resilience in the supply chain.
- Gasification + Fisher-Tropsch (FT): this is a multi-level process that has syngas as an intermediary product. Fisher-Tropsch is a reaction originally developed during the second world war to make up for the oil shortage by the Nazis. This process was studied to convert a gas mixture of carbon monoxide and hydrogen obtained by coal gasification, into liquid hydrocarbons suitable as fuel for tanks. In the case of SAF, the main process

is the same except for the gasification reaction that starts from biomass feedstock. This route has significant emissions reduction and potential but is still not available on a commercial scale (TRL 7-8).

- Synthesized iso-paraffins (SIP): this is based on a fermentation process to directly convert sugar feedstock into hydrocarbon molecules that can be blended until 10% (TRL 7-8).

For this study, due to its availability and readiness, the HEFA route will be considered. For a better understanding of the SAF production chain, let's take a look at Bio4A project [31] [32] [33] [34].

The Bio4A project

This is a project funded by the European Commission that has the goal of scaling up the production of advanced sustainable biofuel for aviation. One of the most interesting points is, of course, the analysis of the SAF production pathway from HEFA route.

This process starts from a lipid feedstock that can be obtained through different sources: the classic one is the vegetable oil. This is a mixture of free fatty acids and triglycerides obtained generally from seeds through mechanical and chemical extraction. The seeds used for this purpose are mainly camelina, soybean or rapeseed. The vegetable oil can also be obtained by recycling used cooking oil or with tallow wastes. Below is the block chart of SAF production process at the producer as reported by the project. [35] [36]

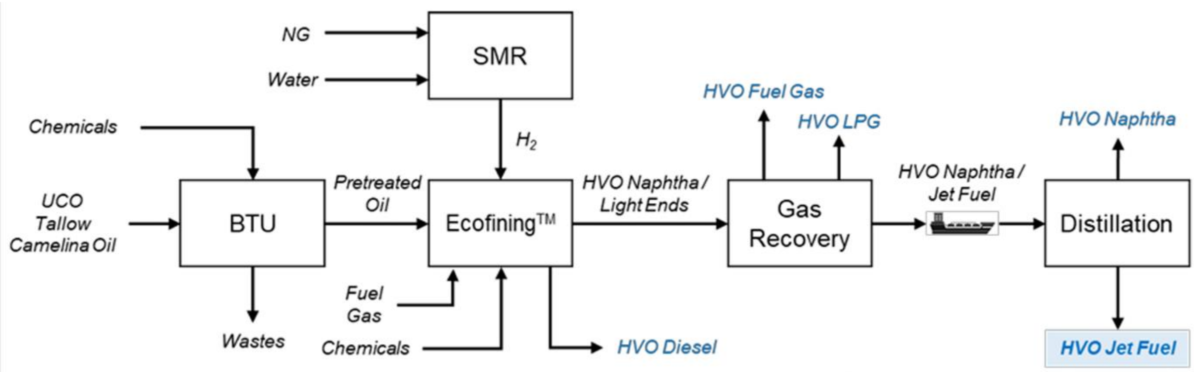


Figure 4: . Block chart of the fuel processing stage at ENI facilities [36]

After pre-treatment, vegetable oil undergoes the main stage of hydrotreatment to remove impurities (Biomass Treatment Unit). To be classified as "drop-in", the fuel needs to undergo a deoxygenation and an isomerization stage consuming H_2. Hydrogen is produced through steam reforming (SMR) from methane with a water gas shift reaction and is used to remove oxygen from the vegetable oil [32]. Then, an isomerization stage is needed to enhance fuel cold properties, converting linear n-paraffins into branched iso-paraffins, reducing freezing and cold point. At this phase, the main product is HVO Diesel that can be directly blended with diesel infrastructure. The remaining fraction undergoes a gas recovery to stabilise and obtain Fuel Gas and Liquefied Petroleum Gas (LPG). The last process is a conventional distillation to separate Naphtha from Jet Fuel (SAF), which can now be used in the aviation infrastructure. Considering the whole project starting from the cultivation, the biorefinery step accounts for 16.3 gCO_2/MJ [36] [35] meaning 50-70 % of the GHG total emission. This is mainly due to the hydrogen requirement that is still fully filled by fossil fuel sources (NG), but in the future, it may be replaced by green hydrogen from electrolysis. Transport contributes to more than 10% of emissions, cultivation and crushing then account for 4-8% with respect to the total value [35].

This production scheme reported by Bio4A, shows that SAF is only the latter product of these processes [35]. Along the pathway, there are several co-products that must be enhanced to maximize its potential. To better understand the product subdivision, below is displayed the share based on the Lower Heating Value (LHV) of the outcomes.

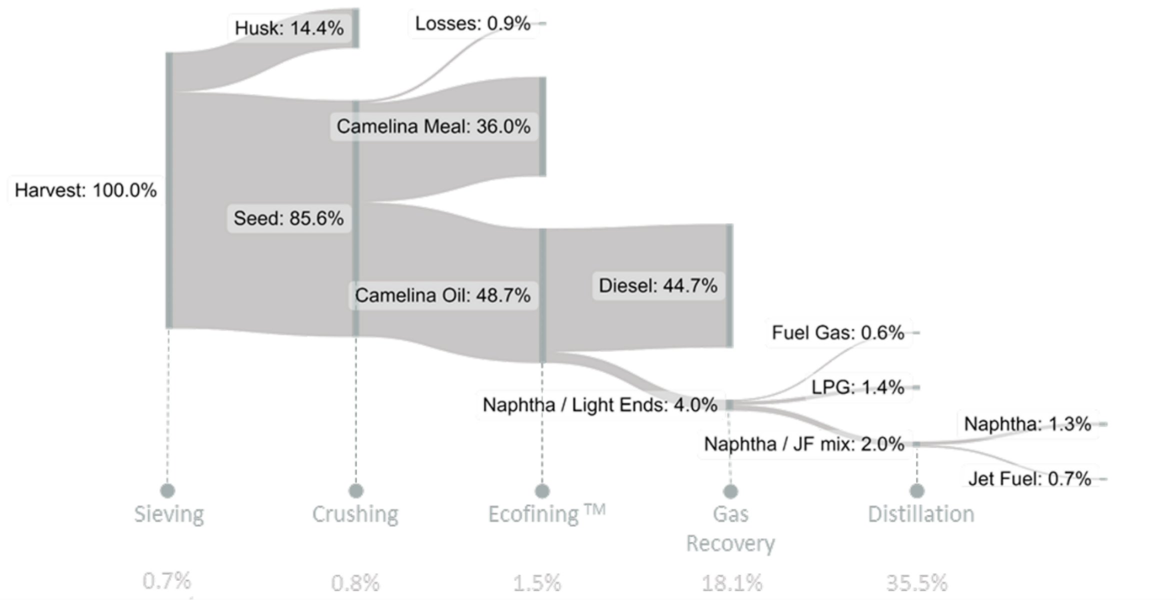


Figure 5: Energy balance (based on LHV of products) and allocation of impacts in the production of SAF along the Bio4A value chain [35]

In the pathway from camelina crops to SAF, it can be entered the biochar application into the soil. This was the solution studied by the Bio4A project, trying also to investigate the agricultural point of view.

Besides examining the situation of the used cooking oil market as a feedstock for SAF, the project also explores the possibility of recovering arid land by promoting sustainable agriculture with biochar. Integrating biochar into camelina cultivation practices makes it possible to consider its impact in calculating fuel emissions, as seen in the RED methodology. By sequestering carbon dioxide and converting it into solid carbon, biochar generates emission deficits that can be transferred to biofuel. As noted earlier, biofuels cannot have a net-zero impact as they consume energy and resources throughout the transformation process. However, enriching the soil in which it is cultivated with biochar, will reduce its emissions, in agreement to the RED methodology's formulas [Eq. 1 and Eq. 2] [1] [9].

The Bio4A project provides data to understand how much carbon remains sequestered in the soil once biochar is added, and this value is used to calculate the sequestration term using the previously mentioned RED II methodology (e_{sca}) [9]. Besides carbon sequestration, the project also assesses the positive impact of the biochar in semi-arid land. As previously said, biochar has the ability to hold better nutrients and water, making it a precious tool to fight desertification [36] [16].

It is essential to consider, as seen before, that there are numerous spillovers in the process of refining fuel to obtain aviation-grade fuel. As reported by the project, starting from biomass collection at each step, there is a loss in terms of both mass and energy, as depicted in the figure 5. Therefore, it is crucial to consider how GHG emission savings distribution is allocated among all the various products obtained. In addition to jet fuel, which is the focus of this study, biodiesel, naphtha, LNG, and fuel gas are also obtained, all of which could benefit from the decrease in emission values.

Starting from the camelina cultivation harvesting, here are reported all the intermediate and final products with their allocation impacts based on lower heating value as reported by Bio4A.

Table 4: Allocation impacts in the production of SAF along the Bio4A value chain [35]

<table>
<tr><td rowspan="8">Harvest 100%</td><td>Husk 14.4%</td><td colspan="4"></td></tr>
<tr><td rowspan="7">Seed 85.6%</td><td>Losses 0.9%</td><td colspan="3"></td></tr>
<tr><td>Camelina Meal 36.0%</td><td colspan="3"></td></tr>
<tr><td rowspan="5">Camelina Oil 48.7%</td><td>Diesel 44.7%</td><td colspan="2"></td></tr>
<tr><td rowspan="4">Naphtha - Light Ends 4.0%</td><td>Fuel Gas 0.6%</td><td></td></tr>
<tr><td>LPG 1.4%</td><td></td></tr>
<tr><td rowspan="2">Naphtha - JF mix</td><td>Naphtha 1.3%</td></tr>
<tr><td>Jet Fuel 0.7%</td></tr>
</table>

Considering that husks and cake are not included as possible energy products and, therefore, do not benefit from the e_{SCA} parameter [Eq.2], it is assumed that all carbon credits generated are distributed among the co-products of camelina oil. This means that the oil will have 100% of allocated credit that are then distributed between all the spillovers. The table below reports first the share between all the production pathways and second the share within the camelina oil.

Table 5: Allocation redistribution considering only the Camelina oil products

	% of total Harvest	% of Camelina oil
Camelina oil	48.70%	100%
Diesel	44.70%	91.79%
Fuel Gas	0.60%	1.23%
LPG	1.40%	2.87%
Naphtha	1.30%	2.67%
Jet fuel	0.70%	1.44%

So, the biochar that should be allocated to the SAF product and account for the e_{sca} term is just 1.44% of the total amount applied. This proper allocation will also consider the fair cost of biochar to apply to this solution.

Energetic analysis of biochar production pathways from oilseed value chains

It is now time to analyse the possibility of integrating the two previously discussed supply chains. On the one hand, the production of biochar through slow pyrolysis has been described, while on the other hand, the entire supply chain for the production of SAF, starting from camelina cultivation, has been outlined. It has been observed how the latter consists of many steps and intermediate co-products. In addition to various types of fuels (Diesel, LPG, naphtha), the major co-product arises from the mechanical extraction of oil from the seeds [35]. This process to obtain vegetable oil produces a solid panel known as oilcake, mainly composed of hemicellulose, typically used as animal feed [20]. However, it contains 45% Dw (dry weight) of carbon [19], which can be recovered through a slow pyrolysis step. It has been mentioned that biochar represents a viable alternative from a waste management perspective by providing new uses for by-products.

Hence, a supply chain for biochar production from vegetable oil residues is being studied and how this, when introduced into the soil, generates a reduction in fuel emissions through the well-known term e_{sca}.

Below is the schematic of the analysed supply chain.

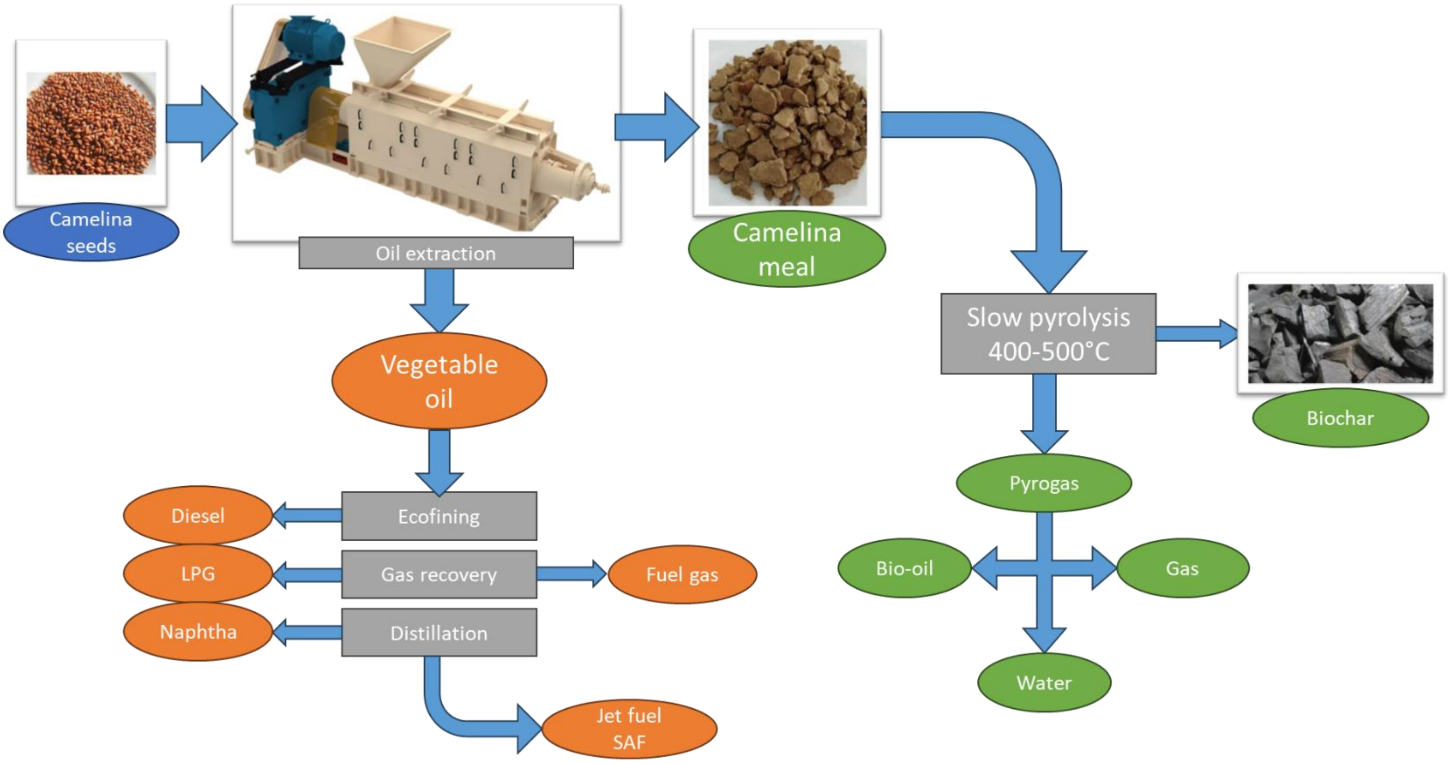


Figure 6: Biochar production value chain starting from camelina seeds

Valorisation of the e_{sca} parameter in the considered value chain

The aim of this paragraph is to evaluate the impact that biochar produced from residues has on fuel emission values for aviation. The assessment will thus be based on the yield of the same crop for the quantity of fuel and biochar obtained. Subsequently, once the quantity of biochar introduced into the soil is obtained, it will be possible to calculate the "esca" parameter for SAF.

