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Bioenergy with carbon capture and storage (BECCS) potential in jet fuel production from forestry residues: A combined Techno-Economic and Life Cycle Assessment approach

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ABSTRACT

In this study, the economic and environmental feasibility of a process configuration based on the Bioenergy and Carbon Capture and Storage (BECCS) concept is assessed. The research analyses the production of jet fuel from forestry residues-derived syngas via the Fischer-Tropsch (FT) technology. Further, the CO_2 removed in the syngas cleaning section is not released to the environment, instead it is permanently sequestrated. The produced Sustainable Aviation Fuel (SAF) has the potential to achieve negative emissions. The present research is a one-of-a-kind study for the jet fuel production within the BECCS concept. The process has been modelled within the Aspen Plus and Matlab software to obtain detailed and realistic mass and energy balances. Based on these balances, the technical, economic and environmental parameters have been calculated. Based on a plant that treats 20 dry-t/h of forest residues, 1.91 t/h of jet fuel are produced, while 11.26 t/h of CO_2 are permanently stored. The inclusion of the CCS chain in the biorefinery increase the minimum jet fuel selling price from 3.03 £/kg to 3.27 £/kg. The LCA results for global warming show a favourable reduction in the BECCS case, in which negative emissions of −121.83 gCO_2eq/MJ of jet fuel are achieved, while without CCS case exhibits GHG emissions equal to 15.51 gCO_2eq/MJ; in both cases, the multi-functionality is faced with an energy allocation approach. It is, then, evident the significant environmental advantages of the BECCS process configuration. Nevertheless, financial feasibility can only be attained through the implementation of existing policy schemes and the formulation of new strategies that would reward negative emissions. The application of the UK's policy "Renewable Transport Fuel Obligation" and a hypothetical scheme that rewards negative CO_2 emissions, breaks-even the Minimum Jet fuel Selling Price (MJSP) at 1.49 £/kg for a certificate and carbon price of 0.20 £/certificate and 246.64 £/tonne of CO_2.

1. Introduction

The increase in air travel has raised awareness of several environmental problems that are increasingly difficult to ignore, especially the contribution of this sector to global warming [1,2]. Estimations claim that the aviation sector is responsible for approximately 2% of the anthropogenic greenhouse gases emissions [3,4]. At the same time, among other sectors, it is believed that aviation will experience an increase in its GHG emissions at a higher rate. The aviation sector could increase dramatically in the coming decades, as from 2036 the passenger demand is projected to rise [3]. Therefore, the implementation of action plans for the decarbonisation of the aviation sector is at the centre of the agendas of different aeronautical organizations. The Air Transport Action Group (ATAG) has set the objective of halving the 2005′s CO_2 global aviation emissions by 2050 [2]. For this, different strategies have been proposed such as improvements in engine efficiency, improvements in operations logistics, changes in infrastructure, and the development of sustainable aviation fuels (SAFs). Among these alternatives, the development of SAFs from renewable sources is the main short-term/mid-term sustainable option for aviation nowadays, and it can also serve as a transitory option to move from the use of fossil fuels to other alternatives such as hybrid-electric or electric aircraft [5-7].

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SAF is a term frequently used in the literature, but to date, there is no consensus about its definition. According to the European Environmental Agency, SAF are defined as "bio-based aviation fuels that reduce GHG emissions relative to conventional aviation fuel while avoiding other adverse sustainability impacts" [2]. SAF are also referred as "Biofuels", alluding to their biological origin. Nevertheless, the evolution of conversion technologies allows using a larger variety of sustainable feedstock, such as waste and other materials of non-biological origin (e.g. CO_2). Therefore, in this study, the term SAF will be used in its broadest sense to refer to all aviation fuels derived from sustainable feedstock [8].

In recent years, there has been an important development of SAF production technologies, therefore, the American Society for Testing and Materials (ASTM) has developed the standard ASTMD 7566 to validate the safe use of SAF without the need to modify the airplanes engines. Up to 2021, seven SAF production processes have been ASTM certified [9-11]. Similarly, the "Technology Readiness Level" (TRL) and "Fuel Readiness Level" (FRL) frameworks are employed to rank from 1 to 9, the technological maturity of the SAF production processes, and fuel compatibility, respectively [9,12,13]. Out of all the certified processes, the Fischer-Tropsch (FT) pathway has one of the highest TRL (6 to 8) and FRL (7) [9]. The FT process is a well-established technology for the conversion of coal or natural gas-derived syngas to long-chain hydrocarbons, such as liquid transportation fuels. On the contrary, the conversion of biomass through FT requires overcoming some drawbacks especially related to the handling of the biomass feedstock and the syngas cleaning up steps [14]. However, the capacity of treating a wide range of cheap feedstocks increases the attractiveness of the FT pathway [15]. As a consequence, the use of residual lignocellulosic-based biomass, such as agricultural or forestry residues, is promising. Apart from their ability to reduce GHG emissions, these "second generation" fuels avoid the controversy on food versus fuel [16-18].

A considerable amount of techno-economic studies analysing biomass conversion through gasification and FT have been published, most of them focused on the production of middle distillates [19-21] rather than exclusively jet fuel [22-24]. Typically, FT process is found to be CAPEX and feedstock intensive [19,21,23-26]. As such, commercial-scale plants are associated with a high level of uncertainty, and [23,27] therefore, appropriate logistics, realistically large scale plant size and use of local resources could result in better economic performance.

Similarly, environmental analysis through LCA for FT fuels has been also assessed for middle distillates, such as diesel [28,29] and kerosene [30-33]. However, the analyses of on-road diesel are the same as that of kerosene, with differences in product yields and changes in energy inputs [34]. Compared with other technologies, FT achieves high GHG emission reductions as a consequence of the energy-self-sufficiency of the process and the excess power production [24,32]. The analysis of its whole life cycle leads to the conclusion that stages associated with the feedstock, such as transportation, biomass cultivation, and fertilizer utilization, have an important contribution to the GHG emissions [32,33,35]. It is also important to highlight that the choice of the method for treating the multi-functionality of the system will have an important impact on the environmental performance of a product and therefore on the results of the LCA [34,36,37]. De Jong et al. [32] analysed the FT pathway using an energy allocation and a hybrid (energy allocation/system expansion) method. Their findings reported important differences for both methodologies due to the high amount of co-products produced in the FT pathway. For this reason, de Jong et al. recommended the energy and economic (for non-energy products) allocation method to avoid the uncertainty introduced by the system expansion.

In recent years, there has been an increased interest in Carbon Dioxide Removal technologies (CDR) since estimations claim that they have the potential of removing between 100 and 1,000 Gt of CO_2 in the 21st century and thus they are included in all strategies that intend to limit global warming to 1.5 °C with limited or no overshoot. There are several CDR technologies, such as afforestation and reforestation, land restoration and soil carbon sequestration, bioenergy with carbon capture and storage (BECCS), direct air capture (DAC), enhanced weathering, and ocean alkalization [38]. Among them, BECCS is a promising technology for carbon removal whose process stages have been independently demonstrated at scale, such as bioenergy plants, and capture, transport, and storage of CO_2 [39]. BECCS processes for energy production are more carbon-efficient (amount of carbon coming from biomass that is reported as negative emissions) than BECCS for biofuel production. However, the latter option has the ability to create negative-emissions alternatives to decarbonise the transport sector that lacks options to reduce its carbon footprint compared to power generation [40]. Despite this, the literature abounds with case studies related to power production through BECCS [41-47].

It is also important to highlight that up to date, the research of FT SAF has focused on determining technical, economic, and environmental performances of SAF from biomass-derived syngas. So far, however, there has been little discussion about the techno-economic and environmental performances of SAF production within the BECCS concept. Tagomori et al. [48] analysed the techno-economic performance of green diesel production via gasification and Fischer-Tropsch. The difference in the levelized cost between the plant without and with carbon capture and storage (CCS) is almost negligible. Likewise, in a special report, the IEA [27] analysed the implementation of two different plants for the production of biofuels integrated with BECCS. This study determined that for the FT scenario, the implementation of a CCS section increases the syncrude production cost by 10%–14%. In the same report, the amount of the captured CO_2 is calculated and translated as a reduction of the emissions from the process. However, a more detailed LCA study could have shown with more accuracy the emissions of the whole syncrude life cycle as well as the influence of the different stages.

From the literature review, it is evident that there exists a plethora of studies assessing the economic and environmental feasibility of liquid fuels produced through the FT process. Nevertheless, few studies have explored the feasibility of FT fuels production from a BECCS perspective. It seems evident that the economic performance of the process is not dramatically affected by the incorporation of the CCS. However, previous studies have failed to provide a detailed LCA that would provide a robust accounting of emissions and a better understanding of the contribution of the different stages of the life cycle of the fuel. At the same time, it is important to state that jet fuel is not the main product of none of the aforementioned studies [27,48]. Considering this gap of knowledge and due to the growing importance of both CDR and SAF production technologies, the current research seeks to determine the economic and environmental performance of producing SAF from forest residues-derived syngas coupled with CCS. To the best of our knowledge, this is the first attempt to assess comprehensively the economic and environmental performance of a bio-CCS jet fuel production route. The assessments are developed for two scenarios: the baseline scenario (referred to as BECCS) and the scenario without CCS (referred to as BE). The outputs of these analyses will establish a clear contrast between the advantages and disadvantages of the BECCS configuration for the production of aviation fuels and can provide meaningful insights to a wide range of audience including policy makers and researchers.

2. Outline of the research

2.1. Goal and scope of the study

The main objective of this research is to evaluate the process, economic and environmental performance of the production of SAF from forest residues through the FT process under the BECCS concept. To this end, a detailed process model is developed in Aspen Plus V10 to obtain accurate mass and energy balances, and therefore, increase the reliability of the TEA and LCA outcomes. A cradle-to-gate (upstream costs for feedstock production and distribution are inherent in the feedstock gate price) economic evaluation of the proposed scenarios is carried out in order to calculate relevant economic indicators, such as the MJSP. Likewise, a well-to-wake (WtWa) LCA is analysed in the software SimaPro, for the calculation of the GWP. The assessments are developed for the baseline "BECCS" and the "BE" scenarios in order to estimate trade-offs due to the CCS addition. Moreover, a sensitivity analysis is applied to determine the parameters with the greatest impact on the economic and environmental performances. Finally, the impact of relevant policies on the viability of the proposed process has also been investigated.