As input to the model, the yields from camelina cultivation, extraction, and vegetable oil refining processes were taken from the results obtained from the Bio4A project [36] [35], initially assuming 1 hectare as the harvesting area. A literature search was conducted for the branch concerning biochar generation through slow pyrolysis.

Previously, the allocation in the SAF supply chain was discussed. However, this is done on an energy basis with specific calorific values. In this case, the yield is on a mass basis, so the yield of the oil and meal separation is different. However, subsequent refining steps remain unchanged as the products have the same energy value. The table presents the entire supply chain with both the yield and quantities considering one hectare of harvested land.

Table 6: Yield of camelina value chain

					Yield [% dw]	Outputs [kg/ha]
				Seeds	100.0%	1312.0
→				Camelina oil	38.0%	498.6
	→			Diesel	91.8%	457.7
	→			Naphtha	8.2%	40.9
		→		Fuel Gas	14.1%	5.8
		→		LPG	35.0%	14.3
		→		Naphtha mix	50.9%	20.8
			→	Naphtha	64.5%	13.4
			→	Jet Fuel	35.5%	7.4
→				Camelina meal	61.0%	800.3
	→			Bio-char	35.0%	**280.1**
	→			Water	40.0%	320.1
	→			Bio-oil	18.0%	144.1
	→			Gas	7.0%	56.0
→				Extraction losses	1.0%	13.1

For convenience, the supply chain starts from the quantity of harvested seeds since this is where the fuels are obtained. However, in the case of camelina considered here, there is a quantity of residues from cultivation represented by husks and woody waste. These are respectively 750 and 2060 kg, according to Bio4A [36]. Similar to before, they will not be considered in allocation but could serve as a biomass source from which to derive additional biochar. After oil extraction from the seeds through mechanical pressure, the meal (or cake) is obtained, representing 61% by mass of the seeds. Camelina belongs to the Brassicaceae family and can be compared to the more common rapeseed in terms of properties and composition [20]. Besides being used as animal fodder, Rapeseed is the second source of vegetable protein after soybean and the third source of vegetable oil after soybean and palm oil [23]. In addition to edible uses, it is used in China as a fertilizer and in the United States as a cover crop during winter [23]. The most interesting aspect is its high carbon content, with a moisture content of about 10%, the oil cake contains 45% dry weight of carbon [19] [20].

Consequently, it undergoes a slow pyrolysis step aimed at maximizing biochar production. As mentioned earlier, pyrolysis parameters determine the product composition; according to Ucar et al. [20] [19] and experiments conducted, pyrolysis between 400°C and 500°C yields biochar ranging from 33% to 38% (dry weight). The other co-product of pyrolysis is pyrogas, which consists of water vapor, condensable gases (bio-oil), and non-condensable gases according to the yield reported in the table 6. On the other hand, once vegetable oil is obtained, the supply chain continues in the biorefinery as previously described to obtain various types of fuel. Ultimately, 7.4 kg of SAF, representing 0.56% dw (dry weight) of the harvested seed mass is produced.

Regarding biochar, an average yield of 35% was considered [19], generating 280 kg for soil use.

The valorisation of carbon sequestration in agricultural practices through the e_{sca} parameter has been defined by the RED II directive [Eq.2] [1]and its previously discussed implementing acts [9].

The formula [Eq.7] is adapted to the current situation as follows:

Eq. 7

$$e_{sca} = C_{fix\_soil} \cdot 3.664 \cdot \frac{1}{p} \cdot \frac{1}{n} \cdot (A.F.)$$

Where:

- C_{fix_soil} is the change in mass of the soil carbon stock; according to Bio4A is 82% of the biochar used, expressed in kg of carbon.
- 3.664 is the quotient obtained by dividing the molecular weight of CO_2 (44.010g/mol) by the molecular weight of carbon (12.011g/mol) expressed in kg CO_{2eq}/ kg C
- $\frac{1}{p}$ is the productivity of the crop (measured as MJ biofuel or bioliquid energy per ha). For this purpose, considering the SAF productivity, is considered 295.8 MJ/ha. Directly considering the productivity of the SAF, already take into account the feedstock factor giving the production of SAF and not entire crops.
- n is the period (in years) of the cultivation of the crop considered, in this case is 1 year.
- $(A.F.)$ is the allocation factor already covered in the Bio4A chapter. It accounts for the subdivision of the emission between the different co-products along the value chain. For this purpose, considering the different lower heating values and moisture content, the allocation factor for the Jet-Fuel is 0.82%.

Here are presented the summarized value with the final result:

Table 7: e_{sca} parameter evaluation

Biochar applied	kg_{char}/ha	280
C_{fix} (0.82*kg_{char})	kgC	230
CO_2/CO ratio	$kgCO_2$/kgC	3.664
SAF productivity	MJ/ha/yr	295.8
Allocation factor	%	0.82%
e_{sca}	gCO_2eq/MJ	23.33

Thus, by applying 280 kg of biochar per hectare, a reduction in SAF emissions of 23.33 gCO2eq/MJ is obtained. This can already represent a valid result from a sustainability perspective. However, it is also interesting to understand how much biochar is necessary to achieve the maximum reduction allowed by the directive (45 gCO2eq/MJ).

Proceeding in the opposite direction, the necessary formula is:

Eq. 8

$$C_{fix\_soil} = \frac{e_{sca} \cdot p \cdot n}{3.664 \cdot (A.F.)}$$

Once obtained the total amount of carbon to be applied into the soil per 1 hectare, one must divide by 0.82% in order to achieve the total amount of biochar needed, which is 542 kg. Considering the starting 280 kg obtained from the camelina meal, 262 kg remain to be found. Looking through the co-products of the chain, there are 750 kg of biomass coming from the husk [35] of the seeds that may be suitable. Their similar composition and particle size make them a perfect solution to increase the biochar generation. Assuming to use the same slow pyrolysis process, the biochar yield will again be 35% [19] giving 263 kg perfectly matching the request.

Therefore, this solution also enhances residues like husk and camelina meal improving the environmental impact of the biofuels. For the purposes of this study, it was evaluated only the e_{sca} parameter of the jet-fuel but also the other biofuels can benefit from the carbon sequestration, improving their emission reduction capability.

Energetic analysis of a slow pyrolysis plant for biochar production

After analysing the environmental impact of using biochar in the aviation fuel-production supply chain, the focus now shifts to evaluating its energy performance regarding a potential plant.

To size this slow pyrolysis plant, it is first necessary to establish the amount of biomass to be processed over the course of a year. Assuming a cultivated area size of seven thousand hectares, as an average dimension relative to the total cultivated area in Italy of approximately twelve million hectares, the land yield is considered as seen in the previous paragraph. Therefore, 800 kg of camelina meal, and 750 kg of husks per hectare are obtained with 1312 kg of seeds . In total, by multiplying by the area of land considered, 10922 tons of biomass are obtained. Assuming an operating time of 7600 annual hours, translates to an average input flow rate of 1.44 t/h. Alternatively, considering only the products from oil extraction and leaving the husks for other uses, the incoming biomass will be less, resulting in 0.74 t/h. Consequently, allowing flexibility between these two average values, the plant will be designed for a 1 t/h nominal flow rate of. The plant's architecture is quite simple. As the incoming biomass has a moisture content of around 10%, it does not require a dryer [20] and can directly enter the pyrolysis reactor. Below is the schematic of the plant considered at maximum capacity.

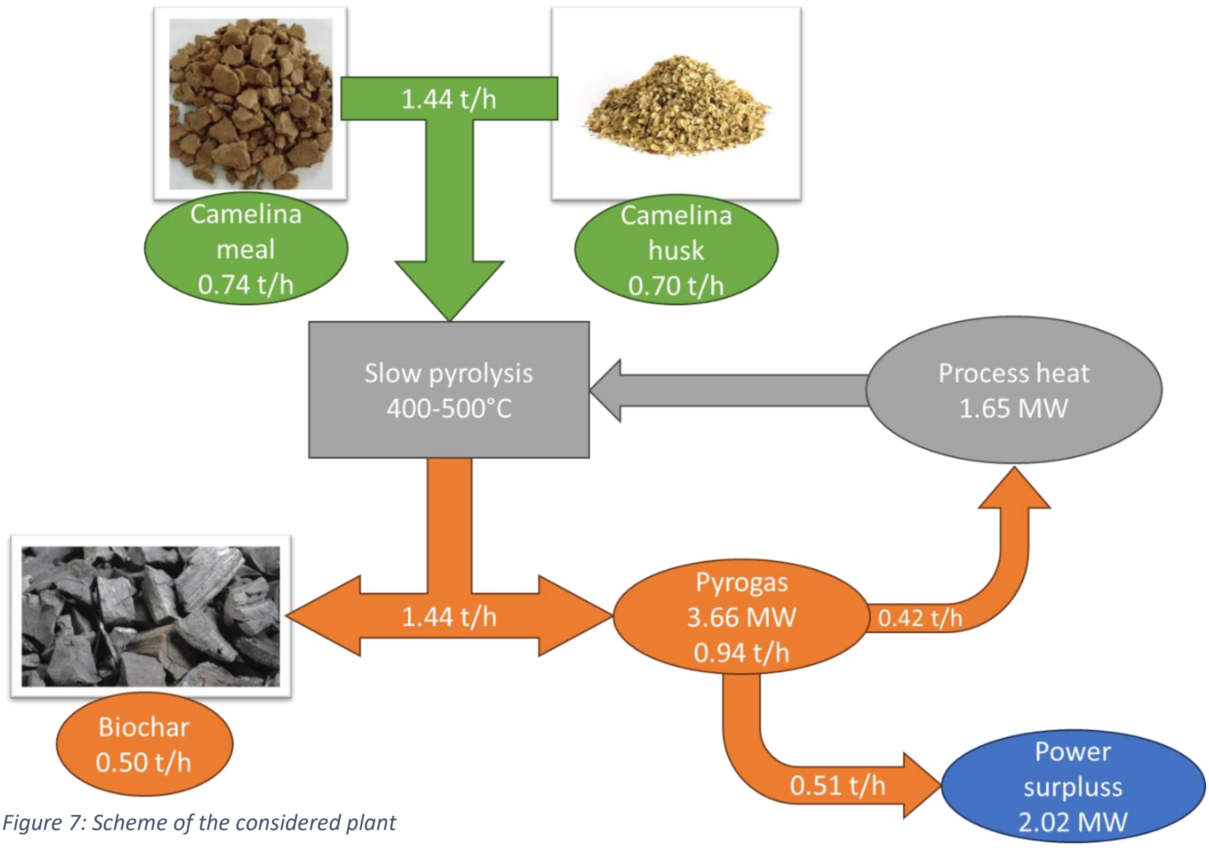


Figure 7: Scheme of the considered plant

The products of slow pyrolysis are divided into two: biochar used as an additive in the soil, and pyrogas, which will partly be recirculated to feed the pyrolysis and partly generate a usable surplus.

To understand the energy balances, an example is taken from a biochar production plant for use in a steel mill studied by the European project MUSIC [25].

This project considers a rotary kiln pyrolizer suitable for this purpose but with a 5 t/h biomass reactor capacity. So, in order to assess our case, the energy balance has been scaled by a factor of five. Below the table 8 with the project values and the updated ones is reported.

Table 8: Scale of the pyrolysis plant

Scaling plant from MUSIC		
Energy input	5 t/h	1 t/h
Required Process heat [MW]	5.88	1.18
Output – Char [MW]	10.81	2.16
Output - Pyrogas [MW]	13.08	2.62

So, to process 1 ton per hour of biomass, the reactor needs 1.18 MW of process heat. As previously introduced, this heat comes from the recirculation of pyrogas produced. Taking off this power from the power of the pyrogas, it remains 1.44 MW of surplus. Biochar yield from the slow pyrolysis is assumed as before, 35% and 65% for the pyrogas. Understood the proportions, now let us see how the plant behaves in the considered case. The table 9 below summarises the mass flow rate of the plant in both cases.

Table 9: Mass flow rate of the case study

Biomass inlet [t/h]	1.44	0.74
Biochar outlet [t/h]	0.50	0.26
Pyrogas produce [t/h]	0.93	0.48
Flue gasses recirculated [t/h]	0.42	0.22
Flue gasses to ORC [t/h]	0.51	0.26

By varying the incoming flow rate between 1.44 t/h and 0.74 t/h, a primary product quantity of biochar ranging from 0.50 t/h to 0.26 t/h is obtained.

Along with this, a pyrogas flow ranging from 0.93 to 0.48 t/h is obtained. This is used to generate energy through a combustor, primarily feeding the pyrolysis reactor. The high-temperature exhaust gases are separated; 44% is used to fuel the reaction, while the remaining flow is utilized to power an Organic Rankine Cycle (ORC). This cycle is coupled through a heat exchanger with an 80% efficiency, ensuring a thermal power input to the ORC, as reported in the table for both cases. The resulting electrical power is obtained assuming an average efficiency of 13% for the ORC [37].

Table 10: Energy balance of the plant studied

Process heat [MW]	1.65	0.82
Pyrogas power [MW]	3.66	1.83
Power surplus [MW]	2.02	1.01
Thermal power [MW]	1.62	0.81
ORC electrical power [MW]	0.21	0.11
Energy produced in 1 year [MWh]	1596	836

Therefore, in addition to fuelling the pyrolysis reaction, the pyrogas coupled with the ORC can generate between 110 and 210 kW_{el}, which can be used to cover the auxiliary plant's consumption.

Carbon markets

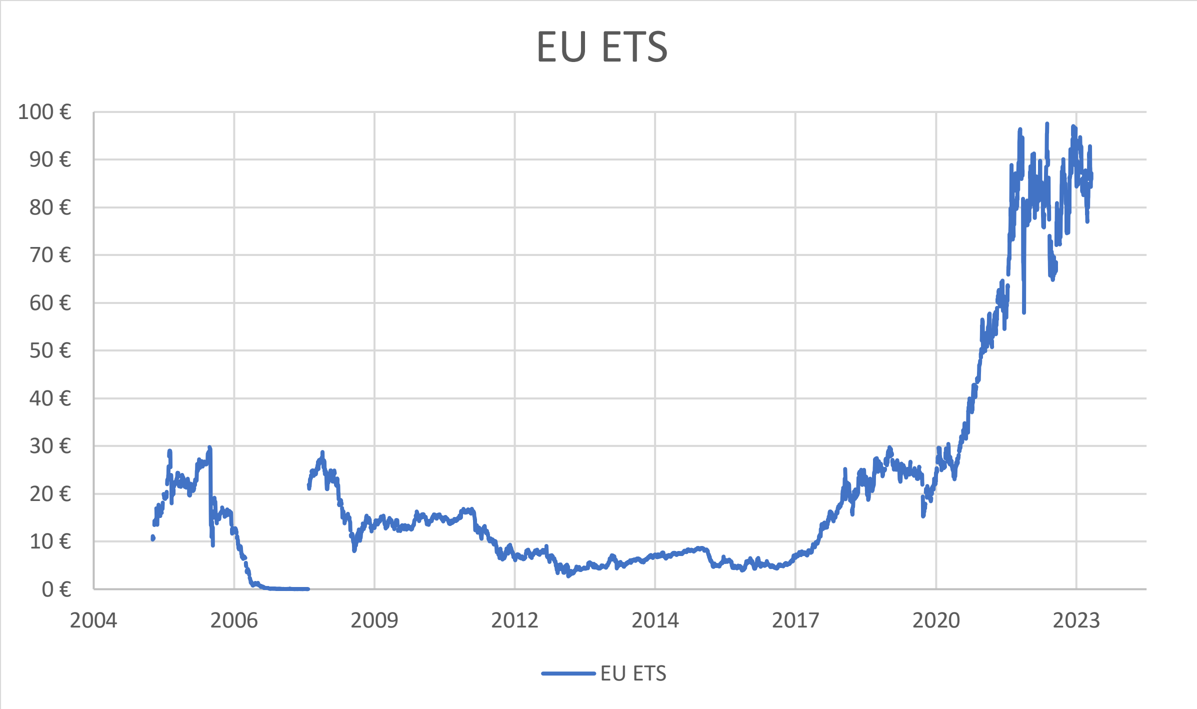
Carbon markets play a pivotal role in the global effort to combat climate change. These markets serve as a mechanism for regulating and trading carbon credits, effectively placing a price on pollution.

Each credit in the market represents one ton of carbon dioxide equivalents (CO_2e) that is sequestered or has not been emitted. CO_2e is used in order to assess the GHG emission potential also of other gasses, like methane and nitrogen dioxide.

In carbon markets several instruments operate, developed by countries already observed as EU ETS and CORSIA. As noticed, there are several types of carbon markets and under-markets. The main distinction to be made is between the voluntary carbon market and the compliance carbon market.

The first one, as the name suggests, is based on the voluntary decision of a company or entity to offset some of its emissions in order to reduce its carbon footprint and meet its climate goals or green claims. This kind of market was born in 1990 but had its boom recently in 2017 after the Paris agreement that recognizes this scheme of carbon crediting as suitable to obtain the emission reduction goals [38]. Under this market category goes the CORSIA scheme, still in its voluntary phase. When it will be fully compulsory, the offsetting requirements would be bought into the global voluntary carbon market. Currently, for the phase between 2024 and 2026, the only Standards acknowledged are the American Carbon Registry (ACR) and Architecture for REDD+ transaction (ART) [13].

The second one, instead, is well represented by the European Emission Trading System (EU ETS) [2]. This is a compliance market where the company must purchase allowances from a closed market well-regulated to cover its emissions. In order to incentivize an emission reduction by the companies, the price of these allowances must be very high. These exchanges happen with strict rules and methodologies guaranteed by countries and international entities and with full transparency on the transactions. The value of a single allowance for the EU ETS is identified as European Allowances (EUAs) and changed as a stock market index. Its value in this last period fluctuates around 75€, and its historic behaviour is reported in the figure below:



Graph 2: EU ETS allowances price trend

In the other case, with the voluntary carbon market, the price differs due to some other parameters. The main distinction is that the type of project that generates the credit, preservation and afforestation does not have so much cost; on the other hand, a direct air capture technology is very expensive, leading to a change in the price of the carbon credit. Other characteristics which must be considered are the Vintage, quality and reputation of the organization that certifies the project, the volume of credit generated, the region or country where it is created and the compliance with the Sustainable Development Goals of the United Nations [39].

Another important characterization is between avoidance or removal of credit.

The first one is the most common and cheap credit; it is based on the principle of avoiding a present emission like burning coal to obtain electricity, changing to a photovoltaic module. Here I do not remove CO2 from the atmosphere, but I prevent more production of it [39] [40] [40].

Removal credit instead, truly takes CO2 from the atmosphere and stores it in different ways. One of these credit types is biochar, where the CO2 used to grow the biomass is converted into solid organic carbon and stored into the soil, generating an effective removal of CO2 from the atmosphere.

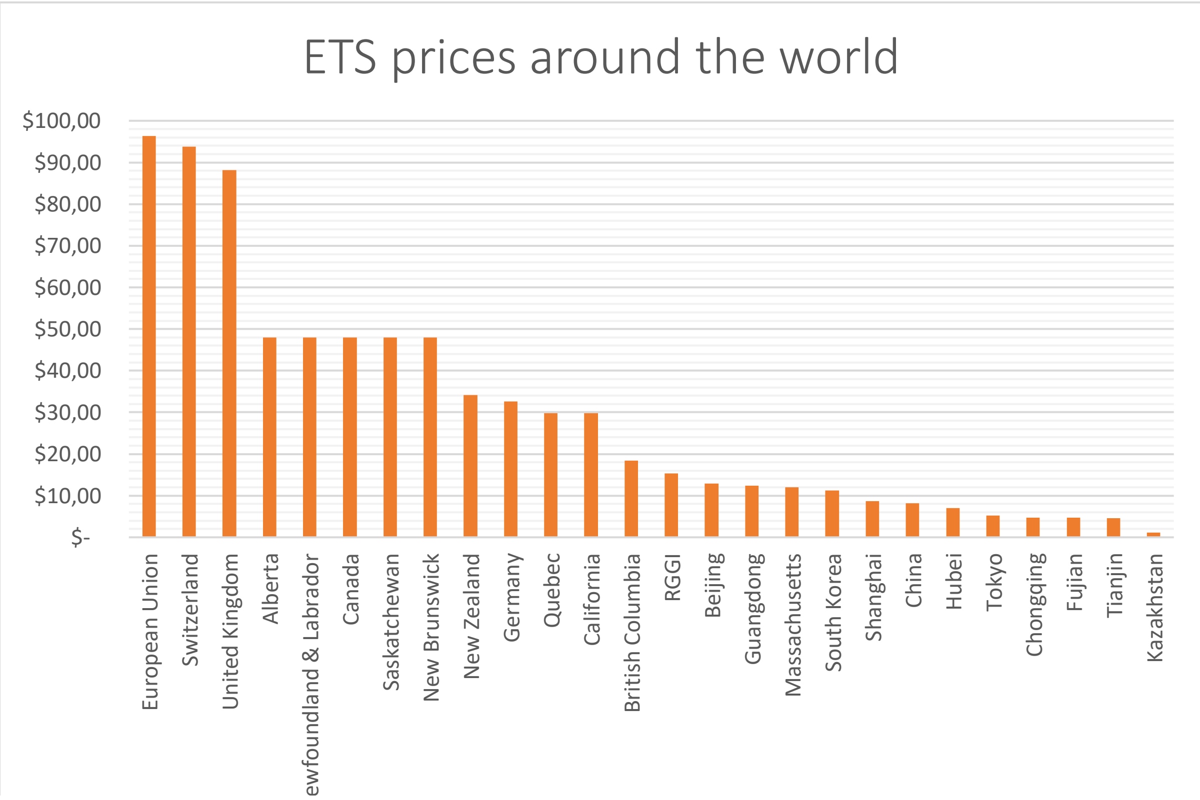
Clearly, the latter option provides greater efficacy, even if at a higher cost.

In the voluntary carbon market, the credits are accounted for every project and certified by the standards made usually by private organizations [41] [42]. The four main carbon standards are:

- Verified Carbon Standard (VCS) that contributes on 68.5% of the total volume of credits.
- Gold Standard (GS) with 20.1%
- Climate Action Reserve (CAR) with 8.3%
- American Carbon Registry (ACR) with 3.1%

Talking about the general volume of voluntary carbon credit issued since 2002, the two main diffused activities are Nature Based Solution (34.66%) and Renewable Energy use (35.8%) [43]. The second is all made by avoidance credits; the first one instead has a 21% removal credit mainly lead by project of reforestation. Looking into this present year, there is a diffusion of the Energy efficiency program (19,84%) guided by household cookstove efficiency enhancing [43].

Of course, the two previous mechanisms (CORSIA and EU ETS) are not the only ones existing in the world. The European Union Emission Trading System is just one of the



Graph 3: Comparison of different ETS scheme price in the world [67]

25 schemes, of which it is the most dated and pricey. In graph 3 are reported the ETS with their prices in 2023 [44].

Nevertheless, of all these systems, just 8 include domestic aviation sector: three Chinese provinces, European Union, United Kingdom, Switzerland, South Korea and New Zealand.

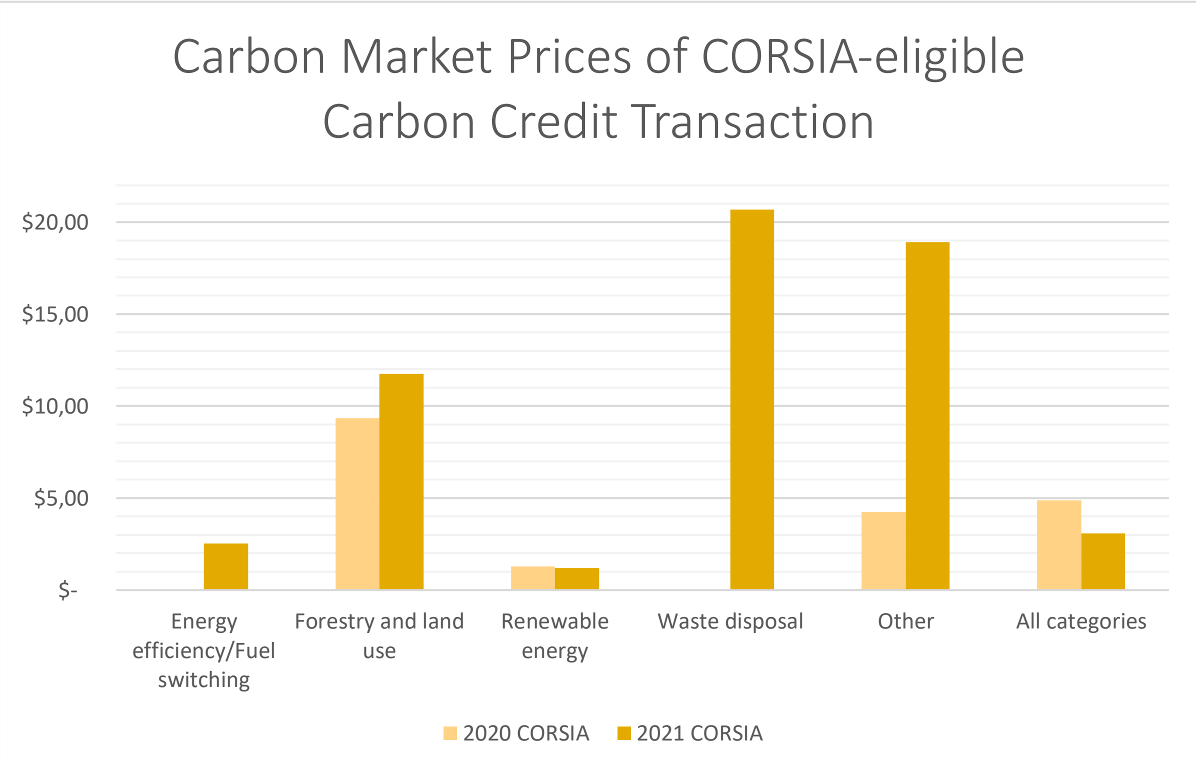
On the other hand, also voluntary carbon markets have developed and spread in recent years. As reported by CSIS [45], the London Stock Exchange recently announced the creation of a new market designation for funds that operate in the global voluntary carbon markets. This solution was adopted with the main goal of supplying quality worldwide and increasing the financial source for projects that reduce the carbon in the atmosphere. It is an interesting approach since VCM lacks transparency, standards unification, and more government assurance [45].

Another fascinating solution could be the hybridization of the two systems: Japan developed the Japan GX League, which is a voluntary emission reduction and trading system with voluntary participation from companies [45]. So, with this system, the corporations freely choose to participate in the GX League, but then compliance with the rules and emissions reduction targets is mandatory to remain in the league. Moreover, participants must declare their emissions reduction targets and roadmap to obtain them; if they do not succeed, they are required to explain why they failed. Since this system is voluntary, the success is based on the companies' involvement. Considering the past May, the system covers 40% of Japan's national emissions, which is the same share that EU ETS covers for European emissions [45].

Talking now about our area of interest, there are some specific markets to consider. As previously said, EU ETS is a closed market with the value of the allowances clearly defined that in this period fluctuates around 70 – 80 € per tonnes of CO_2 equivalent. From 2026, this would be the value that European airline operator would have to pay for purchasing all the allowances they will need.

Concerning the VCM, instead, to define a single clear value is impossible. As previously said, there are too many parameters that have to be considered. Given the area of interest of this study, biochar amendment into the soil undergoes the classification of Carbon sequestration in agriculture (CSA). Looking into the data given by Climate Focus [43], only 17 projects are registered under this nomenclature over 4794 total projects, with 11.3 million credits issued over 1.639.3 million (from 2002 to date). Digging more into these data and considering the Nature Based Solutions (NBS) to which it belongs, CSA represents almost 2% of the total credit issued from 2002; nevertheless, it reached a peak in 2022, where it delivered more than 6 million of credits (half of its total value) with a share of 6.49% between NBS [43].