2.2. Capacity of the plant and description of the process

Biomass is identified as an important constituent of the future UK energy grid, and forest residues (FR) are highlighted as one of the main sources of biomass supply [49,50]. Therefore, this study considers FR as the main feedstock for the SAF production process, assuming that it is supplied entirely by the UK's forestry industry. Consequently, the capacity of the plant is fixed by the country's availability of this feedstock. FR are originated from the unutilized remaining parts of felled trees, which are generally left on the forest and that include tops and limbs. The below-ground part of stumps and a percentage of the branches and stem tips are left on-site due to sustainability reasons, performing a major role with their anti-erosion effect, their capability of avoiding loss of soil carbon and nutrients, as well as providing habitats [50,51]. The major advantage of considering FR as the feedstock is that they are not related to any land use change as some energy crops could imply [48].

In the report elaborated by E4tech [52] for the total availability of sustainable forest residues in the UK, it was determined that 1.35 Mtonnes/year are available, of which 0.8 Mtonnes/year are originated in Scotland. The same report, proposed three potential locations for advanced biofuel production plant, all of them placed in Scotland due to its high forest residues production capacity as well as the short transport distance between feedstock collection points and potential conversion plants. Therefore, it is assumed that the biorefinery is located in the Solway Firth area owing to its short distance to two of the largest forest of public ownership in the UK (approximately 50 km) [52]. Based on this information, the capacity of the SAF production plant is fixed as 20 dry-tonnes per hour (0.16 million of dry-tonnes per year) of FR; a feedstock requirement that could be supplied by the local production.

The UK potential for the storage of CO_2 has been assessed in the past years, reaching to the conclusion that the available capacity for at least 600 potential storage sites, could go as high as 78 Gtonnes of CO_2 [53,54]. Most of the storage options are found as offshore saline aquifers, while some depleted hydrocarbon fields are also available; both options are primarily located in Scotland [55]. A major disadvantage of the facilities that are the most suitable for CCS projects is their large size, which makes their usage less prone to be quickly expanded for strategic projects. In this sense, the Hamilton store (with a storage capacity of 5 Mtonnes/y of CO_2) located in the East Irish Sea has been proposed as the best candidate for relatively small scale CCS projects [53] such as the proposed SAF scenario. Another advantage of this location is the distance to the process plant, as it is below 200 km and no additional electricity for recompression is needed [56]. At the same time, its storage capacity is suitable for the amount of CO_2 that could be sent for storage (around 0.1 $MtCO_2$/y).

3. Methods

3.1. Process design and modelling

This section provides the foundation of the process design along with key methods and assumptions for the process modelling of the involved unit operations. In addition, the key technical performance indicators are presented and discussed.

3.1.1. Basis for process design

Aspen Plus V10 has been used to create the process models of the proposed scenarios with the aim of obtaining detailed mass and energy balances. The main thermodynamic property package "Redlich-Kwong-Soave-Boston-Mathias (RKS-BM)" has been assigned to the overall process plant as this method is widely applied for gas-processing, refinery, and petrochemical applications [57]. Nevertheless, the CO_2 capture plant uses a different thermodynamic package, i.e. "ELECNRTL", in order to represent the ionic interactions of the electrolytic species associated with the amine solvent [57]. Ash and biomass have been considered as non-conventional solids without particle size distribution (PSD), while char has been modelled as a conventional solid. The ultimate and proximate analysis of the feedstock can be found in Table 1. Steam tables have been used to define the properties of the steam produced for the process requirements, as well as those for the CHP unit.

Most of the reactors have been modelled based on operating conditions and efficiencies obtained from experimental and pilot plants documented in previous studies. The pyrolysis and gasification sections have been modelled in a more comprehensive way. Experimental correlations and kinetic expressions have been used with the intention of producing mass and energy balances that can accurately reflect the operation of a dual fluidised bed gasifier at industrial level.

3.1.2. Process design

Figure 1 depicts the boundaries for the process modelling and the economic analysis of the BECCS scenario. In this section an overview of the incorporated unit operations is presented. For a more comprehensive outline of the approaches used in the Aspen Plus modelling and the operating conditions used as well as the detailed process flow diagrams, the reader should refer to section S1 of the Supplementary Information. It is also important to mention that the BE scenario will have a similar process configuration, with the only difference being that it does not include a CO_2 compression section.

- **Biomass pre-treatment:** The process starts with the biomass pre-treatment, that aim to adjust the feedstock to conditions suitable for gasification. It should be mentioned that FR pre-processing steps, such as on-forest chipping and drying have not been modelled in Aspen plus but considered in the LCA. Initially, the particle size of the FR chips is reduced to 2 mm in a hammer mill [59]. After the grinding section, the biomass is dried in order to reduce its water content from 30% to 10% (w/w) [60].
- **Gasification section:** Subsequently, the treated biomass is introduced into a dual fluidised bed gasifier (DFBG) in which several chemical reactions take place in order to produce syngas (mainly composed of H_2 and CO). The DFBG consists of two separated compartments: Biomass is introduced in the first bed for gasification with steam, while the unreacted char is sent to the second bed for combustion. The advantage of this configuration is that the combustion with air takes place in a separated chamber, avoiding the excessive

Table 1
Proximate and ultimate analysis of forestry residues [58].

Proximate analysis (mass %)	Wood
Moisture (as received)	30.00
Fixed carbon (dry basis)	17.16
Volatile matter (dry basis)	82.29
Ash (dry basis)	0.55
Ultimate analysis (mass %)	
Carbon	50.54
Hydrogen	7.08
Nitrogen	0.15
Sulphur	0.57
Oxygen	41.11
Ash	0.55

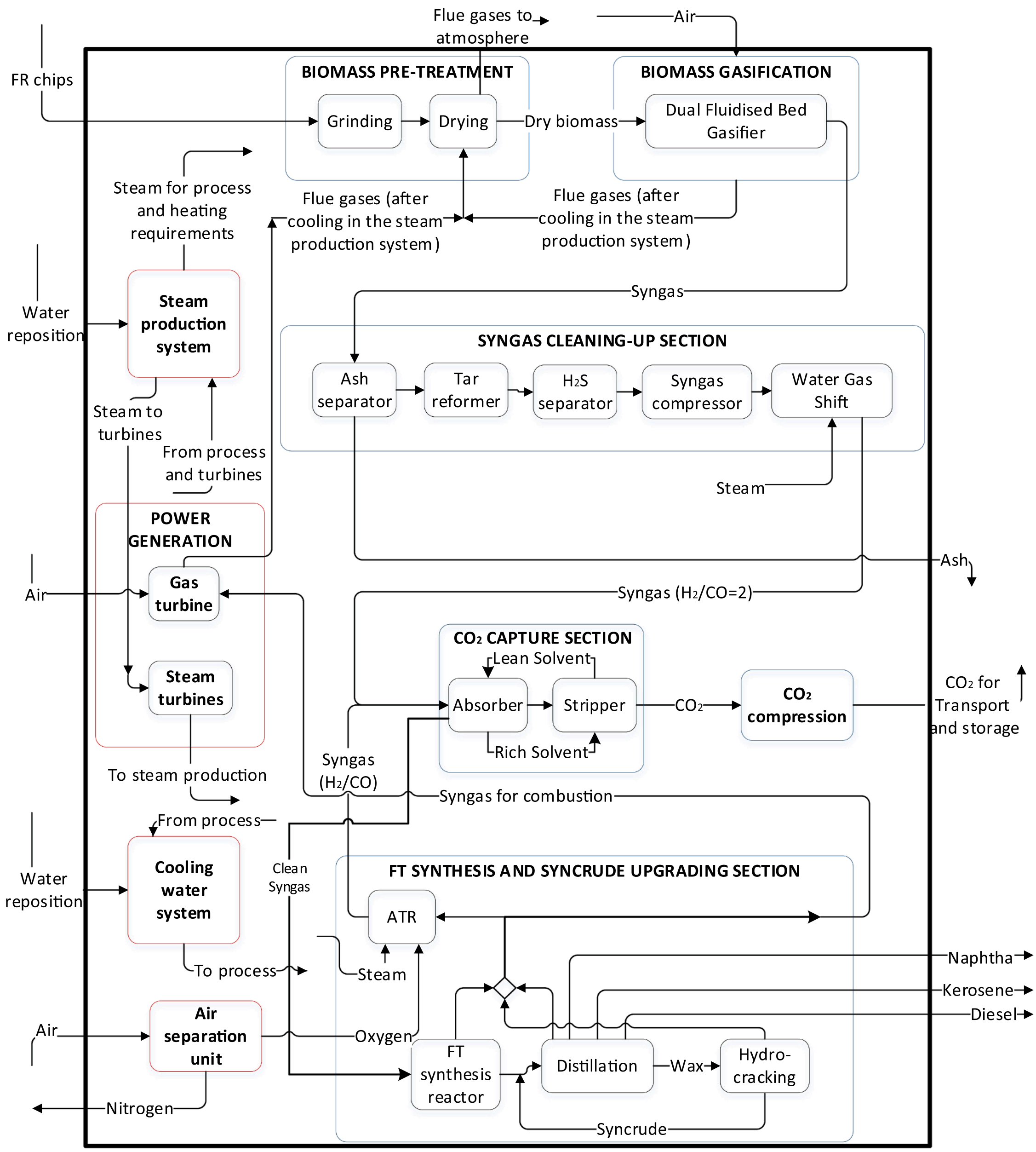


Fig. 1. Block flow diagram of the BECCS scenario. The boundaries include the units that have been modelled in Aspen Plus. Also, the same boundaries have been used for the economic assessment.

presence of N_2 in the resulting syngas. Then, heat is transferred to the first compartment (for the endothermic reactions) by circulating the inert bed particles [61]. It should be noted that the pyrolysis product distribution is calculated by using empirical mathematical correlations [62,63], while the gasification reactions are modelled through a kinetic approach [62,63]. The differential equations for the reaction rates have been solved in Matlab and then the solutions have been transferred to Aspen Plus. For more details of the modelling methodology of this section, refer to section S.1 of the Supplementary Information.

- **Syngas cleaning-up section**: Due to the intolerance of the FT catalyst to certain contaminants, the synthesis gas that leaves the DFBG enters the cleaning section, which comprises a series of physical and chemical processes aiming to reduce the amount of the pollutants to acceptable levels: 1) Ash separator; 2) Tar and methane reformer [64,65]; 3) ZnO bed, for H_2S removal [66,67]; 4) WGSR, to adjust the ratio H_2/CO to 2.1 [18]. It is relevant to mention that in this section, the syngas free of pollutants is compressed from atmospheric pressure to 25 bar [20,68].
- **CO_2 capture plant:** Following the cleaning section, the syngas is directed to the capture plant, that separates 90% of the CO_2 contained in the syngas [20,68-70]. A typical chemical absorption-stripper configuration, using as solvent monoethanolamine (MEA) is considered here to capture the CO_2. In addition heat is exchanged between the lean and the rich solvent in order to reduce the energy penalty associated with the solvent regeneration [20,68].
- **CO_2 compression section:** Prior to transportation, CO_2 should be appropriately treated to meet the required delivery conditions such as temperature, pressure and humidity levels, and essentially ensure that a dry single-phase flow is achieved. To facilitate long haul transport, CO_2 is liquefied. For this purpose, the CO_2 is treated in a series of compressors, a water separation unit, a cooling heat

exchanger and a pump. Initially, the CO_2 goes through a multi-stage compressor with intercooling stages that keep the temperature at 80 °C; also, condensed water is separated from the gas stream [64,68]. Later, in another multistage compressor, the CO_2 is compressed to 80 bar, which is already above its critical pressure of 73.8 bar. Then, cooling to 30 °C is applied to obtain CO_2 in the liquid state, and finally, a pump compresses this liquid CO_2 to 153 bar, which is the required pressure for pipeline transport [56,68].