Considering the price of the carbon credit made by biochar amendment into the soil as an agricultural practice, there is very few data available, and it changes a lot depending on the general assumptions. Ecosystem Marketplace produced a dashboard of the global carbon market data with the price of the credits according to some classifications, such as project type, standard, and region and with a special evaluation for the CORSIA carbon credit transaction [46] [46]. Unfortunately, with all these classifications it is not clear which is more suitable for a credit generated by carbon sequestration in agriculture. Looking directly into CORSIA values, they are reported for the years 2020 and 2021 and divided by sector as reported in the graph 4.



Graph 4: CORSIA emission units price trend [46]

Biochar amendment into soil could be considered both a practice related to land use but also, if produced with residue, could come from emission reduction of waste disposal.

In addition, here in the weighted values are reported both avoidance and removal credits, but it is understood that removal credit (like biochar) is more valuable, but avoidance one drives the market in terms of volume (values reported in figure 8).

	2020		2021 (through August)	
	Volume ($MtCO_2e$)	Price (USD)	Volume ($MtCO_2e$)	Price (USD)
Removals	9.0	$7.93	5.6	$7.98
Reductions	84.4	$1.60	52.9	$1.71

Source: *Ecosystem Marketplace, a Forest Trends Initiative.*

Note: Volumes are calculated from EM Respondents that reported trade data as of 31 August 2021. Respondents did not always respond to all survey questions; differences in the totals (for example, between the total annual volume and the sum of project category volumes) can be attributed to this. Throughout the remainder of 2021 and beyond as more organizations report to EM for the first time, and as existing EM Respondents report new transactions, these figures for 2020 and 2021 will likely continue to be updated. This will be reflected in future installments of EM's SOVCM report and on the EM Data Intelligence & Analytics Dashboard (https://data.ecosystemmarketplace.com).

Figure 8: Carbon credit price according to [46]

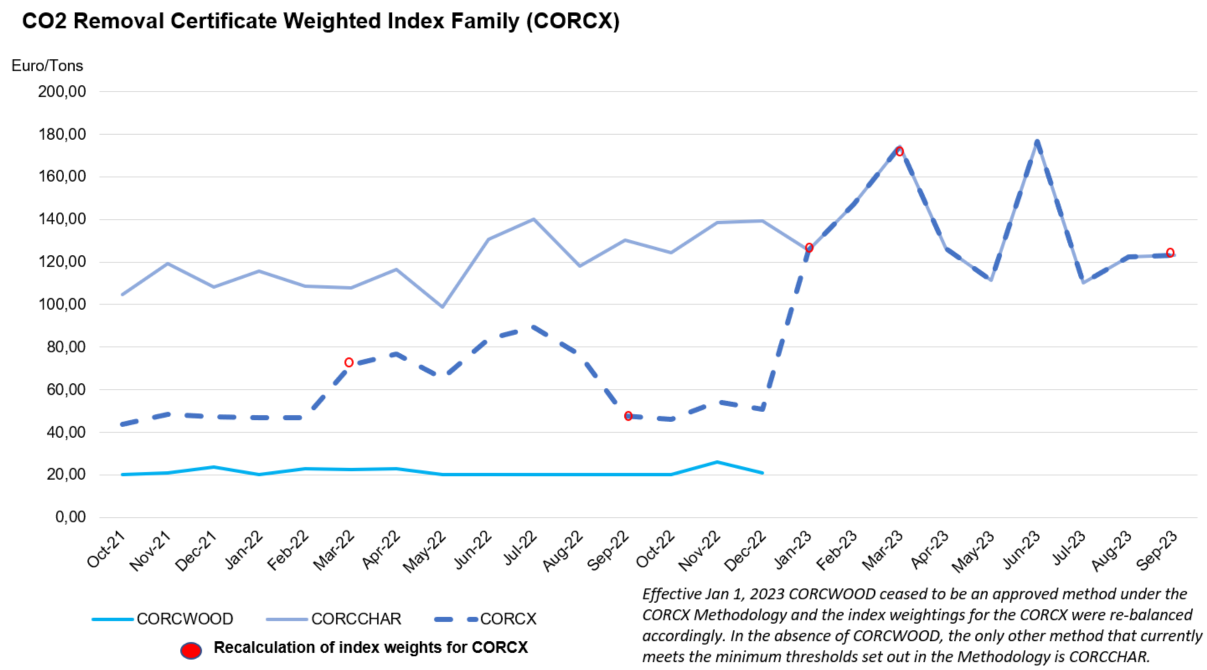
However, as previously said, biochar credit generated by carbon sequestration are scarce, so these values do not represent their real value. Nevertheless, a comparison between the general VCM and the CORSIA under-market could be interesting. As reported below by Ecosystem Marketplace [46], the average price of the credit eligible for CORSIA is always higher than the general Voluntary carbon market considering each project category. On average, CORSIA credit has an increase of price of 76% in 2020 and 161% in 2021. Due to a more regulated market and restriction, this must be considered when discussing the price of carbon credit in the CORSIA scheme.

Table 11: Price of carbon credits according to its project category [46]

Project Category	2020	2020 CORSIA	increase 2020	2021	2021 CORSIA	increase 2021
Energy efficiency/Fuel switching	$ 1,03	-	-	$ 1,57	$ 2,52	61%
Forestry and land use	$ 5,60	$ 9,35	67%	$ 4,73	$ 11,76	149%
Renewable energy	$ 0,87	$ 1,28	47%	$ 1,10	$ 1,19	8%
Waste disposal	$ 2,76	-	-	$ 3,93	$ 20,67	426%

Other	$ 2,00	$ 4,25	113%	-	$ 18,92	-
All categories	-	$ 4,89	-	-	$ 3,08	-
Average increase			76%			161%

Reevaluating the specific carbon credit generated by soil amendment with biochar, an important role is played by puro.earth [47]. This is the leading platform for carbon removal technology that developed the methodology used to assess carbon sequestration into soil, that will be explained later. Together with Nasdaq, they generate three commodity price indexes based on puro's certificate [47]. This consists of an index that tracks the price of all carbon removal transactions as well as a separate index for biochar and bio-based construction materials. The behaviour of these indexes in the past two years is reported in the graph 5 below.



Graph 5: Price trend of CORCX [47]

So, as chosen by Blue Forest for their market analysis [48], a suitable range for carbon credit generated by biochar soil amendment can be between 95-125 $ per ton equivalent of CO_2.

To summarise all this market analysis, here are the values considered for the economic assessment of the possible scenarios considered.

Table 12: summary of the prices

Carbon market	Current price [€ / tCO_2e]	Forecast price 2030 [€ / tCO_2e]
EU ETS (EUAs Allowances)	70 - 80	130 - 150 [49]
CORCchar	100 - 120	150
CORSIA eligible carbon credit	3.08	Probably lower

These prices are subject to numerous variations due to external factors; energy markets, in particular, have a strong influence on them.

This makes it very difficult to predict its evolution and evaluate a precise quantification.

Carbon credit generation with biochar

Since it is a viable solution to mitigate the climate change, biochar is recognized as a technology usable for carbon credit generation. The methodology developed by [puro. earth] [50] set a standard for quantify the Carbon dioxide sequestration made by biochar application into the soil. This pathway can produce stand-alone carbon credit that can be sold on the different carbon markets around the world.

A peculiarity of biochar is its different composition and properties. On the one hand, this allows different possible feedstock to be converted into biochar, but on the other hand in terms of CO2 removal, it precludes a general easy rule to compute the evaluation in every case. As pointed out by Woolf [29] there is a clear need for GHG accounting protocols that quantify the mitigation impact of CO2 removal practices since the LCA usually relate only to specific conditions or locations and are not generalizable.

To assess the quantity of carbon that biochar leaves into the soil, puro.earth set a cradle-to-grave system boundary approach, following the principle of Life Cycle Assessment (LCA) defined in ISO 14040 [50]. The system must consider all the emissions for each step of biochar formation. The 5 steps identified are:

- Biomass: these are the emissions that came from the cultivation and harvesting of biomass. Considering the use of waste biomass, one can consider this value zero; this is a conservative assumption, since it does not take into account the emissions coming from the decomposition or combustion of this biomass, that could lead to CO2, or much worst CH4 emissions. In these emissions should also be considered direct land use changes that represent emissions related to the site of cultivation. In many cases, this is considered null but needs to be justified sufficiently.
- Transport: it is important also to consider logistics; the production facility cannot be too far from the site where the biomass is collected since this would generate transport emissions.
- Production: this phase takes into account the conversion from raw biomass into biochar following all the technical steps. Besides pyrolysis reactor, emissions come from the drying stage, the chipping and the post-processing operations.
- Transport: again, once the biochar is finalised, it is distributed to the point of final usage.

- Use: this phase includes its application that can be into the soil, so maybe a tractor is needed, or it could also be used as biomass fuels and therefore emissions must be considered.

To compute the Carbon dioxide Removal Certificates (CORCs) according to puro.earth the IPCC methodology [50] is used, which is reported in Annex 4 and used also by Woolf [29]. As previously said, with its adaptations, this equation, evaluates the variation of mineral soil organic carbon stocks from biochar amendments. So, after obtaining the increased value of carbon into the soil, one must connect this value with the CO_2 from the atmosphere converted into solid carbon. Found the value of E_{stored}, then the emissions coming from the biomass production ($E_{biomass}$), the biochar production ($E_{production}$) and biochar use (E_{use}) must be evaluated.

Eq. 9

$$CORCs = E_{stored} - E_{biomass} - E_{production} - E_{use}$$

Where E_{stored} is evaluated as follows:

Eq. 10

$$E_{stored} = Q_{biochar} \cdot C_{org} \cdot F_p^{TH,T_s} \cdot \frac{44}{12}$$

Where:

- $Q_{biochar}$ = biochar quantity applied into the soil express in dry metric tonnes
- C_{org} = this is the organic carbon content of the biochar produced expressed in dry weight of organic carbon over dry weight of biochar. C_{org} varies a lot for different classes of biochar and can be evaluated with a laboratory analysis. However, if considered dry ash-free basis, this value can be estimated with an exponential regression function of pyrolysis temperature. The ash content is assumed to be conserved during pyrolysis so there is no need to evaluate its content. Then, going through the dry ash-free biochar yield as a function of temperature and feedstock lignin content, the final carbon fraction is obtained. Every passage is reported with equation and coefficient by Woolf [29].
- F_p^{TH,T_s} = is the permanence factor also known as carbon stability, evaluated in a time horizon *TH* in a given soil temperature T_s. With these parameters, the permanence factor is a function only of the molar H/C_{org} ratio: $F_p^{TH,T_s} = c + m \cdot {}^{H}/_{C_{org}}$
- $\frac{44}{12}$ = is the conversion factor from carbon to CO_2.

Among the GHG emissions impacts of biochar application into soil, there is also the modification of N_2O emissions. Converting biomass into biochar avoids emissions from the decomposition, as previously said and applying into soil enhances crop productivity, reducing fertilizer requirements and leading to a reduction also in GHGs from fertilizer production and transportation (50% reduction, according to Roberts [22]). According to Woolf [29], it can be evaluated an overall GHG inventory method considering also nitrogen dioxide emission reduction:

Eq. 11

$$GHG_{biochar} = Q_{biochar} \cdot C_{org} \cdot F_p^{TH,T_s} \cdot \frac{44}{12} + 0.23 \cdot n \cdot GWP_{N_2O}$$

Where, in addition to the previous discussed terms, there are:

- *n* = baseline annual nitrous oxide emissions
- GWP_{N_2O} = is its global warming potential, currently 273 times the CO_2

Once computed these calculations, in order to implement biochar as a carbon credit scheme, it is mandatory to evaluate all the LCA of the biochar. Hence, as previously reported in equation () it is needed to compute the values of biomass collection and biochar production ($E_{biomass}$ and $E_{production}$).

As said earlier, biochar can differentiate a lot from the different types of feedstocks used. In the review performed by Matustik [26] there are 27 articles selected to assess the LCA of biochar that differ in feedstock, pyrolysis unit, properties, functional unit, effect on soil LCA software and impact categories analysed. As a result, it is very difficult to identify a single value of emissions for each ton of biochar produced.

Overall, this review points out some interesting considerations; all the feedstock analysed shows valuable GHG positive impact; nevertheless, waste biomass is more suitable since the production process is not attributed to the biochar boundaries. In addition, as the feedstock will be producedin any case, converting it into biochar avoids waste management costs and emissions, giving them a second life. Another interesting characteristic could be the choice between centralized pyrolysis units, more efficient but with a higher cost of transport, or decentralized ones with worse efficiency but better logistics. This depends, of course, on the location chosen also in relation with the amount of biochar and consequently biochar used.

An insightful perspective is offered by Roberts [22], that evaluates the LCA of biochar produced by five different feedstocks: corn stover, yard waste, and switchgrass feedstock. This combination presents an interesting comparison between "waste biomass" and bioenergy crops. As this study demonstrates, if one considers an energy crop like switch grass, one needs to pay attention on the effect that Land-use change produces on the life-cycle impact. The scenario proposed (switchgrass B), considers these energy crops grown mainly on existing cropland, generating an emission related to land-use change of about 939 kgCO_2e/dry tonne.

Nevertheless, the other scenario highlights a significant possible appreciation of biochar as GHG emissions reduction tool. All the other four scenarios deliver a net GHG emission reduction and a possible economic worth when considering the carbon credit generated with the soil amendment. In this study (2010) [22], the value per tonne of CO_2e is evaluated for two possible scenarios: a low value of 20 $/t and a high value of 80 $/t.

CORSIA solutions: parametric analysis between fossil fuel and SAF

The goal of this study is to assess the various possibilities that the aviation sector can undertake to cut down its GHG emission. For this aim, it is necessary to evaluate the economic feasibility of the different potential options from the point of view of the airline. All the data and numeric evaluation are made in MATLAB or Microsoft Excel environment.

The starting point of this evaluation is the current scenario where the aviation industry still uses a carbon fossil fuel (identified with the name Jet-A1 fuel) with its current price related to the oil one. The first point to assess is whether the Sustainable Aviation Fuel is a viable alternative in terms of price and costs. As previously said, the only SAF path available at a commercial scale is the HEFA route. While it is easy to determine the price of the jet-fuel, due to the various possible feedstock and processes, the price of a ton of SAF varies a lot. To find the best approximation, here are reported the prices identified by five different agencies and media.

Table 13: Price of SAF according to different source

Source	SAF price [€/ton]
IATA (Sept. 23) [51]	2193
IRENA (Sept. 20) [31]	1913
Reuters (Nov. 23) [52]	1988
Argus Media (Nov. 22) [53]	2700
S&P (Nov. 23) [54]	1713

Despite a discrepancy, the mean value is around 2100 €/ton, whereas, regarding the Jet-A1 price, 1000 €/ton is chosen, being less than half of the SAF price.

Nevertheless, it should be considered that these prices could vary in the future, probably with an increase in the oil price due to lack of resources, and, on the other hand, with a reduction of SAF price due to enhancement of technology and feedstock collection.

In parallel, there is the cost related to the emission generated by the fuel. This varies depending on the different directives considered. Looking at the ICAO environment, as reported previously, the offsetting requirements are estimate with equations 5 and 6. Thinking through this case, the evaluation is made by comparing the Jet-A1 with simple SAF, so after considering the different prices, it is added the Emission Units purchased costs.

As reported by CORSIA, in the fossil fuel case, there is no available possibility to claim an emission reduction, so its offsetting requirement is computed with equation 4.

On the other hand, with a SAF, it is possible to claim a remission reduction due to its lower Life cycle emission value (LS) [55]. ISCC reports these values for every conversion process [56].

As said before, here is just considered the HEFA solution as eligible fuels and the LS values are reported in the table below.

Table 14: Life cycle value for different fuel feedstock

Fuel Conversion Process	Fuel Feedstock	LS [gCO_2e/MJ]
Hydroprocessed esters and fatty acids (HEFA)	Tallow	22.5
	Used cooking oil	13.9
	Palm fatty acid distillate	20.7
	Corn oil	17.2
	Soybean oil	40.4
	Rapeseed oil	47.4

So, the emission reduction is computed according to equation 6, and it gives the final offsetting requirement an airplane operator needs to purchase for each tonne of fuel consumed.

Two evaluations are carried out: one varying the price of SAF (fixing LS value as rapeseed oil) and the second varying the LS values according to the different primary feedstock.

The first one is made to assess the possibility of future technology development in which the SAF cost production will be lower, and instead the fossil fuel will be more expensive due to resource scarcity.

Since these two evaluations are made in relation to emission units' prices, the expected results should identify the minimum price needed in order to make the sustainable solution feasible.

The analysis is performed in MATLAB environment.

Different life cycle emissions

The analysis starts with considering fossil fuel as a baseline scenario. In this case, according to CORSIA methodology, the offsetting requirement will be maximum as shown in equation 3. When one starts considering the use of a SAF, the airline could claim a reduction of the offsetting requirements due to its lower life cycle emissions. So, this emissions reduction is converted in terms of euros per tonne of SAF used.

Table 15: input parameter for the analysis

	Jet-A1 fossil	SAF
Price [€/ton]	1000	2100
Emission reduction	-	$3.16 \cdot \left(1 - \frac{LS}{89}\right)$

For each LS value, the emission reduction obtained is reported below (table 16).

Table 16: Emission reduction for each LS value

LS value [gCO_2e/MJ]	22.5	13.9	20.7	17.2	40.4	47.4
Emission reduction [$kgCO_2/kgFuel$]	2.36	2.67	2.43	2.55	1.73	1.48

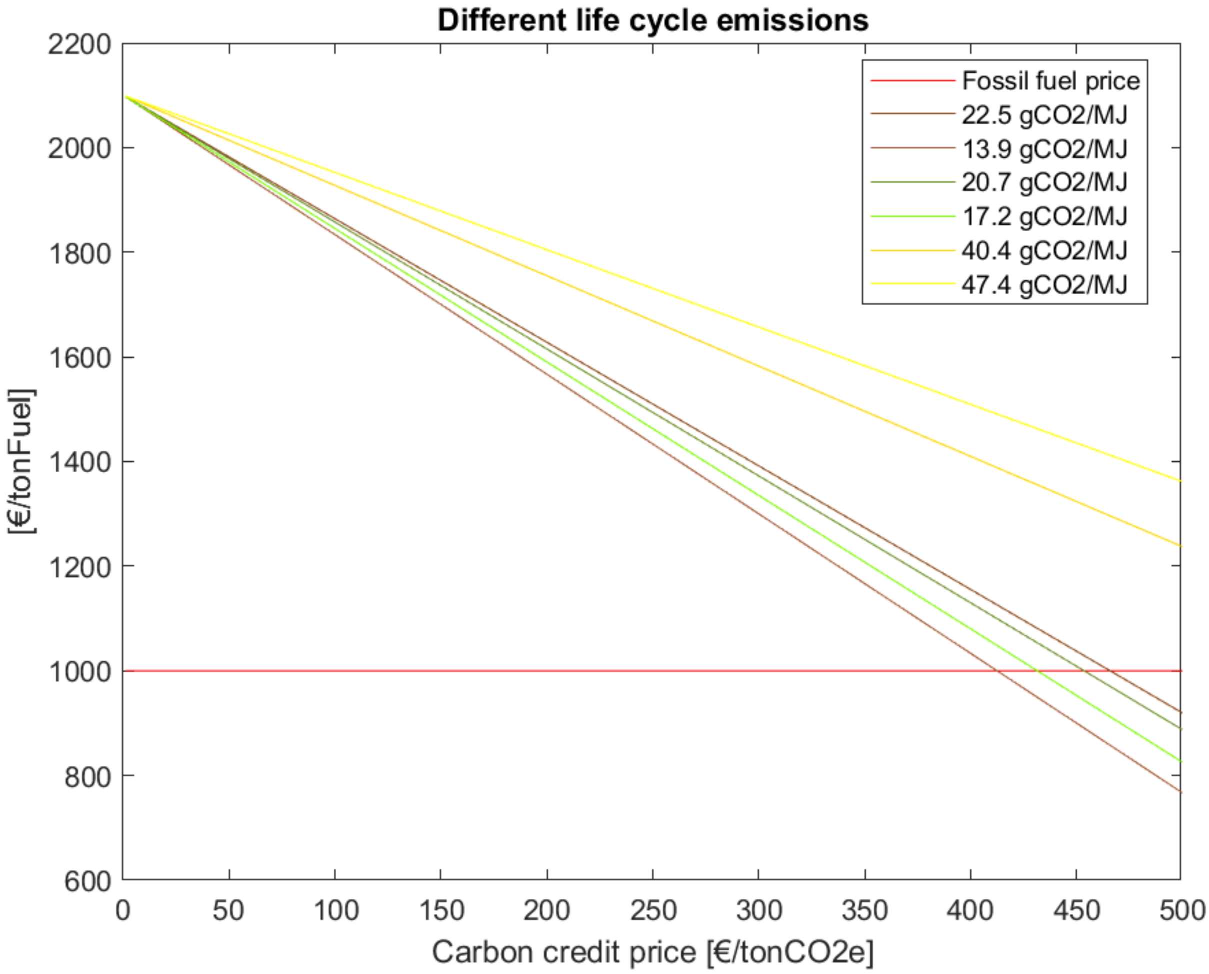
These values show how little it is worth the offsetting requirement account according to CORSIA. Assuming a price for emission-unit of 100 €/tonCO2 (toward the highest part of the expected variation range), the use of SAF will produce a reduction of 200-300 € for each tonne of fuel used. Since the price of SAF is 1100 € higher than fossil, it comes as no surprise that the sustainable solution is not yet profitable according to CORSIA.

To complete the analysis, it is evaluated the minimum carbon credit price for each LS value that match the fossil fuel price.

Table 17: Minimum carbon credit price for each LS value

LS value [gCO_2e/MJ]	22.5	13.9	20.7	17.2	40.4	47.4
Minimum carbon credit price [€/tonCO2]	466	413	454	431	637	745

Below the comparison of different SAFs depending on the carbon credit price is reported.



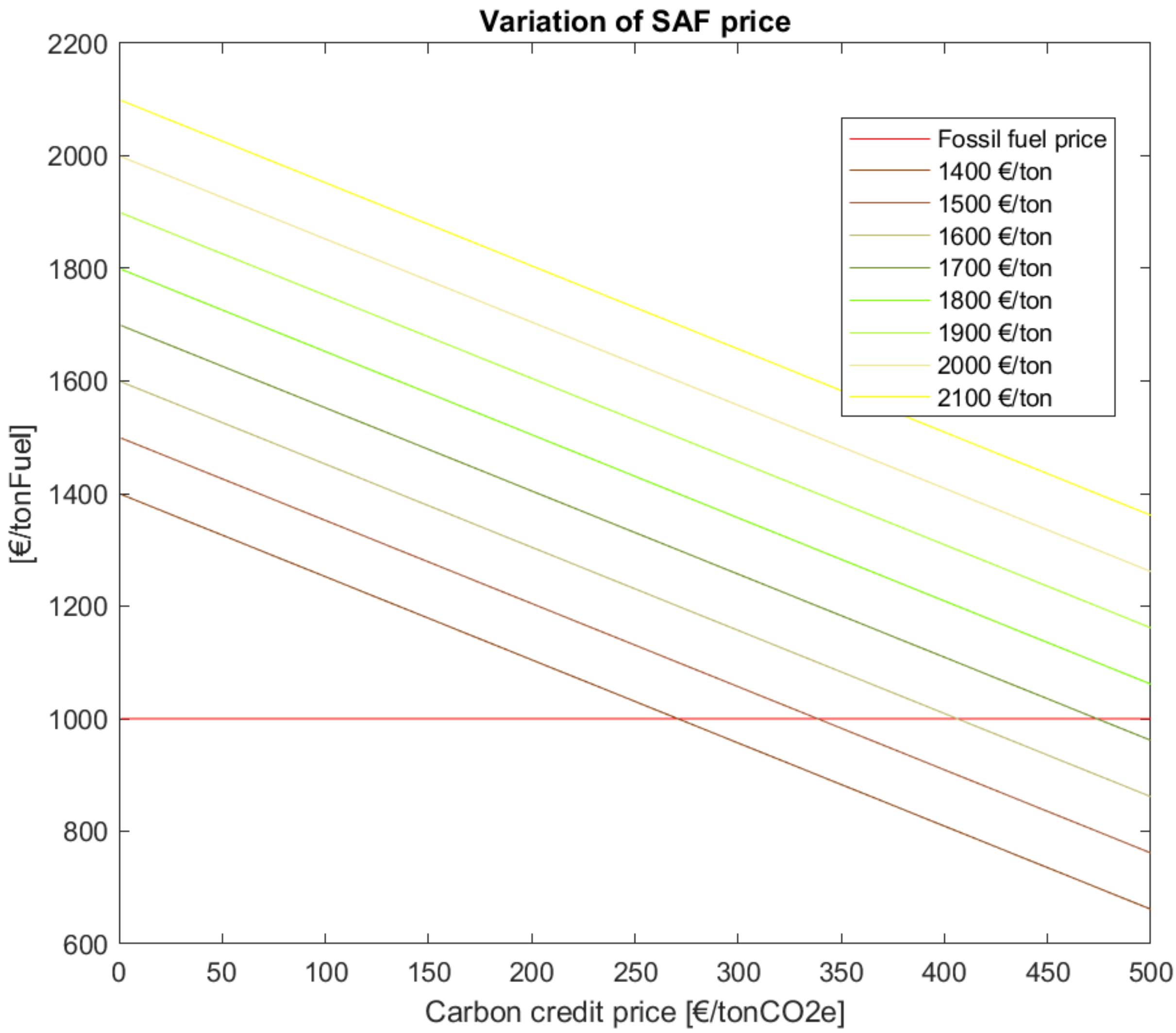
Graph 6: Price evaluation comparison between Fossil fuel and different SAF

The graph clearly shows how the gap between the solutions is still high, and the offsetting mechanism developed by ICAO still does not encourage a shift to a sustainable fuel.

Variation of SAF price

To better understand this system, another evaluation is performed changing the SAF price. In fact, as previously said, in the following years, the SAF price should see a reduction due to technology improvements and a better collection of feedstocks. Indeed, the main obstacle is the collection of feedstocks, especially for HEFA route that starts from other process waste (Used cooking oil, tallow, palm fatty acid). For this evaluation, the SAF considered is made by rapeseed oil through HEFA pathway (47.4 gCO_2e/MJ).

The results obtained are shown in the graph below.



Graph 7: Price evolution comparison changing the SAF price

Since the life cycle emission (LS) is fixed, the reduction obtained by increasing the carbon credit price is equal, as all the lines have the same slope. The only thing changing this time is the starting point that represents the SAF price.

So, it can be pointed out that a reduction in SAF price can enhance the competitiveness of the sustainable solution.

In this regard, the minimum carbon credit prices that match the two solutions are reported below.

Table 18: Minimum carbon credit price for different SAF price

SAF price [€/ton]	1400	1500	1600	1700	1800	1900	2000	2100
Minimum carbon credit price [€/tonCO2e]	271	339	406	474	542	609	677	745

This time, the values can fall significantly until 270 €/tonCO2, clarifying how future research and policies must focus on reducing SAF prices making it competitive.

Assessing biochar contribution towards decarbonization pathway

After considering the price difference and its possible impacts with CORSIA methodology, is due to assess the possible solutions aviation can undertake to follow the decarbonisation pathway decided by European Union. As stated before, ETS is the system that regulates the aviation sector by gradually limiting its emissions. Indeed, the total allowances allowed, starting from 2024, will be reduced of 4,3%, and from 2028 4,4% each year [2]. In this scenario, airlines must reduce their emission accordingly.

To evaluate the right solution, this study tries to assess the costs a generic airline would undergoes with different solution for this decarbonization pathway. First of all, it is essential to understand the airline traffic in this last period and, most important, how it will change until 2030. Aviation, due to Covid-19 pandemic, has been subject to a critical drop in terms of flights in the last four years. In 2023, the number of flights approaches pre-pandemic levels (91% of 2019), and this year should match it [57].