- **FT synthesis and crude upgrading section:** In order to obtain long-chain hydrocarbons, the operating conditions of the FT synthesis reactor are 240 °C and 25 bar, using a cobalt-based catalyst [71]. In the FT reactor, a fraction of the synthesis gas is converted into a variety of gaseous and liquid hydrocarbons, which is known as synthetic oil or syncrude. Then, the products from the FT reactor are sent to a series of separators, where three phases are obtained: gaseous hydrocarbons (C_1, C_2, C_3, mainly), liquid hydrocarbons (C_5-C_{30}) and water. The liquid hydrocarbons head to the upgrading section, while a portion of the unreacted syngas (15%) is sent to a CHP unit; in this way accumulation of inert gases in the recycling loop is avoided. The value of 15% has been chosen as this amount of gas can raise electricity that can match the power demand of the biorefinery. The remaining unreacted syngas fraction is treated in an ATR section and then recirculated to the process, more precisely at the inlet of the CO_2 separation section, where it is treated before being sent back to the FT reactor; thus increasing the global conversion of the CO. The syncrude is sent to the atmospheric distillation column, where it is fractionated to different range of hydrocarbons. The partial condenser located at the top of the column produces a gaseous and liquid distillate. The gas stream, consisting mainly of C_1, C_2, C_3 and some C_{4+}, is recycled to the process along with the unreacted syngas exiting the FT reactor. The liquid distillate is equivalent to the gasoline fraction, which is mainly made up of C_5 to C_7. A few stages below the top of the column, the jet fuel fraction (C_8 to C_{16}) is recovered and, further down, the diesel fraction (C_{17} to C_{20}). Finally, heavy hydrocarbons (C_{21+}) or waxes are extracted from the bottom of the column.

For this study, wax is not a desired product, and to maximise the jet fuel production, a hydrocracking unit is incorporated in the process. The aim of the hydrocracker is to break down long hydrocarbon chains in order to obtain smaller hydrocarbons. The operating conditions, such as temperature, pressure and H_2 inlet flow, define the severity of the hydrocracking reactions and therefore, the product distribution. This work adopts the operating conditions proposed by Teles et al. [72], i.e. 50 bar, 277 °C and 1.5% of H_2 in the reactor inlet stream, in order to favour a mild hydrocracking that leads to the production of middle distillates. Theoretically, this operation mode allows a complete conversion of the waxes with an assumed average product distribution of 50% of jet fuel, 30% of diesel, 15% of gasoline and 5% to light gases (all in a mass basis) [19,20,72-74]. The uncertainty of this product distribution is further analysed in the sensitivity analysis section.

- **CHP and cooling water system:** The design of the biorefinery aims to provide energy autonomy in terms of both electricity and heating duties. The process is energetically integrated, since the high temperature process streams are cooled in heat exchangers, where steam at different conditions is produced, namely superheated steam (500 °C and 50 bar), steam saturated at high pressure (215 °C and 20 bar), medium pressure (177 °C and 10 bar) and low pressure (135 °C and 3 bar). Subsequently, the steam generated in the different processes is sent to the plant, to cover the heat requirements (distillation columns, heat exchangers, e.g.). The remaining steam fraction is sent to steam turbines to generate electricity. In total, there are three turbines, which operate at different pressures. Due to the high power requirements of the plant, a gas turbine is coupled to the process, where 15% of the recycling gaseous stream to the FT process is combusted [20]. The cooling water system works with water at 15° C, the temperature of which is controlled by a cooling tower. It was assumed that a water loss of 5% accounts for the losses due to drift, evaporation and blowdown [75].

3.1.3. Performance indicators

The importance of the energy and mass performance indicators lies in the possibility of being able to compare the study carried out with others that can be found in the literature. Among them, it is important to introduce the carbon fixation or carbon conversion efficiency, which is the indicator that accounts for the level of conversion of the feedstock into the product. This indicator is determined by the Equation 1, which relates the moles of carbon ($\dot{n}_{C,products}$ in kmol/h) in the products with the moles of carbon in the feedstock ($\dot{n}_{C,feedstock}$ in kmol/h) [76,77].

$$C_{fix} = \frac{\dot{n}_{C,products}}{\dot{n}_{C,feedstock}} \quad (1)$$

Equation (2) and Equation 3 calculate the total fuel mass efficiency and specific jet fuel mass efficiency. Where $\dot{m}_{gasoline}$, $\dot{m}_{jetfuel}$, $\dot{m}_{diesel}$ and $\dot{m}_{drybiomass}$, refer to the mass flow in kg/h of the gasoline, jet fuel, diesel and dry biomass respectively [22,78].

$$massefficiency_{fuel} = \frac{\dot{m}_{gasoline} + \dot{m}_{jetfuel} + \dot{m}_{diesel}}{\dot{m}_{drybiomass}} \quad (2)$$

$$massefficiency_{jetfuel} = \frac{\dot{m}_{jetfuel}}{\dot{m}_{drybiomass}} \quad (3)$$

The energy balance from the simulation enables the study of the energy performance of the case studies. Energy indicators, such as jet fuel efficiency and overall energy efficiency shown in Equation 4 and Equation 6 respectively, are used to evaluate the process efficiency [23]. The jet fuel efficiency of the process is identified as the ratio between the energy of the main product, jet fuel, to the energy content of the feedstock, which is expressed as follows:

$$\eta_e = \frac{|\dot{m}_{jetfuel} \bullet LHV_{fuel}|}{|\dot{m}_{feedstock} \bullet LHV_{feedstock}|} \quad (4)$$

Where η_e is the jet fuel efficiency of the conversion process, $\dot{m}_{jetfuel}$ (in kg/h) is the mass of the jet fuel obtained, $\dot{m}_{feedstock}$ (in kg/h) is the mass of the feedstock converted in the process, LHV_{fuel} and $LHV_{feedstock}$ are the lower heating value (LHV in MJ/kg) of the fuel and feedstock. The LHV of the FR on a dry basis (db) is equal to 19.54 MJ/kg [79], and this value is recalculated at different moisture contents (MC) as received (ar) in accordance with the Equation 5 [79].

$$LHV\left[\frac{MJ}{kg}a.r.\right] = \left(1 - \frac{MC(w/w\%)}{100}\right)*LHV_{db} + -\frac{MC(w/w\%)}{100}*2.44 \quad (5)$$

$\eta_{overall}$ is the overall energy efficiency, which establishes the global efficiency of the process, by taking into account the energy of all the products, such as fuels and electrical power produced (P_{El} in MJ/h), and the input energy of the feedstock and the power demand from external sources ($P_{El,de}$ in MJ/h), which is expressed in Equation 6 as follows [77]:

$$\eta_{overall} = \frac{|\dot{m}_{fuel} \bullet LHV_{fuel}| + P_{El,prod}}{|\dot{m}_{feedstock} \bullet LHV_{feedstock}| + P_{El,de}} \quad (6)$$

3.2. Economic evaluation

3.2.1. System boundaries of the economic assessment

This section delivers a cradle-to-gate (GTG) analysis, which is also represented by the boundaries of the block diagram of Fig. 1, which includes the following sections: 1) biomass pre-treatment, 2) biomass gasification, 3) syngas conditioning and cleaning section, 4) CO_2 capture and compression and 5) gas and steam turbines. It is important to mention that the production of the forest residues chips has not been modelled; however, the associated costs of harvesting, chipping and transporting them to the process plant, are included in the price of biomass "as received". The transport and storage of CO_2 costs are considered herein as variable costs.

3.2.2. Basis for the economic evaluation

The main purpose of the economic assessment is to estimate economic indicators of great importance, such as CAPEX, OPEX and MJSP. Uncertainty about the future price of jet fuel and SAF is significant, thus, the preferred method for the determination of economic feasibility of a specific conversion pathway is through the MJSP [23,80]. The MJSP of SAF is the price value at which the NPV is equal to zero, at an IRR of 10% [23,80]. A typical discounted cash flow analysis (DCFA) is used to determine the MJSP, whose financial parameters and assumptions, such as the discount rate, depreciation method, income tax rates, plant life, and construction start-up period and so on, are detailed in Table 2.

It is also important to mention that the nth plant approach is considered for the present economic analysis. The key assumption of the nth plant is that the analysed technology is not a pioneering plant but that it has been successfully scaled to a commercial level, with several plants operating at an industrial level [80,81]. Since the main objective of TEA is to study new processes and their economic impacts, Humbird et al. [81] recommend the premise of the nth plant approach to avoid unnecessary artificial inflation of project costs related to pioneer plants uncertain characteristics, such as risk financing, longer start-ups, overdesign of the equipment and so on.

The purchased equipment cost (PEC) of the various common process units, such as heat exchangers and pumps, absorber and stripper are estimated by using the Aspen Plus Economic Evaluator tool. For other equipment, such as gasifiers and catalytic reactors, bibliographic research was conducted to find baseline costs from vendor quotes or other authors. Because the equipment capacity and the year of the economic analysis are not the same as in this study, the equipment or process unit costs will be adapted by Equation 7 [80,82] and Equation 8 [83].

$$C = C_0\left(\frac{S}{S_0}\right)^f \quad (7)$$

Where C is the cost of the unit at the actual capacity S, and C_0 is the base cost at a specific base size S_0 or capacity. The scaling capacity factor f has different values, in accordance to the kind of process equipment, and it has the aim of reflecting the effect of the economy-of-scale [80].

$$C_{baseyear} = C_0\left(\frac{index_{baseyear}}{index_0}\right) \quad (8)$$

Where the values of $C_{baseyear}$ and $index_{baseyear}$ correspond to the assumed year of the study while the other variables, C_0 and $index_0$, refer to the year in which the original cost was obtained. The indexes are taken from the "Chemical Engineering Plant Cost Index (CEPCI)" that serves as an important tool for chemical-process-industry projects in the adjustment of equipment price from one year to another. When the original prices of the equipment were not reported in £, a conversion factor was applied, corresponding to the year where this equipment price was detailed. Table 3 contains information about the equipment cost estimation parameters.

Table 2
Parameters for conducting the discounted cash flow analysis [20,64].

Location	United Kingdom
Plant life	20 years
Currency	£
Base year	2019
Plant capacity	20 dry-tonnes of FR/year
Discount rate	10%
Federal tax rate	30%
Construction period	3 years
First 12 months' expenditures	10%
Next 12 months' expenditure	50%
Last 12 months' expenditures	40%
Depreciation method	Straight line
Depreciation period	10 years
Working capital	5% of FCI
Start-up time	6 months

Following the calculation of the PEC, the Indirect Costs and Total Direct Costs are calculated as depicted in Table 4. To include the cost of installation, the PEC is multiplied by a factor, which represents the cost of auxiliary equipment, the cost of labour for installation, the cost of engineering, and the cost of contingencies [83]. Subsequently, the FCI is estimated as the sum of Indirect Costs and Total Direct Costs. The interest during construction is calculated considering that the investments during the first, second, and third year are 10%, 50%, and 40%, respectively, at an interest rate of 10%. Finally, the CAPEX is estimated by adding the start-up cost and the interest during construction. The working capital is considered to be 5% of the CAPEX.

Similarly, the OPEX (operating expenditures) or manufacturing costs is determined by summing up the estimated values of fixed operating, and maintenance costs (FOM), variable operating costs (VC), and plant overhead costs, as shown in Table 5. VC are calculated by adding the cost of raw materials, utilities and, catalysts (that are replaced every three years) and which prices are also summarized in Table 5. In turn, the labour is calculated using the empirical relationship, Equation 9, proposed by Peters et al. [92].

$$h_{labour}\left[\frac{h}{year}\right] = 2.13 \times plantcapacity\left[\frac{kg_{fuel\_output}}{h}\right]^{0.242} \times n_{process\_steps} \times \frac{h_{plant\_operation}}{24} \quad (9)$$

In this correlation, the "plant capacity" refers to the amount of jet fuel produced, expressed in kg/h, "$n_{process\_steps}$" or the number of process steps, refer to the number of sections within the process, where significant chemical and/or physical changes occur. In addition, "$h_{plant\_operation}$", refers to the annual operating hours of the plant, which is considered to be 8,000 h/year. Once the hours of labour "h_{labour}" are estimated, the cost of the labour is calculated by considering that the price of one hour of labour is equal to 15 £/h [67,93].

3.3. Life cycle assessment (LCA)

The LCA is constructed by the sequence of four main steps, including the definition of the goal and scope of the study, elaboration of the inventory analysis, impact assessment and interpretation of the results. To guarantee the reliability and transparency of LCA studies, the standardized methodology depicted in ISO 14040 and 14044 should be followed [97].

3.3.1. Goal and scope definition, functional unit

The goal of the present LCA study is to assess the environmental sustainability of processing forest residues for jet fuel production via gasification and Fischer-Tropsch coupled with CCS. To quantify the global warming potential (GWP) of the whole supply chain of these processes, a WtWa LCA has been performed. The impact of adding CCS has been measured by analysing the same scenario, but without the capture of CO_2 (BE scenario), and finally, the results of both analyses have been compared against the GWP of conventional jet fuel.

The selected functional unit is 1 Megajoule (MJ) of SAF while the LHV of the SAF is considered as 42.8 MJ/kg [10]. The purpose of this choice (based on energy output) is to easily compare fuels with different origins when they have the same end-use (e.g. combustion in the same aircraft) [35]. Further, SimaPro V.9 is utilised to carry out the LCA with a focus on the Global Warming Potential (GWP).

Table 3
Purchased equipment costs at base capacity and year of reference.

Equipment	Base cost [MM £]	Base capacity	Unit	Scaling factor	Base year	Reference
ASU	147.535	145	kg/s O_2	0.50	2014	[84]
ATR	13.028	12.2	kg/s total feed	0.67	2014	[84]
Biomass receive and unload	1.751	198.1	wet t/h	0.62	2007	[85]
Biomass storage, preparation, feeding to atmospheric gasifier	1.294	64.6	wet t/h	0.77	1999	[86]
Compressor	0.395	413	kW	0.68	2014	[87]
Cooling tower	2.422	4530.3	kg/s	0.78	2014	[84]
Cyclone	0.040	1	m^3/s total gas	0.70	2014	[87]
DFBG	9.184	100	$MW_{th,LHV}$ at moisture content of 20%	0.72	2010	[79]
Drier	5.064	1	air or hot gas m^3/h	0.8	2003	[79]
FT-REACT	153.607	2,420	MW of fuels produced	0.75	2011	[85]
Hydrocracker	6.233	1.13	kg/s (feed mass flow)	0.70	2014	[87]
Isomerization	16,288	1	t product/year	0.62	2015	[88]
PSA	4.710	0.294	kmol/s purge gas	0.74	2014	[87]
Steam turbine	0.274	10.5	MW	0.44	2014	[87]
TAR-REF	0.682	12	Nm^3/s	0.6	2010	[79]
WGS reactor	2.224	150	kg/s total feed	0.67	2014	[87]
ZnO guard bed	0.016	8	m^3/s total gas	1.00	2014	[87]

Table 4
Methodology for the calculation of the CAPEX [89-91].

Component	Cost, MM £
Installed direct costs (IDC)	**PEC+(A + B + C + D + E)**
A) Purchased equipment installation	0.39*PEC
B) Instrumentation and controls	0.26*PEC
C) Piping	0.31*PEC
D) Electrical systems	0.10*PEC
Non-installed direct costs (NIDC)	**E + F + G**
E) Buildings	0.55*PEC
F) Yard improvements	0.12*PEC
G) Land	0.06*PEC
1) Total direct costs (TDC)	**IDC + NIDC**
2) Indirect costs (IC)	**0.255*PEC**
3) Fixed Capital Investment (FCI)	**TDC + IC**
4) Start up costs	**0.05*FCI**
5) Interest during construction	**Calculated**
Total Capital Requirement (TCR) or CAPEX	**3 + 4 + 5**
Working Capital	**0.05*FCI**

Table 5
Fixed operating and maintenance cost, and variable cost [83,89-91].

Fixed Operating and Maintenance (FOM)	Value		
A) Labour	Equation 9*15 £/h		
B) Supervision	0.25*A		
C) Direct overhead	0.5*(A + B)		
D) General overhead	0.5*(A + B + C)		
E) Maintenance Labour	0.015*FCI		
F) Maintenance materials	0.015*FCI		
G) Insurance and tax	0.010*FCI		
H) Financing WC	0.1*Working Capital		
FOM	A + B + C + D + E + F + G + H		
Variable Cost (VC)			
A) Feedstock			
	Price		Reference
Chips of FR	58.53 £/t		[94]
B) Utilities			
	Price		Reference
Ash disposal	20.218 £/t		[73]
CO_2 T,S&M	19 £/t		[64]
Waste water treatment	0.415 £/t		[73]
Cooling water	0.025 £/t		[64]
Feed boiler water	0.784 £/t		[73]
C) Catalysts			
	Price	Lifetime [years]	Reference
FT synthesis	16 £/kg	3	[95]
Tar Reformer	3% of VC	3	[64]
Wax hydrocracking	18 £/kg	3	[95]
WGS	13,836 £/m3	3	[95]
PSA	0.85 £/kg	3	[67]
ATR	42,452 £/m3	3	[96]
VC		A + B + C	
OPEX		FOM + VC	

3.3.2. System boundaries for the LCA

The boundaries of the LCA section are broader than those of the techno-economic analyses (TEA), and this is because the latter only focuses on the conversion process (GTG approach). Fig. 2 shows in detail the stages considered in this environmental assessment: i) Production and chipping of forest residues through sustainable forest management; ii) Transport of feedstock to the process plant; iii) Conversion of forest residues into SAF (Gasification and FT); iv) Compression, transport and storage (T&S) of CO_2; v) Transport and distribution of SAF, and; vi) Combustion of SAF. At the same time, these limits also expand towards the production and transport of the secondary material inputs and energy required by some stages of the life cycle. Since the LCA of this SAF production process considers the emissions from the field where the feedstock is collected until the wake of the aircraft, this analysis is of a well-to-wake (WtWa) kind [98].

3.3.3. Life cycle inventory (LCI) and description of the life cycle stages

The elaboration of the LCI for this study is based on two main sources. The first data source, as depicted in previous sections, is the mass and energy balances, resulting from the process modelling in Aspen Plus. This data includes the normalized values (for 1 MJ of jet fuel) for the conversion of the main feedstock into jet fuel and the secondary products (gasoline, diesel and electricity). Seemingly, the data contains information about the different emissions and waste streams generated in the conversion process. The second data source is the inventories of the "Ecoinvent-3" database. The inventories of the system stages depicted in Fig. 2 are detailed in section S.6 of the Supplementary Materials, however, their construction are explained as follows:

Stage 1 of the life cycle in Fig. 2 depicts the production of FR chips, mainly composed of whole tree early thinning's, small roundwood, stem tips and branches. The FR chips are considered as co-products of the timber production process [49,99]. To achieve more complete and reliable mass and energy balances, the life cycle inventory of this stage is taken from Ecoinvent 3.6 [100,101]. The generic sustainable forest management database analyses the production of different wood