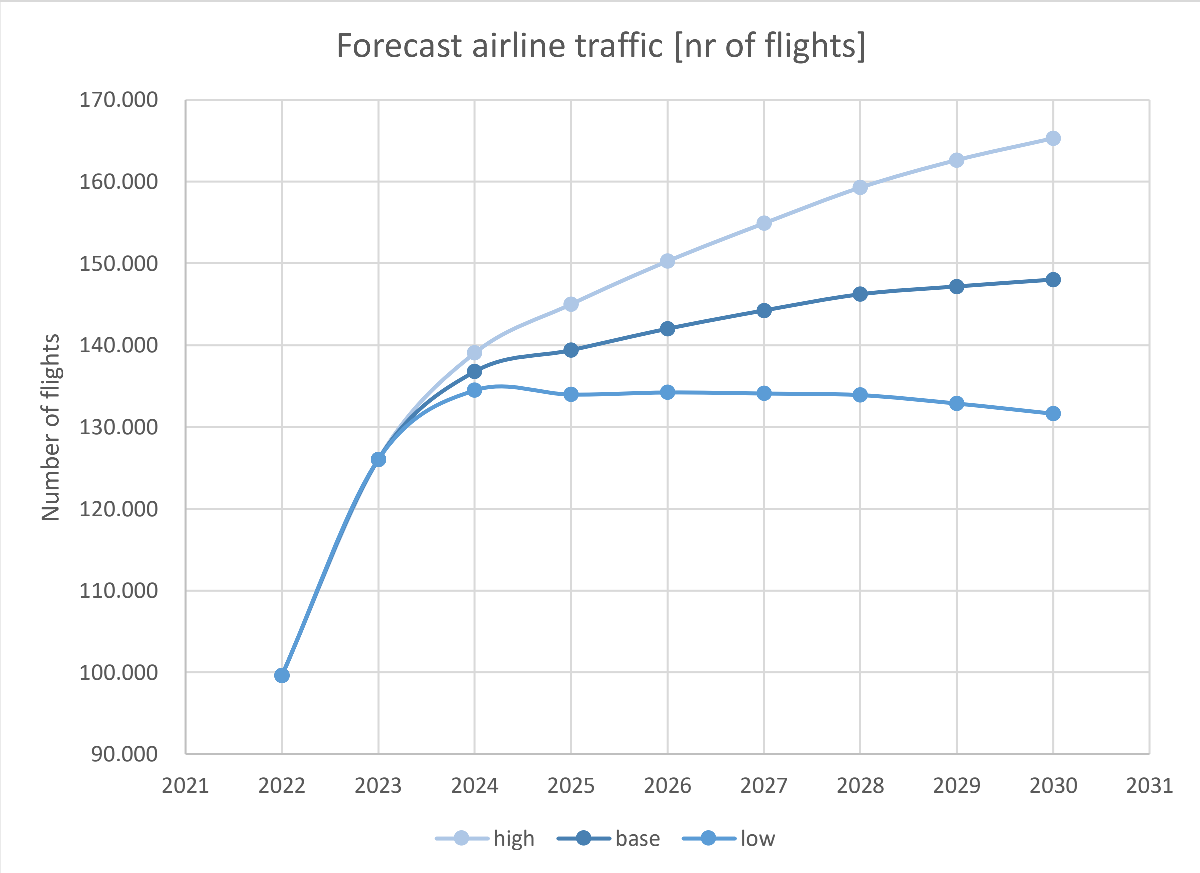
Volume analysis of an airline scenario until 2030

Starting from the number of flights in 2023 for a generic airline it is applied the forecast scenario made by Eurocontrol about the air traffic growth until 2030 [57]. This forecast on seven years, made for every European country, considers three possible scenarios (high, base, and low) and its values for Italy are reported in the table below.

IFR Movements (Thousands)		2024	2025	2026	2027	2028	2029	2030
Italy	High	2.193	2.287	2.370	2.443	2.512	2.565	2.656
	Base	2.142	2.183	2.224	2.259	2.290	2.305	2.351
	Low	2.090	2.082	2.086	2.084	2.081	2.065	2.068
IFR Movements (% Growth)		**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Italy	High	10.3%	4.3%	3.6%	3.1%	2.8%	2.1%	1.6%
	Base	8.5%	1.9%	1.9%	1.6%	1.4%	0.7%	0.6%
	Low	6.7%	-0.4%	0.2%	-0.1%	-0.1%	-0.8%	-0.9%

Table 19: Airline traffic forecast scenario in Italy [57]

These annual variations are applied to the number of flights an Italian airline will take to obtain its forecast evolution until 2030. Starting from the 2022 and 2023 number of flights, the cumulative forecast evolution until 2030 is shown in the graph below.



Graph 8: Airline traffic evolution until 2030

This graph clearly displays the recovery from Covid-19 pandemic until 2024, and then three possible steady trends the airline traffic can undergo.

After assuming the number of flights in the considered period, it is necessary to evaluate the fuel consumption. Looking through the annual accounts of the airline [58] considered, it is reported the number and total flight hours which lead to an average flight duration of 1.5 hours. Finally, the mean fuel consumption of a medium-range plane, like Boeing 737, is 4500 litres per hour [59], which with a fuel density of 0.8 kg/l, means 3.6 tons of fuel per hour. This should give the final consumption of fuel needed until 2030; however, it is necessary to consider one last thing. As it was considered the traffic growth throughout the period, one must also evaluate the possible improvements in the aviation industry. According to Eurocontrol [60], there are two major improvements to consider: one is due to fleet upgrades with more efficient technology, and the other is an improvement of ATM (Air Traffic Management), which accounts for a more efficient management of routes and ground operations. The cumulative upgrades according to Eurocontrol in 2030 are summarized in the table below.

Table 20: Technology and traffic management improvement [60]

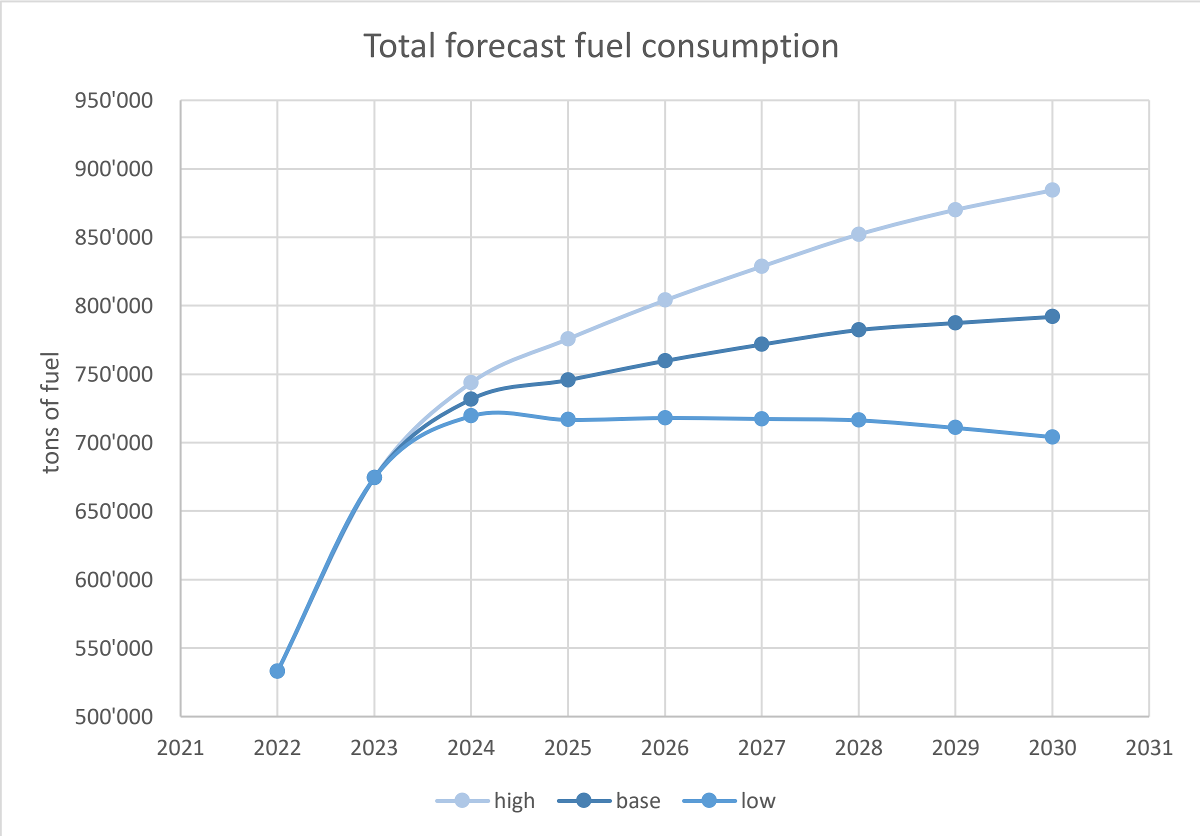
2030 scenario	high	base	low
ATM improvement [%]	12.4	10.4	8.3
Fleet upgrade [%]	3.0	2.1	1.2
Total improvement [%]	**15.4**	**12.5**	**9.5**

For the purpose of this study, it will be considered only the base scenario, divided for each year (2024-2030), which gives an annual improvement of 1.78 % [60]. This will lead to an annual reduction of airline fuel consumption.

Table 21: Final airline fuel consumption each year

	Final fuel consumption [ton of Fuel]		
	high	base	low
2022	532'969		
2023	674'274		
2024	743'804	731'659	719'363
2025	775'686	745'663	716'609
2026	803'837	759'668	717'986
2027	828'597	771'623	717'298
2028	852'000	782'212	716'265
2029	869'976	787'336	710'758
2030	884'232	791'835	704'099
Total	5'758'131	5'369'995	5'002'378

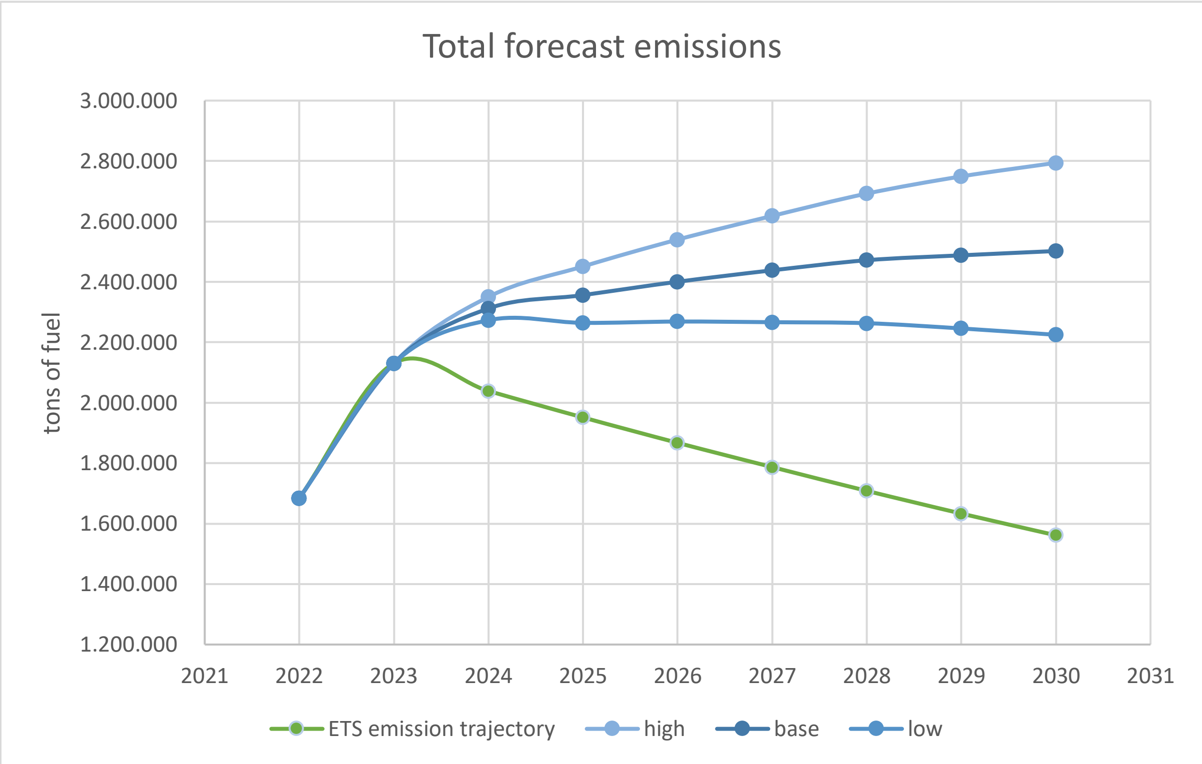
So, putting everything together, here are the airline fuel consumption until 2030.



Graph 9: Evolution of fuel consumption until 2030

The evolution obtained strictly follows the number of flights forecast and gives a total fuel requirement between 2024 and 2030 of 5.4 million for the base scenario.

Finally, to assess the greenhouse gas emissions, the fuel conversion factor is set by CORSIA as 3.16 tonne of CO_2 per tonne of Fuel [4] [61]. This gives the airline an impact on greenhouse gas emissions for the next seven years; however, European Union has defined a decarbonization pathway through ETS allowances reduction [2]. So, starting from 2023 values, the trajectory is determined according to ETS reduction to understand how much emissions the airline should avoid in this period. Below the projected airline emissions previously calculated and the ETS total allowances granted are reported.



Graph 10: total emission with ETS reduction trajectory

Besides the forecast airline emissions, it is interesting to notice the gap with the ETS established trajectory. This is due to the increase of airline traffic on one side and the reduction of emissions the European Union seeks to achieve. Below is performed a cumulative sum of the entire period with the gap of avoidance emissions the airline must cut. In addition, first it is calculated the emission reduction as emission to be avoided on total cumulative emissions forecast, and then, assuming a fuel 50% SAF and 50% fossil it is evaluated the emission value of the SAF in order to obtain the required reduction. Here is reported the used formula:

Eq. 12

$$\frac{E_{fossil} - \left(E_{fossil} + E_{SAF}/_{2}\right)}{E_{fossil}} = emission\ reduction\ [\%]$$

Where:

- E_{fossil} is the emission value for Jet-A1 fossil: 94 gCO_2/MJ.
- E_{SAF} is the emission value for the SAF one is looking for.
- $emission\ reduction = {emissions\ to\ be\ avoided}/_{total\ cumulative\ emissions}$

Below is reported the table with the results obtained.