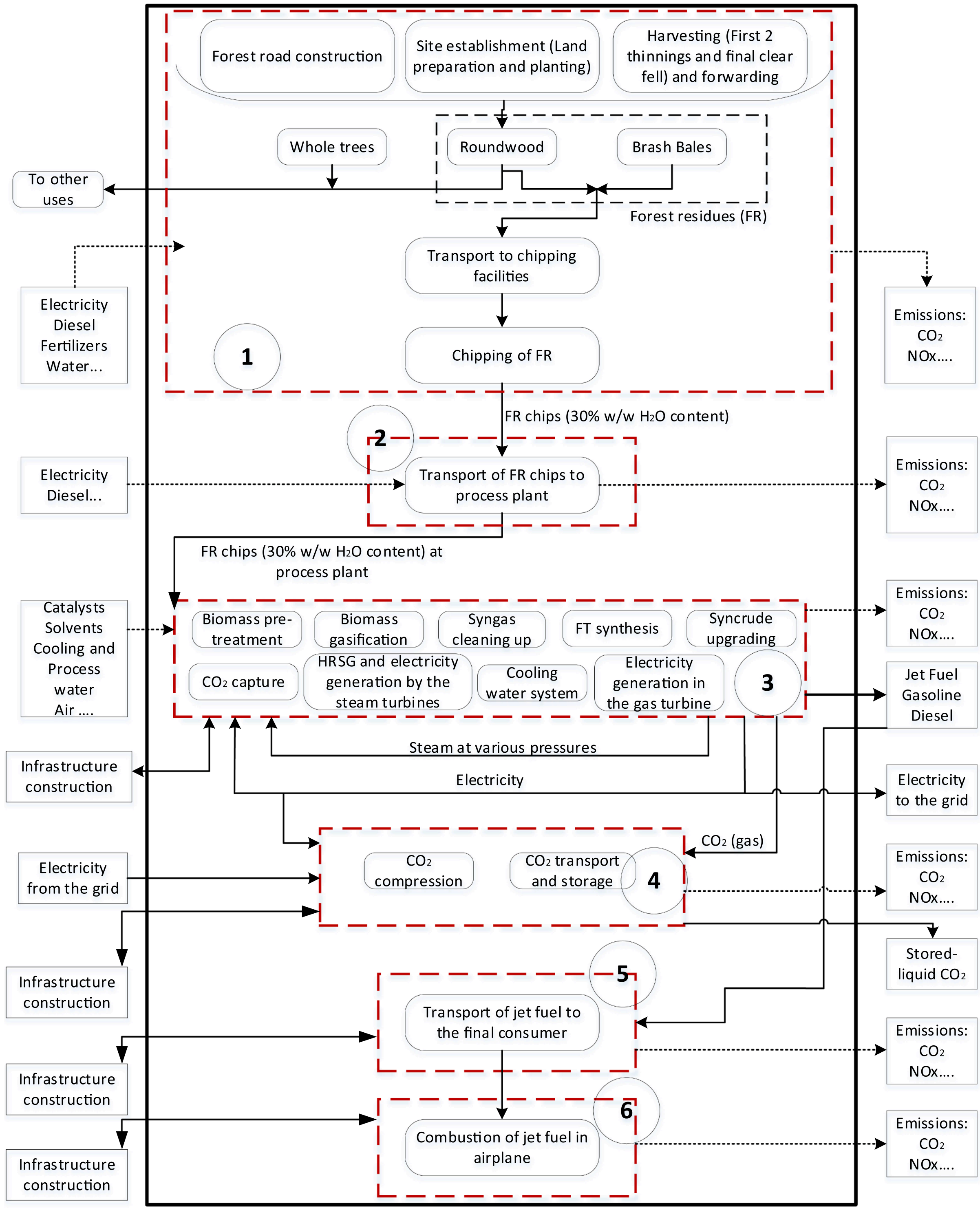


Fig. 2. The System Boundary Diagram for the LCA of the BECCS scenario.

products over one stand's rotation period, including site preparation and all processes associated with forest management such as clearing, tending, pruning, thinnings, harvesting operations, and the maintenance of forest roads [102]. The three produced assortments, which are saw-logs, industrial wood, and wood fuel (which is further processed to chips and cleft timber) are allocated with the environmental load of the aforementioned activities, according to their economic values [100-102]. Ecoinvent offers regional and tree-species adjusted databases since the assortment distribution varies depending on the tree species and the regional markets. For more processed assortments, such as the wood chips, the database "Wood chips, wet, measured as dry mass {RoW}| sustainable forest management | Cut-off, U" is chosen. Apart from including the production of the basic wood assortments, this database also includes the processes for further processing wood fuel into chips. The wood chips production stage ends with their natural drying at the forest road, before transportation to the process plant [102].

It is also important to mention that a fraction of branches and stem tips should remain in the forest site due to sustainability reasons

[49,51,103]. However, there is no existing threshold that determines the FR percentage that should be left on-site in the UK [103]. Therefore, the data presented in the selected Ecoinvent inventory for wood chips is also adopted in this study. The chosen database does not present this information as the amount of FR that are left on-site, instead, it provides the amount of wood assortments harvested per hectare of stand over one rotation period (in accordance with the prevailing principles of sustainable forest management practices in Europe) [102]. As mentioned before, the environmental loads of the stand establishment, management, and harvesting steps are distributed among the wood assortments, therefore, FR left onsite are not attributed with any environmental impact [100-102]. Because the wood chips production databases are elaborated according to the sustainable forest practices of Germany [102,104,105], the assortment distribution and the amount harvested could fail to exactly represent the UK's practices, and the environmental load of the FR chips could be slightly different. For this reason, the GWP of the stage of wood chips production is included in the sensitivity and uncertainty analysis of the LCA.

Finally, in this study, the tree species that give origin to the forest residues were chosen according to the data on wood production presented by the UK's Forestry Commission estimation for 2018 [106]. In agreement with this source, 93.2% of the roundwood comes from stands of softwood while 6.8% comes from hardwood; herein, the same share is considered for the wood chips. Sitka Spruce and Oak are the tree species representing softwood and hardwood respectively, since they represent a higher proportion of the stands found in the UK [107].

Stage 2: The second phase of the life cycle consists of transporting the chips to the process plant by road, since this is the most common mode for the carriage of commodities in the UK [108]. Similarly to stage 1, the transport of forest residues is taken from the database presented by Ecoinvent [109] but slightly modified to fit the conditions of this study. Originally, this database considers that each kg on a dry basis of forest residue chips contain 1.4 kg of H_2O and the transport distance to the processing plant is 50 km. In this study, it is considered that the chips are left in their place of production until their moisture content naturally reduces to 30% (0.43 kg of H_2O for each kg of dry biomass) [99,110]. The average transport distance of the forest residues is considered as 50 km[52]. In addition, if the requirement of the plant could not be satisfied by the regional provision of forest residues, the transport distance is another parameter to consider for the sensitivity analysis.

Stage 3: The third stage of the life cycle begins with the reception of forest residue chips and ends with the final production of fuels and electricity. In this section, the inventory is built from the mass and energy balances resulting from the modelling of the process. However, not all the material inputs are obtained from Aspen Plus and therefore, some rough estimations have been made. The amounts of the catalysts needed for the process are calculated according to the methodology mentioned in the economic analysis section and it is considered that they will be changed every 3 years. There are no life-cycle inventories for the production of the catalysts but they are represented in the inventory by considering the production of the main constituent of the catalyst and therefore, the amount of this material is equal to the total mass of its catalyst. In regards to the operation of the gasifier, the fluidising medium considered is sand and its reposition ratio is taken from a database of wood gasification in a fluidised gasifier found in Ecoinvent [111]. The construction of the process plant is represented by the inventory related to a generic "Chemical factory organics" that can be found in Ecoinvent. For this plant, the capacity is about 50,000 tonnes/year (PC_1) with a lifetime of 50 years. To adjust to the process plant, a six-tenths factor rule was applied (Equation 10) [112] in order to find the fraction of the original Ecoinvent plant (PU_1) that is needed for this process (PU_2), considering the capacity (PC_2) equal to the sum of the gasoline, diesel and jet fuel mass flows and a plant's lifetime of 20 years.

$$PU_2 = PU_1 \left(\frac{PC_2}{PC_1} \right)^{0.6} \tag{10}$$

- **Stage 4** represents the compression of the CO_2 coming from the capture section of stage 3 and its transport & storage. The compression section uses electricity produced by the plant, and for the infrastructure, the compressors are considered by using the inventory for an "Air compressor screw type of 300 kW" available in Ecoinvent [113]. Similarly, to the infrastructure considerations of stage 3, Equation 10 is used to adjust this database according to the energy requirements (instead of capacity) of each compressor.

In regards to the CO_2 transport & storage subsection, the life-cycle inventory is developed as proposed by Wildbolz (Fig. 3) [56]. The inventory of the "Transport infrastructure" considers the construction of the pipeline by considering the materials needed, the construction and land use, the dismantling and disposal at the end of the lifetime of the pipeline, as well as the monitoring of the operating pipeline by helicopter. Wildbolz [56] also considered an overpressure of 30 bar in respect to the place of injection (gas field or aquifer). According to their calculations, the operation of the pipeline considering a distance of 200 km does not need a recompression station since the CO_2 stream arriving at the injection point meet the overpressure requirement. Therefore, the inventory of the operation section only considers the infrastructure construction and the leakage being 0.026% per 1000 km. Another important section is the "Deep Drilling and Well infrastructure". Wildbolz [56] considers the establishment of a double well with the option of occupying an aquifer or a depleted gas field. In the UK, saline aquifers have the highest storage option, but the understanding of their properties is highly uncertain, thus, gas fields are preferred [114]. Fig. 3 depicts the life cycle of the stored CO_2:

Stage 5: This stage encompasses all the processes related to the transport of the fuel from the process plant to the final user and is represented by the database for "Market for kerosene" in Ecoinvent [115]. This database includes the transportation of the fuel, the operation of the storage tanks and the emissions due to the evaporation and treatment of the effluents.

Stage 6: The last stage of the life cycle is the use of jet fuel in the airplane. The emissions from the combustion of SAF are taken from the database of Ecoinvent for medium-haul aircraft for passengers, without considering the incurred environmental impact of the aircraft and airport construction. This assumption is considered valid since the chemical properties of SAF are close to jet fuel [32]. In this stage, it is also important to mention that the carbon neutrality [116] of CO_2 emissions from combustion of SAF is assumed, which means that biogenic CO_2 emissions are considered to be zero.

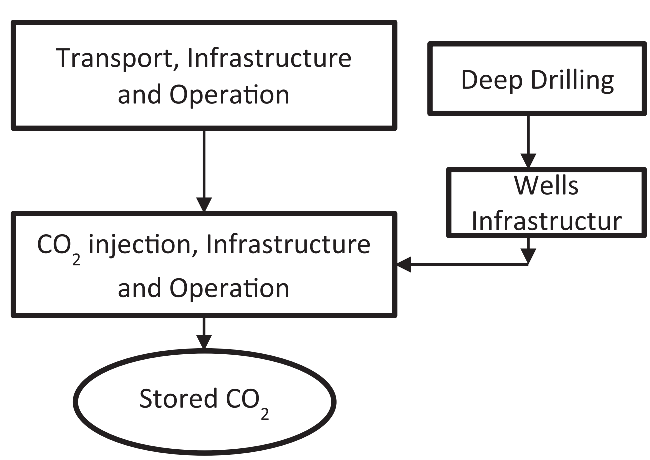


Fig. 3. Scheme of the transport and storage chain [56].

3.3.4. Multi-functionality

When multiple products and by-products are produced within the studied system, the attribution of energy and environmental impacts between products and co-products is done through allocation or substitution methods. The choice of attribution procedure is challenging as each method leads to results with significant differences [34]. The allocation method assigns emissions to products according to their flow properties, such as the content of carbon, energy, mass, or according to the economic value [117]. The SAF and the by-products of the process plant are all used for energy purposes, therefore, the energy allocation is the main method to be considered in this assessment [34,36]. Even though the associated uncertainty, the system expansion or substitution method is also recommended since it considers the environmental impacts of the displaced by-products [34]. In this sense, also this method is applied herein in order to determine the effect of the choice of the attribution methodology on this environmental assessment.

3.3.5. Impact assessment

The ReCiPe impact assessment methodology has been utilised in this study. This ReCiPe method calculates 18 midpoint indicators and 3 endpoint indicators. The main difference between the midpoint and endpoint indicators is that the former ones focus on single environmental problems, while the others show these impacts at three aggregation levels: 1) effect on human health, 2) biodiversity and 3) resource scarcity. The use of endpoint impact assessment makes the interpretation of the LCA more simple, but increases the uncertainty of the results. Also, the midpoint approach provides more insights on the emissions breakdown at each stage of the jet fuel production line. Therefore, for this study, the chosen impact assessment is the "Recipe 2016 midpoint (H)", which is used to determine the GWP of the BECCS, BE and fossil jet fuel scenarios for a 100-years' time horizon.

The benefit of using the BECCS concept in a process design is the potential of achieving negative emissions. The negative emissions claimed by the BECCS scenario need to be demonstrated and supported by a LCA. Conventional LCA of systems with biogenic inputs considers that the consumed atmospheric CO_2 is released at the end of the product's life cycle [118]. Therefore, the LCA impact methods assign a Global Warming Potential (GWP) of zero to biogenic CO_2 emissions. Time plays an important role in the definition of "negative emissions", since CO_2 removed from the atmosphere and the biosphere to storage, is transferred from a short-term cycle to a long-term pool (geological) [119]. According to the 2006 IPCC Guidelines, the calculation and report of the emissions associated with CCS in the energy of industrial sector do not consider any particular difference between CO_2 from fossil or biogenic sources. In this sense, the emissions of the processes using biomass will be zero, while the captured biogenic CO_2 will be subtracted resulting in negative emissions. Emissions from transport, injection and storage of CO_2 are accounted regardless of its fossil or biogenic origin [120].

3.4. Sensitivity analysis

The sensitivity analysis, which has been performed for both, the economic and the life cycle assessment, is of the type of "scenario analysis". The main goal is to provide an insight view on how the economic or environmental outputs are affected by the change of important parameters that are varied one at a time within reasonable and realistic ranges. Therefore, the results of these optional scenarios can be compared with those of the baseline scenario (BECCS scenario).

3.4.1. Sensitivity analysis on the MJSP

The parameters associated with high uncertainty are varied as indicated in Table 6 for the BECCS scenario. The CAPEX is changed between a low and a high value of −30% and + 50%, according to the recommendations of the classification of the AACE International, for plants of low level of maturity as the case of a biomass to liquid fuels process plant [121]. The feedstock price is changed by ± 50% with respect to the nominal value, in order to reflect the market volatility and uncertainties related to the commercialization logistics of the forest residues [64]. Different values for important economic parameters such as tax and discount rates are also analysed. The discount rate is associated with the risk of investing in a particular project. An optimistic value of 8% is proposed for biorefinery investments [122], whereas the pessimistic discount rate is proposed as 12%. The tax rate optimistic value is set at 0%, to reflect a scenario in which the biorefinery may be eligible for tax exemptions, while the higher value is set at 40%.

Table 6
Parameters for the sensitivity analysis.

Parameter	Low Value	Nominal	High value	Unit
CAPEX	130.38	186.25	279.38	MM £
Feedstock cost	29.26	58.53	87.79	£/t
CCS cost	13.38	24.38	36.38	£/t CO_2
tax rate	0	30	40	%
Discount rate	8	10	12	%

Regarding the CO_2 transportation and storage, the low and high sensitivity costs of 8 and 31 £/t CO_2 have been retrieved from the literature [123]. For a better interpretation, these values are adjusted in order to include the cost of the CO_2 compression. The cost of the CCS is then obtained by adding the cost of the T&S and the annualised CAPEX of the compressors (see Equation 11 [64], where i_d is the internal rate of return and n the lifetime of the plant); it should be noted that the electricity for the CO_2 compression is generated on-site and as such it is not included in the CCS cost of the compression section and the respective energy penalty is captured in the electricity exported to the grid. The bounds of the investigated variables are presented in Table 6.

$$ACAPEX = CAPEX \bullet \frac{i_d \bullet (1+i_d)^n}{-1+(1+i_d)^n} \quad (14)$$

3.4.2. Sensitivity analysis on the GWP

A sensitivity analysis has been also conducted for the LCA results to identify the process sections with the greater influence on the GWP of the BECCS scenario. When uncertainty data is not available for life-cycle stages, reasonable ranges have been chosen (see Table 7).

The share of the jet fuel could be slightly different, due to different process conditions and the uncertainty around them, as for example in the product distribution of the hydrocracker. Therefore, a deviation of ± 10% is considered. According to the proposed plant location, the transport distance for the FR chips is 50 km. However, in case that the required feedstock could not be supplied by the surrounding forests, the possibility of getting it from the northern region of Scotland (travel distance of about 150 km) is also analysed [52]. The chances of developing FT catalyst more resistant to inert gases and/or increasing the efficiency of the CO_2 capturing plant is also examined by changing the amount of CO_2 that could be separated from the syngas and subsequently stored. Finally, concerning the other parameters of the Table 7, as explained in the LCA section, they are associated with some level of

Table 7
Variables used for the sensitivity and uncertainty analyses.

	Nominal Value	Units	Variation (%)
Share Jet Fuel (Energy basis)	58.35	%	±10
FR Chips production	6.04	gCO_2e/MJ	±30
Transport FR Chips	1.30	SAF	−30, +200
Biorefinery	3.40		±30
CO_2 compression-T&S (operation + infrastructure)	0.22		±10
CO_2 stored	90	%	−15, +5 *
SAF distribution	0.69	gCO_2e/MJ	±30
SAF combustion	4.36	SAF	±10

*percentage points.

uncertainty, since their inventories were adapted from existing databases for similar processes and different geographic locations. Therefore, their GWP are also varied by ± 30% and ±10%, depending on whether this uncertainty is high or moderate.

3.4.3. Monte Carlo uncertainty analysis

Understanding the effect of varying the uncertain parameters at the same time is important; therefore, a stochastic or uncertainty analysis has been performed. The sensitivity analysis varies one at a time each parameter, whereas, the interaction of varying them simultaneously requires a statistical method, such as the well-known Monte Carlo analysis. This analysis has been considered for the same LCA uncertain parameters that are presented in Table 7. It was assumed that all of them follow a triangular distribution. A Monte Carlo analysis is performed in Matlab, where a code randomly varies these parameters and recalculates the GWP of the system in 10,000 trials. The results are presented as a histogram of frequency, for which the mean value is calculated as well as the standard deviation; finally, it is possible to determine the 95% confidence interval.

4. Results and discussions

This section reports in details the TEA and LCA results. Firstly, the technical parameters in conjunction with the mass and energy balances are presented. Subsequently, the economic and environmental performance indicators are calculated for the following scenarios: I) the base case or BECCS process; II) the BE scenario. Finally, a sensitivity analysis determines the impact of different parameters on the economic and environmental results of the BECCS scenario, as well as the effect of the plant capacity (economies of scale). In addition, the effect of existing and suggested policy schemes on the feasibility of the SAF produced through the BECCS scenario is investigated.

4.1. Process modelling

4.1.1. Gasification and pyrolysis section

The predicted composition of the syngas obtained through the modelling methodology described for the gasifier and pyrolysis sections is presented and compared with the experimental data, found in a report of E4Tech [124], in Table 8. From these results, it can be inferred that there is a good agreement between the results obtained from the model and the pilot plant outputs [124], especially concerning the major components of the syngas (H_2, CO, CO_2 and CH_4).

4.1.2. Carbon distribution

The mass and energy balances of the process have been obtained and they are presented in detail in the section S.2 of the Supplementary materials. Based on the ultimate analysis of the feedstock, and the resulting mass balances of both processes, it is possible to calculate the carbon efficiency. The input of 20 dry-tonnes/h of forest residues will result in the production of 0.31 tonnes/h of gasoline, 1.91 tonnes/h of jet fuel, and 0.93 tonnes/h of diesel, for both scenarios. In reference to the BECCS scenario, carbon is lost as CO_2 at different points of the plant, but mainly in the combustion of char at the gasifier (12.32 tonnes/h of CO_2), and in the gas turbine (3.68 tonnes/h of CO_2). In addition, CO_2 is separated from the syngas in the CO_2 capture section and is stored underground (11.26 tonnes/h of CO_2). Therefore, as depicted in Fig. 4, the carbon balance indicates that 26.26 % of the carbon is found in the products, 43.24% is wasted in the flue gases, and 30.50% is captured and permanently stored. Hence, according to Equation 1, the carbon efficiency of the BECCS scenario is equal to 26.26%. The resulting carbon balance of the BE scenario is only different to the baseline scenario only regarding the stored CO_2, which is now included in the share of the flue gases. Hence, the carbon efficiency is equal to the BECCS case. Therefore, the carbon efficiency is not affected by the addition of the CCS.

The results of both scenarios are in agreement with Swanson et al. [20] who obtained a carbon efficiency of 26.26% for a low temperature gasifier + FT scenario, and they are slightly different to Marchese et al. [77], i.e. 32%, and Hillestad et al., i.e. 38% [125]; but they have considered either different process configuration [77] or gasification technology [125]. According to Equation (3), the jet fuel mass yield of both scenarios equal 9.6%, agreeing with the 9.7% value obtained by Atsonios et al. [22], while the total fuel mass yield (Equation (2)) is equal to 0.16, which properly falls in the range of 0.13–0.22 determined by de Jong et al. [78].

4.1.3. Energy performance of the process

In terms of energy balance, both cases have been designed to be energy-autonomous, by fixing at 15% the amount of unreacted syngas burnt in the gas turbine. The basis for the design was the BECCS scenario, as it requires additional electricity to compress the captured CO_2. This parameter has been also adopted for the BE, which resulted in higher production of excess electricity. Table 9 presents a detail of the power interactions among the plant for both cases. The major consumer of electricity is the syngas compressor due to the difference in operating pressures between the gasifier and the FT reactors, which work at atmospheric and 25 bar respectively. This huge differential pressure could be avoided by using a gasifier that can operate at higher pressures [20]; however, the drawback of this kind of gasifiers, such as the entrained flow gasifiers, is that more power is required to chop the biomass in fine particles, the high capital cost as well as the low H_2 content in the syngas [98].

Table 10 presents a summary of the use and production of steam at different pressures, as well as the amounts that are sent to the steam turbines for power generation for both scenarios. The process streams, from which heat cannot be recovered for steam generation, are cooled down with cooling water; the consumption of which is also reported in Table 10. From the data presented, it can be seen that the CCS section does not affect the steam requirements of the process as the CO_2 capture unit is an integral part of both scenarios. The cooling water requirements are minimally increased for the BECCS case.