Table 22: Cumulative results with the requested emission reduction

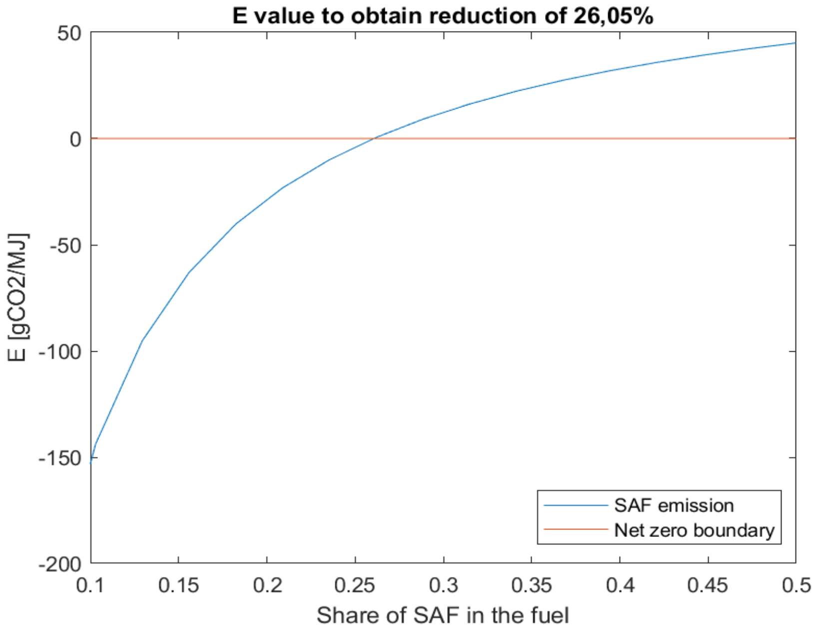
2024 - 2030 cumulative results			
high	base	low	
18'195'693	16'969'185	15'807'514	Total emissions forecast [tonCO_2]
12'548'614	12'548'614	12'548'614	Theoretical emission according to ETS reduction [tonCO_2]
5'647'079	4'420'571	3'258'899	Total emission to be avoided [tonCO_2]
31,0%	**26,05%**	**20,6%**	Emission reduction [%]
35,7	45,0	55,2	Emission of the SAF with 50% blending [gCO_2/MJ]

Therefore, considering the base scenario, to comply with the ETS allowances, the airline must avoid 4.4 million tons of carbon dioxide. The goal of this evaluation is to assess the possibility of SAF in this decarbonization pathway. How much SAF should the airline need? How much will it cost? Which emission value of SAF is needed?

It is assumed as a starting point, a blending condition of 50% (maximum limit) [3] [1] to understand the highest emission value the SAF could have. Then, the variation of SAF emission value is evaluated changing the blending condition. It is expected to be an evolution where, at lower blending conditions, the emission value of the SAF should be lower to maintain the same emission reduction.

Table 23: Emission value with the related blending condition

Blending condition [%]	E value [gCO2/MJ]
10%	- 150.9
15%	- 69.3
20%	- 28.4
25%	- 4.0
30%	12.4
35%	24.0
40%	32.8
45%	39.6
50%	45.0



Graph 11: Emission value trend changing the blending condition

This evaluation is performed in MATLAB environment because of its more straightforward equation solution.

This assessment has an interesting perspective to consider. Due to SAF's higher cost, one should try to reduce its consumption while still maintaining the reduction requested. The only possible solution is to obtain a SAF with an extra emission reduction capacity given by, for example, the biochar contribution. However, the 50% blending condition required 40.05 gCO_2/MJ can still be achieved with classical soybean or rapeseed oil (40.4 – 47.4 gCO_2/MJ) [56].

Alternative possible solutions to comply with emission reduction

After considering the theoretical subjects, it is crucial to assess the economic potential of the different decarbonization solutions. The table above has reported the total amount of carbon dioxide the airline must avoid emitting from 2024 to 2030. The starting point of the evaluation is the maximum blending limit of 50%. As seen before, SAF is more expensive than Jet-A1 fossil so that this solution will be the less cheap. Then, on the other side, there is the minimum share of SAF; according to ReFuelEU, the share of SAF must be at least 5% by 2030. Considering that the blending condition would vary during the period, it is considered both boundaries case with full fossil fuels and 5% blending condition.

The main focus, however, is on the benefit that biochar can give to the decarbonization pathway. As said before, SAF suffers because of its higher price, so, reducing the quantity needed is an actional solution.

As seen in the legislative framework, the ETS system establishes that the emission value of a biofuel that meets sustainability criteria can be considered as 0 [2]. In emissions calculations, this would ensure a reduction in the quantity of SAF while avoiding emissions, thus reducing costs. The necessary sustainability criteria, as outlined in Article 29 of RED II [1], state that a fuel can be defined as sustainable if it achieves an emission saving of 65%. This factor is calculated as follows [1]:

Eq. 13

$$Saving = {E_F - E_B}/{E_F}$$

Where:

- E_F: is the default value for fossil fuel emission 94 gCO_2e/MJ
- E_B: is the emission value for the biofuel.

So, to meet this requirement, the SAF must have an emission value below 32.9 gCO_2e/MJ. As seen before, biofuels such as rapeseed have higher values, and thus, the use of biochar can help them fall within this classification and take advantage in the ETS emissions calculation.

Biochar application in the soil can be embedded in the HEFA production pathway, as seen before in the Bio4A project [35]. The assumed biochar quantity and carbon credit generated established two possible scenarios to be considered; here are summarized the 5 possible solutions evaluated.

- 50% SAF
- SAF considering all biochar
- SAF considering just allocated biochar
- Full Jet-A1 fossil
- 5% SAF (ReFuelEU)

To account for the decarbonization potential of the SAF, it is proposed the following reason. Considering the fossil as a baseline scenario, for every ton of SAF the airline would use, it will obtain an emission reduction given by the difference between their emission values. This means that, when using a ton of SAF instead of Jet-A1 one generates an emission avoidance identified as "Factor of reduction", and computed as follows.

Eq. 14

$$Factor\ of\ reduction = (94 - E_{SAF}) \cdot LHV \cdot \frac{1}{1000} \left[\frac{kgCO_2}{kgSAF}\right]$$

Where:

- 94 gCO_2/MJ is the emission value for the Jet-A1 fossil according to RED II
- E_{SAF} is the SAF emission value express in gCO_2/MJ
- LHV is the lower heating value of the fuel reported by [] as 44 MJ/kg
- $\frac{1}{1000}$ is needed to convert from grams into kilos.

The next step is to calculate the amount of SAF needed to avoid the amount of GHG emission estimated in the three scenarios before (high – base – low). Simply dividing the total emissions by the factor of reduction, one gets the total SAF quantity. The next step depends on the solution and will be considered one at a time.

50% SAF

Here, the blending conditions are fixed, so the amount of SAF and Jet-A1 are equal. Moreover, with an emission of 45.02 gCO_2/MJ as found before, a factor of reduction of 2.155 $kgCO_2/kgSAF$ is obtained.

SAF considering all biochar

As previously explained, biochar can have a huge impact on the decarbonization and removal of carbon credits. Renewable Energy Directive [1] gives the possibility to account for the soil carbon sequestration due to agricultural management through the e_{sca} term seen before [Eq.2].

The estimation of this value, since it derives from agricultural experiments, was provided by Bio4A final derivable 4.3 [35]. This report studies different solutions also considering use of compost; for the purpose of this study, it is considered just the 100% biochar soil amendment performed in Spain. According to these experiments, an e_{sca} value of 16.73 gCO_2/MJ is obtained when the application rate of biochar is 230 kg/ha per year. Since the purpose of this study is to maximize the potential of biochar, it is assumed to have the maximum e_{sca} value established by Renewable Energy Directive, which is 45gCO_2/MJ. This was done because there is not an optimal value for application rate indeed the relationship between biochar and e_{sca} is linear, meaning that the highest value must be chosen. So, making a proportion, the biochar applied to the soil should be around 647 kg/ha per year. Since the feasibility study was done in terms of tons of SAF, it is necessary to assess the application rate as biochar over tons of fuel produced instead of hectare. The conversion value was provided by SAF productivity according to Bio4A experiments. Sustainability assessment identifies a SAF productivity of 296.20 MJ/ha per year, which, considering SAF's lower heating-value, implies that in one year, a hectare produces 6.73 kg of sustainable fuel. The last step to evaluate the biochar impact on the SAF value chain is its ratio to the ton of fuel produced, that is, the amount of biochar needed for one ton of SAF. In this way, it is possible to account for biochar prices in the economic analysis.

Below an overview table of these passages for biochar accounting is reported.

Table 24: Biochar accounting assumptions

	Method	Value
Experimental biochar application rate	From Bio4A report	230 kg/ha
Maximum biochar application rate	230 * 45 / 16	647 kg/ha
SAF productivity (energy)	From Bio4A report	296.20 MJ/ha
SAF productivity (mass)	296.20 / 44 (LHV)	6.73 kgSAF/ha
Final biochar application rate	647 / 6.37	96.14 kg/kgSAF

The final biochar application rate will be the factor to be multiplied by the total amount of SAF. It can already be seen that the total biochar mass will be huge with respect to the SAF and will probably impact a lot in the costs. Speaking on the subject, the cost of biochar must now be assumed.

The biochar costs of production are taken from the literature, table 25 below reported values from three major studies reported by Meyer [62].

Table 25: Biochar cost of production review

Reference	Biochar production cost	Comment on feedstock
Norgate and Terry *[63]*	342 €/t	Production based on wood processing
Roberts et al. *[22]*	47 €/t	Biochar produced from yard waste
Brown et al. *[64]*	249 €/t	Biochar from corn stover

These production costs show differences due to the different feedstock used and consequently the type of plant required. Among the various options, corn stover appears to be the most aligned with the case being studied and will therefore be taken as the benchmark.

It was chosen these values and not a market one, because from the perspective of an SAF producer, it is reasonable to assume a possible biochar production facility.

For this solution, all the biochar cost is allocated to the economic analysis even if the carbon sequestration obtained is divided between all co-products. This implies that other co-products can benefit from carbon sequestration. However, due to the considerable biochar cost, a solution was provided to enhance the biochar spread between co-products as a carbon credit that can be sold on the voluntary carbon market. Recalling the puro.earth methodology, the surplus biochar was transformed into Carbon dioxide Removal Certificates according to the ratio suggested. As seen before with the biochar emission allocation, only 1.44 % of it is used to generate the reduction of e_{sca} parameter. The remaining part (98.56%) was considered as pure carbon sequestration and accounted with the puro.earth methodology [50]. As previously explained, this methodology establishes a correlation between the quantity of biochar placed on the ground and the effective amount of net CO_2 removed from the atmosphere according to various ambient parameters.

Considering the global mean soil temperature of 14.9 °C, with one thousand tonnes of biochar with 93% of organic carbon, a carbon sequestration of 3225tonnes of CO_2 is obtained. Using this proportion, the amount of carbon credits generated was calculated [Eq.10]. The price for these credits sold on the voluntary market is assumed to be 40 €/tonCO_2. This is a reasonable estimate, previously, it was reported that the removal certificates in 2021 were about 8 €, however Voluntary carbon market is developing fast and certification bodies are becoming more widespread. Therefore, considering that the credits are calculated according to the methodology presented earlier by puro.earth, it is also interesting to assess their profitability with the price of credits indicated in the CORCX index, which currently stands at over €150/ton. So, the total cost will also be calculated considering a doubled selling price of carbon credits of 80 €/tonCO_2.

After considering the biochar cost, the last assessment is about the emission of the SAF; as seen in the RED II methodology, the e_{sca} value should be subtracted from the emission value of the fuel. Considering the life cycle emission value of rapeseed oil reported by CORSIA, the final emission value for the SAF is 2.7 gCO_2/MJ. However, as stated before in the legislative framework, ETS considered emission of a biofuel null if it respects the emission saving of 65%.

Consequently, the factor of reduction is nearly doubled with respect to the normal SAF 4.136 kgCO_2/kgSAF. This results in a halving of the required amount of SAF, which will reduce its costs.

SAF considering just allocated biochar

As previously talked about allocation, the co-products of SAF can exploit its emission reduction independently in their application sector. Hence, in this solution, just the cost of biochar related to the SAF is allocated accordingly to the share reported in table 5. In this way, it will be accounted only the biochar responsible for the emission reduction (e_{sca}), which is 1.44 % as the table 5 states. Compared to the solution presented before, in this case the cost would be modest, but there will not be revenue from the voluntary carbon market.

Full Jet-A1 fossil

This solution should assess the unchanged scenario with no decarbonization strategy applied. All the excess emissions due to an increase of air traffic will be covered by purchasing extra allowances on the ETS market. Considering all Jet-A1, the cost of fuels will be the lowest, but on the other hand there will be a cost linked to the carbon credit price. ETS market has recently suffered a price drop, but some analysis believes in a subsequent rise until 2030. The starting price of this evaluation was assumed to be 75 €/tonCO_2.

5% SAF (ReFuelEU)

This final option was introduced to take into account the ReFuelEU initiative. As previously explained, the European Union identified a minimum share of 5% for sustainable aviation fuels in 2030 [3]. Hence, even if the interval considered for this study ends in 2030, the sum of all the fuel consumption was considered composed of 5% of SAF. This solution will be similar to the last described; there will be a little amount of SAF additional cost, and a lower amount of carbon credit to purchase.

Results

This economic analysis was done in Excel environment to obtain more detectable results. The table below summarises the five studied solutions that will be commented on later, considering the base scenario of air traffic growth.