The jet fuel efficiency of the process is calculated as 22.1% for the production of jet fuel (in BECCS and BE scenarios), considering a LHV of 42.8 MJ/kg for the jet fuel [10], and a value of 12.95 MJ/kg for the biomass as received (moisture content equal to 30%). Based on the results of the process modelling, the overall energy efficiency is calculated through Equation 6, by taking into account the energy in all the products, such as gasoline, diesel, jet fuel and electricity, as well as the input energy of the forest residues. The overall energy efficiency equals 37.9% and 38.9% for the BECCS and BE scenarios respectively. The efficiency of the BE scenario compares well to the ones obtained in other similar studies [23,126] and as expected, its overall energy efficiency is higher than in the baseline scenario, due to the higher amount of electricity produced (or equally the more electricity consumed in the BECCS case). Therefore, the CCS section does not compromise the energy efficiency of the process, since the energy penalty is only 2.57%; a value similar to the one reported in IEA [27].

Table 8
Modelling results of the DFBG compared to experimental data [124].

Composition (dry basis)	Experimental [124]	This model
H_2	41.50%	33.35%
CO	22.50%	24.07%
CO_2	21.50%	23.56%
CH_4	10.50%	12.69%
C_2H_4	2.50%	3.74%
C_2H_6	0.50%	0.09%
C_6H_6	8.00 g/Nm^3	18.66 g/Nm^3
C_7H_8	0.50 g/Nm^3	3.00 g/Nm^3
$C_{10}H_8$	2.00 g/Nm^3	3.40 g/Nm^3

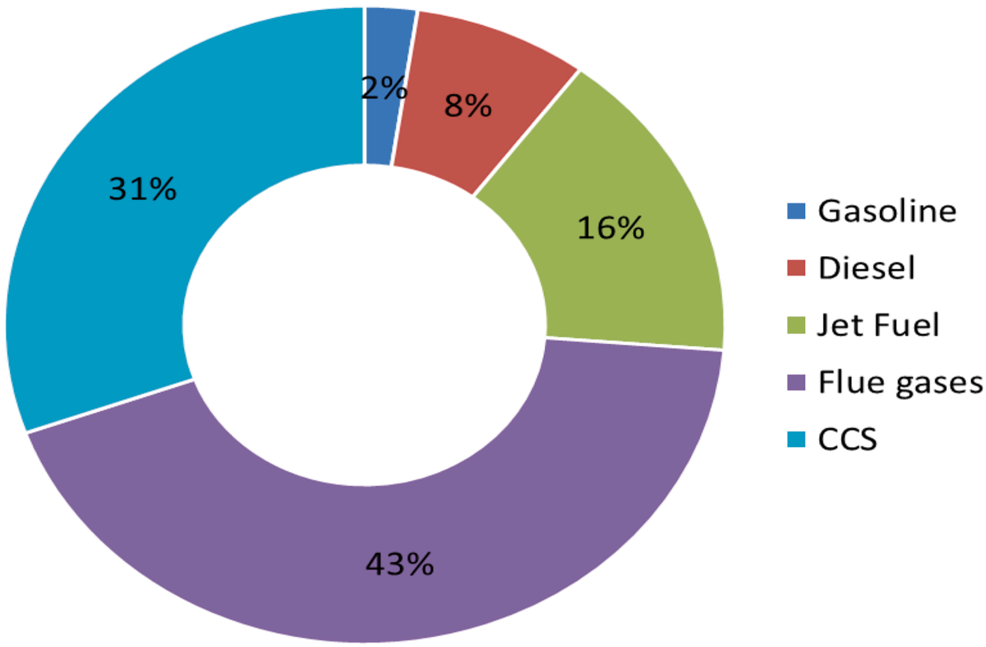


Fig. 4. Biomass carbon distribution for the BECCS scenario.

Table 9
Breakdown of power generation and usage.

Power (MW)	BECCS scenario	BE scenario
Total Generation	10.39	10.39
Gas Turbine	5.36	5.36
Steam Turbines	5.02	5.02
Total Usage	8.93	7.93
Grinder	0.43	0.43
Syngas compressor	5.74	5.74
Amine pump	0.12	0.12
CO_2 compression	1.00	0.00
PSA compressor	0.033	0.033
Wax compressor	0.006	0.006
Recirculated syngas ....compressor	0.027	0.027
ASU + O_2 compressor	1.57	1.57
Net Export	1.46	2.46

4.2. Economic evaluation

The mass and energy balances are the basis for the economic evaluation since they provide the necessary information for sizing the equipment. Table 11 presents the breakdown of the purchased equipment cost according to the main areas of the process plant, for the BECCS and BE scenarios. The total amount of PEC does not have a significant change between both scenarios. In both cases the PEC expenses are dominated by the Biomass Pretreatment + Gasification and the FT synthesis section while the cost of the CO_2 compressors for is relatively small and does not have a significant impact on the total PEC.

Table 11 also presents the FCI and CAPEX for both scenarios. The obtained results are of the same order of magnitude as in previous studies that evaluated the economic performance of biofuels production through the FT technology [25,26,127,128]. The incorporation of the CO_2 compression section for the BECCS case increases the CAPEX only by around 2%. Similar differences have been also reported in the literature [27,48]; even if these studies are not oriented to the production of jet fuel, they may serve as a reference to validate the results.

Table 11
Results for Purchased Equipment Cost, Fixed Capital Investment and Total Capital Requirement.

	Cost [MM £]	
	BECCS Scenario	BE Scenario
Biomass Pre-treatment + gasification	12.37 (21.66%)	12.37 (22.09%)
Syngas cleaning up	4.29 (7.51%)	4.29 (7.66%)
CO_2 capture	0.69 (1.21%)	0.69 (1.23%)
Fischer-Tropsch synthesis	28.15 (49.29%)	28.15 (50.28%)
Syncrude upgrading	5.50 (9.63%)	5.50 (9.82%)
CO_2 compression	1.12 (1.96%)	–
HRSG + Gas turbine + Cooling Tower	4.99 (8.74%)	4.99 (8.91%)
PEC	**57.11**	**55.99**
Fixed Capital Investment (FCI)	**173.91**	**170.50**
Total Capital Requirement (TCR) or CAPEX	**186.25**	**182.60**

Table 10
Steam generation & utilization and cooling water requirements.

Steam generation and utilization for the BECCS and BE scenarios				
Steam [tonnes/h]	Generation	Consumption in process	Use in distillation columns	To steam turbines
Superheated steam; 500 °C; 40 bar	16.33	12.85	1.65	1.83
High pressure steam; 210 °C; 20 bar	23.98	0.00	0.00	25.81
Medium pressure steam;177 °C;9bar	21.35	0.00	0.00	47.16
Low pressure steam; 135 °C; 3 bar	15.27	0.00	15.27	0.00
Cooling water requirement [tonnes/h]				
BECCS scenario			1733.21	
BE scenario			1683.89	

Yearly operating costs or OPEX are presented as £/kg of SAF in Fig. 5. Among these incurred expenses, the major contributor to the OPEX is the cost of the feedstock (forest residues). Similar results have been found by Tijmensen et al. [19] where the cost of the biomass accounts for at least 30% of the total production cost. Therefore, an increase or decrease in the FR cost could highly influence the value of the MJSP of the BECCS scenario; this is further analysed in the sensitivity analysis section. When comparing both scenarios, the higher OPEX of the BECCS scenario is justified by the cost of CO_2 T&S.

Finally, a break-even analysis has been developed and by using a DCFA the MJSP has been calculated. The DCFA estimated MJSP of 3.27 £/kg and 3.03 £/kg, for the BECCS and the BE scenarios respectively. The inclusion of the CCS supply chain increased the MJSPs by 7.92%; this figure is in agreement with the results of a previous study available for BECCS, in which the price of the syncrude increases by 10% with the addition of the CCS section [27].

4.2.1. Sensitivity analysis on the MJSP

Results from the sensitivity analysis for the alternative scenarios proposed are presented in Fig. 6. The MJSP is primarily sensitive to CAPEX. If the gasification and FT technologies continue developing, in the upcoming years, equipment prices would drop, which in turn could help improve the economic feasibility of the SAF. In addition, the MJSP exhibits great sensitivity to the feedstock prices; in order to limit volatilities in the feedstock price longstanding procurement deals at ideally fixed costs with forest management corporations are necessary. It is also apparent that the CCS does not have a significant impact on the MJSP and hence future implementations in biorefineries come at relatively low cost and risk. Finally, the discount rate and the tax rate have moderate influence on the MJSP.

4.2.2. Effect of the economies of scale

The effect of economies of scale has been also analysed for the BECCS scenario. The CAPEX of the plant is not linearly related to the capacity; therefore, an overall scaling factor of 0.65 was used for upgrading CAPEX [64]. The OPEX (apart from labour) have been assumed proportional to the size of the plant and hence the product yields, waste streams and utilities have been linearly adjusted to the capacity of the plant. In particular, the labour cost has been recalculated for each case by using Equation 9. Fig. 7 shows the MJSP as a function of the plant capacity. The slope for plant's capacities between 20 and 100 dry-tonnes/h is quite steep, and this results in a significant decrease of the MJSP, i.e. 2.16 £/kg. For a plant size beyond 100 dry-tonnes/h, the MJSP continues to drop but at a slower rate. On the other hand, the increase in the size of the plant implies the need for more feedstock, which availability is limited in the UK. As reported by E4tech [52], 0.8 dry-Mtonnes/year of forest residues are produced in Scotland, where the biorefinery is assumed to be located, meaning that all the available feedstock should be used in a plant treating 100 dry-tonnes/h. This, in turn, will most probably not be a realistic scenario since there exist competing sectors such as CHP.