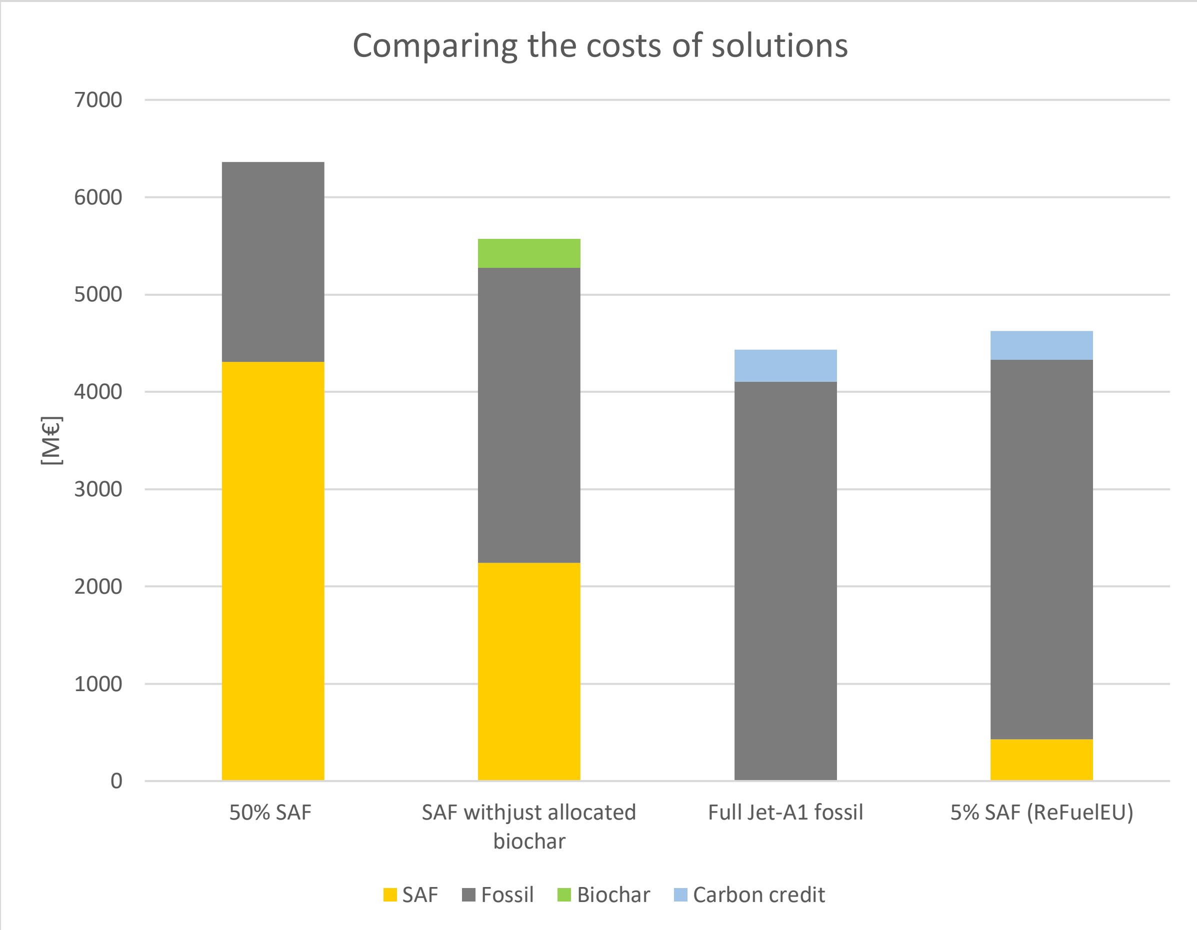
Table 26: Final cost comparison between the five solutions

		50 % SAF	SAF with all biochar	SAF with just allocated biochar	Full Jet-A1 fossil	5 % SAF (ReFuelEU)
Total amount of CO_2 to avoid [tonCO_2]		4420571				
Blending condition		50.00%	26.82%	26.82%	0.00%	5.00%
SAF emission [gCO_2/MJ]		45.02	0	0	-	45.02
Emission of the blending [gCO_2/MJ]		69.51	69.51	69.51	94.00	91.55
Emission reduction [%]		26.05%	26.05%	26.05%	0.00%	2.61%
Factor of reduction [kgCO_2/kgSAF]		2.155	4.136	4.136	-	2.155
SAF	Quantity [ton]	2'051'401	1'068'803	1'068'803	-	'205'140
	Cost [M€]	4'308	2'244	2'244	-	431
Fossil	Quantity [ton]	2'051'401	3'033'998	3'033'998	4'102'801	3'897'661
	Cost [M€]	2'051	3'034	3'034	4'103	3'898
Biochar	Quantity [ton]	-	102'720'707	1'476'478	-	-
	Cost [M€]	-	25'577	368	-	-
Carbon credits	Quantity [ton]	-	326'512'638	-	4'420'571	3'978'514
	Cost [M€]	-	-13'061	-	332	298
TOTAL COST [M€]		6'359	17'795	5'649	4'434	4'627

Here are reported the five solutions proposed with each cost term. It can be seen that fossil-based solutions (last two columns), still present a lower cost with respect to the SAF-based solutions. 50% share of SAF hypothesis is more expensive due to the higher amount of SAF requested. In this regard, biochar contribution allows to approximately halve the cost of SAF (from 4308 to 2244) leading to a reduction of total cost of 14%. Nevertheless, as seen before in the SAF parametric analysis, the price of sustainable fuel is still too high, and the ETS allowances (75 €/tonCO_2) do not incentivise this emission reduction scenario with respect to the fossil-based solutions. Over the seven years of operation considered, the airline operating using biochar would spend just under a billion more compared to the scenario with a 5% SAF set, according to ReFuelEU. Consequently, by maintaining these fuel prices, companies will not be incentivized to use sustainable fuel. However, as seen in ReFuelEU, there will be an increase in the minimum fuel quotas after 2030 , which will still force companies to move towards using SAF.

Regarding the solution involving SAF with all the biochar, it can be seen that the cost is too high and not comparable to other solutions when taking a credit price of 40 €/tonCO_2. However, if the price is doubled as described earlier, the revenues will also double, and the total cost of the solution will be 4735 M€ which will be in line with the other solutions.

To further analyse the cost allocation, below are shown four of these solutions with their cost distributions.



Graph 12: Quantitative cost analysis

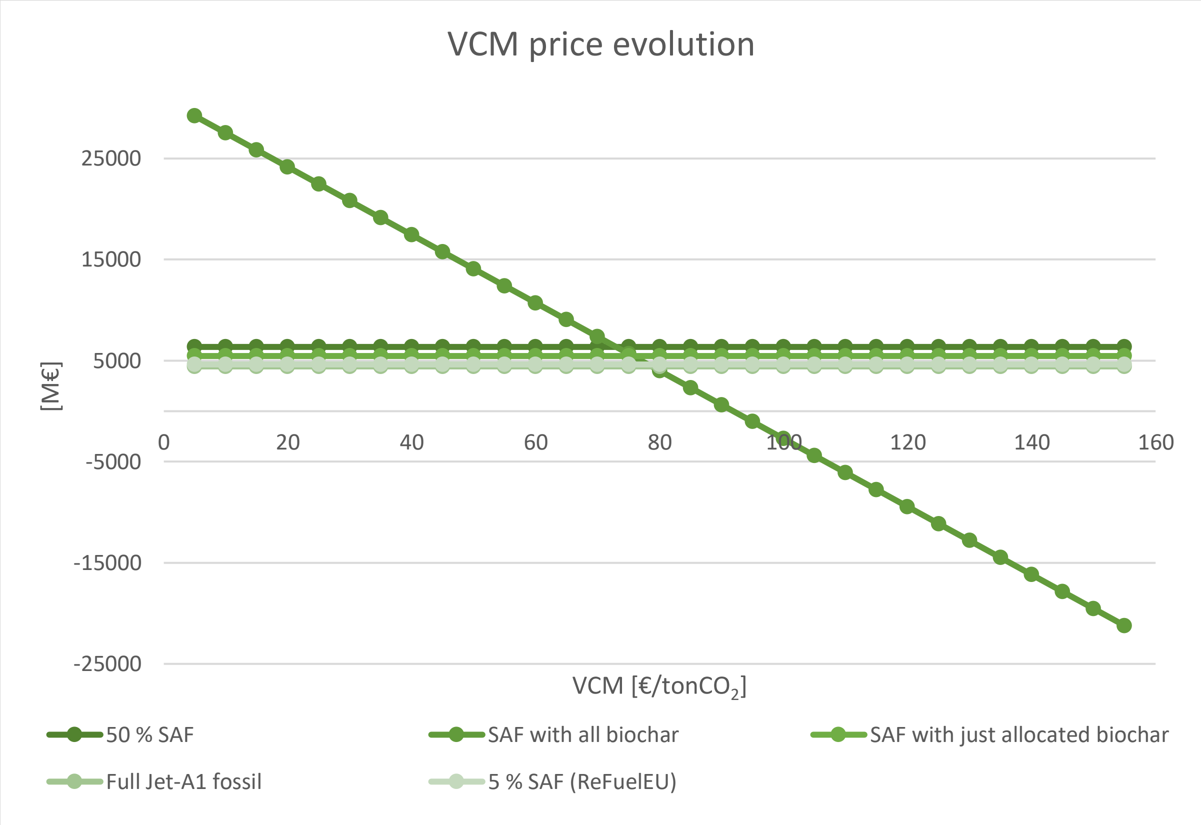
The graph above shows clearly how carbon credits do not impact a lot on the economic point of view. Besides a significant amount of CO_2 to offset, the price to purchase these credits is too low to affect the total and the amount of fuel responsible for these emissions represents the major cost.

On the other hand, looking at the first two columns, it can be seen that biochar with its marginal cost, is able to reduce a lot the SAF price influence. The cost related to sustainable fuel is almost halved, while the fossil cost shows a smaller increase. This gives the idea of the potential that biochar can represent.

In this graph the solution with all the biochar is not reported because of its revenue and elevated costs, which makes it out of scale and difficult to compare.

However, that solution has some exciting developments that need to be explored further. Since the amount of biochar and related removal carbon credit generated is quite large, there is a possible additional revenue source.

So, an analysis is performed by changing the price at which the carbon credits are sold on the voluntary carbon market.

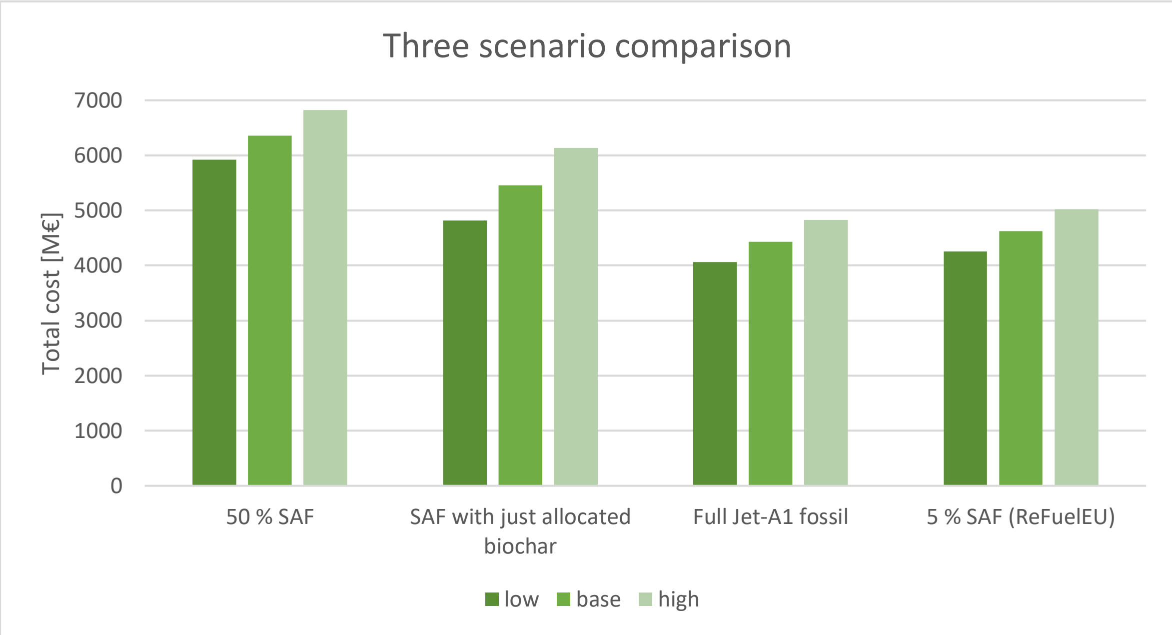


Graph 13: Total cost changing the price of the carbon credits sold on the voluntary carbon market

The graph clearly shows the sensitivity of the solution to the price change. This is explained by the large amount of credits generated by biochar that, with a small variation, can influence a lot the total cost. Raising the price from 40 €/tonCO$_2$ to 80 €/tonCO$_2$, lead to a reduction in the total costs, making it more profitable with respect to the fossil-based solutions. Assuming the price of these credits as the CORC index or 150 €/tonCO$_2$, the solution will not only be more profitable but even generate earnings.

The sensitivity shown highlights the importance of market evolution in this field in the coming years. An increase in regulations and standards for carbon credit generation, together with a rise in demand due to increased diffusion, could lead to an upsurge in the price of carbon credits and potential revenue.

For completeness of information, below the comparison between the three airline forecast traffic scenarios is reported.



Graph 14: Cost comparison between the three different traffic forecast scenarios

Assessing the variation of total SAF-based solutions cost with respect to the 5% SAF; it can be seen that with the lower traffic forecast scenario, the SAF solutions reduce its gap. These variations are reported in the table below.

Table 27: Cost variation compared to the 5% SAF case

	50 % SAF	SAF with just allocated biochar
low	39.3%	13.4%
base	37.4%	18.0%
high	35.8%	22.1%

Starting from the base case, where biochar solutions cost 118% more than 5% SAF solution, if the air traffic would decrease its growth in the considered period, the gap between SAF and fossil solution will have thinned out. On the other side, an increase in traffic would lead to greater fuel consumption and consequentially higher SAF costs.

Conclusion

The results of this work show that there is still a significant cost gap between Sustainable Aviation Fuels (SAF) and fossil fuels. In the various scenarios here analysed, fossil fuels remain the most economical choice, highlighting the need to address raw material costs. A significant example is the market for used cooking-oil, which is considered a waste product for the food industry but could be an essential resource for extracting aviation fuels. Collection and conversion practices can lead to a reduction in SAF costs, improving competitiveness, especially if waste is available at reduced or even free costs. In this context, slow pyrolysis has proven to be a valid technique for valorising biomass waste present in agricultural realities.

In this context, research regarding biochar's contribution to the aviation sector allowed us to highlight the potential positive, achievable results. Biochar proves to be an economically feasible solution to contribute to the SAF sector. Biochar can play a significant role in climate change mitigation and adaptation. Its water retention capacity can contribute to combating desertification, while in agriculture, it can reduce fertilizer use and improve soil nutrient retention, with a positive impact on greenhouse gas emissions. Furthermore, biochar can serve as a source of carbon credits, which are particularly valuable in growing markets. Biochar can significantly reduce biofuel emissions at considerably lower costs than other solutions. This benefits not only aviation fuels but also the entire production chain, including diesel, which can reduce its impact and find usage in sectors such as heavy-duty road transportation, which are not yet ready for electrification.

The system proposed by the European Union can reduce emissions in the near future, but emission allowance prices are still too low and do not sufficiently incentivize the adoption of more sustainable sources and fuels. This remains the path to follow, and it is hoped that other countries will take similar actions to address climate change seriously. Cooperation among nations will be crucial to ensure coordinated action toward sustainable development. As an example, although the CORSIA package is being launched and will become mandatory in 2027, it is not yet possible to fully evaluate the effectiveness of the tool.

In conclusion, the study allowed demonstrating that viable pathways for decarbonization exist for aviation, and biochar emerges as a promising solution to reduce emissions and contribute to the environmental sustainability of the SAF sector.

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