4.3. Life cycle assessment

The inventory of the BECCS and BE scenarios have been developed based on the mass and energy balances, that have been first normalized on a basis of 1 MJ of jet fuel along with the databases of Ecoinvent 3. In addition, the the ReCiPe 2016 Midpoint (H) impact assessment method

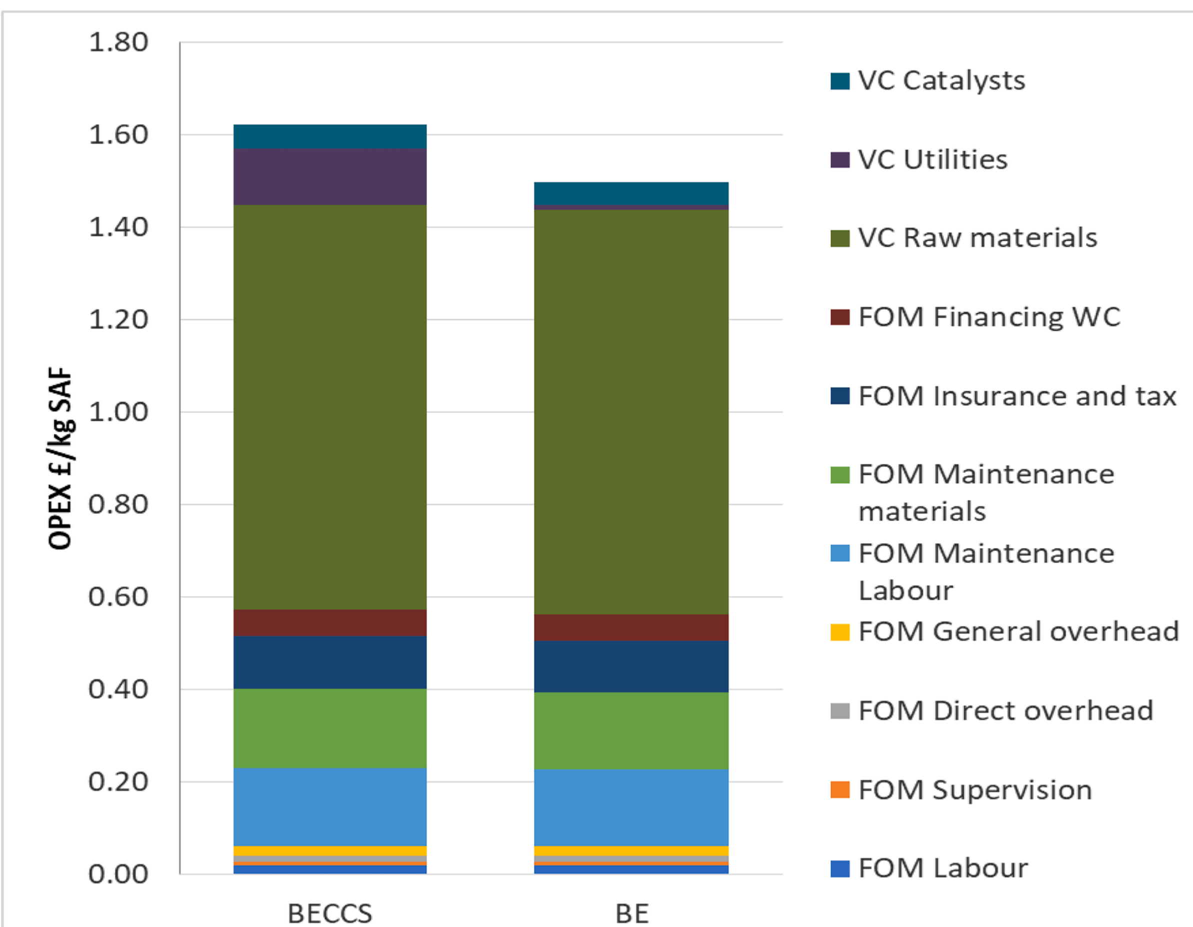


Fig. 5. Normalized OPEX for the BECSS and BE scenarios.

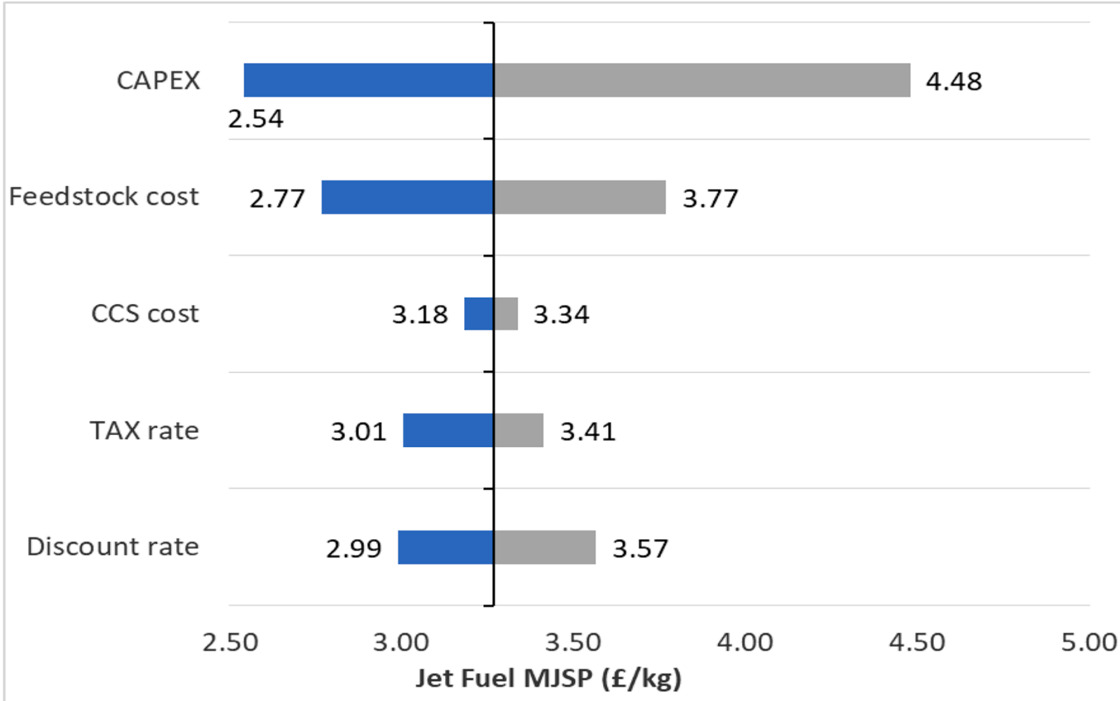


Fig. 6. Effect of the governing parameters on the MJSP.

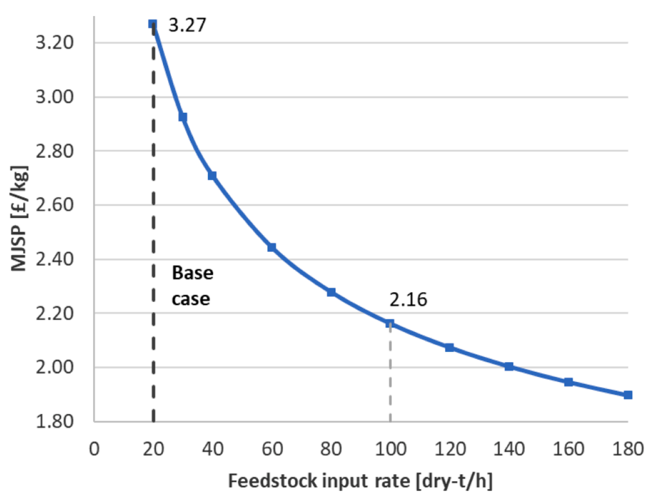


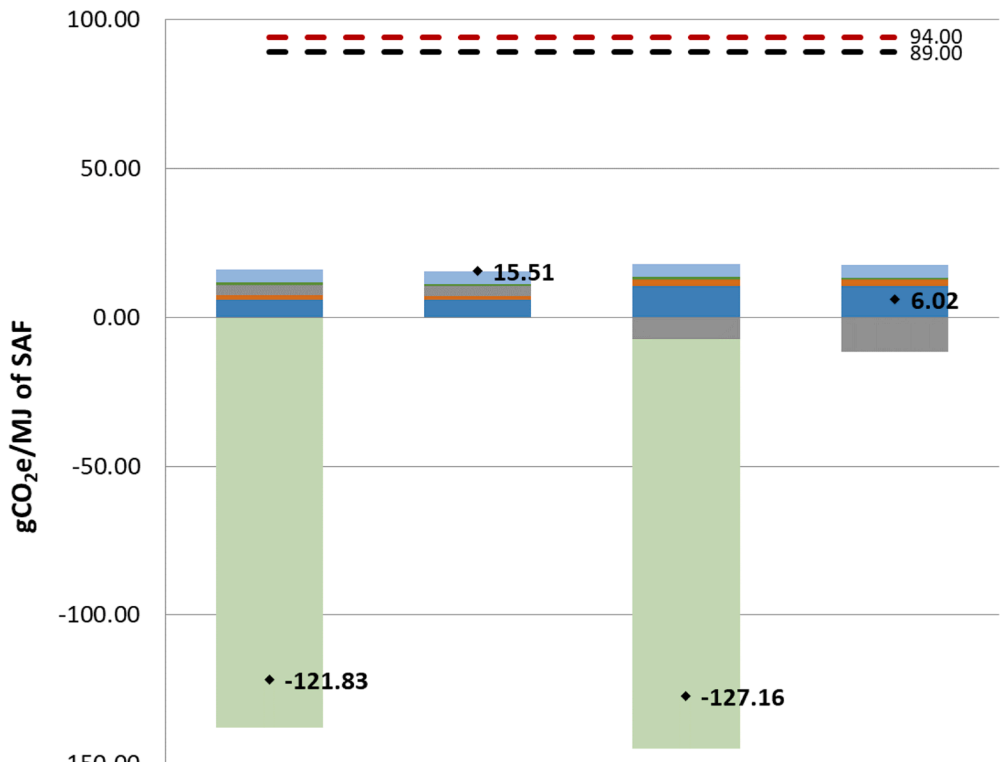
Fig. 7. Effect of the size of the plant on the MJSP.

has been used. Fig. 8 presents the results for the GWP (100) for both scenarios at the different life cycle stages (as depicted in Fig. 2). When the multi-functionality is treated with an Energy Allocation approach, the WtWa results of the GHG emissions for the BECCS and BE, are –121.83 gCO_2eq/MJ and 15.51 gCO_2eq/MJ, respectively, while the system expansion method yields −127.16 gCO_2eq/MJ and 6.02 gCO_2eq/MJ, respectively. In both cases, it can be noticed that the stages that contribute the most to the total GHG emissions are the production of forest residues as well as their transport to the process plant. Regardless the multifunctionality method used, the GWP of the BECCS scenario is negative, due to the characterization factor of −1 for the biogenic CO_2 that is stored. The results for the GWP of the BE scenario (for both multifunctionality methods) are positive, and although it could not approach a net-zero scenario, it still achieves a considerable reduction in emissions when compared to the fossil jet fuel.

The results of the GHG emissions for both scenarios are compared against the carbon intensity of conventional jet fuel. Previous studies considered a reference value for the average WtWa GHG emissions equal to 87.50 g CO_2eq/MJ [32,129]. However, as the GWP depends on several factors, the carbon intensity of fossil aviation fuel varies according to different regulations,such as 89 gCO_2eq/MJ or 94 gCO_2eq/MJ, for the U.S. Renewable Fuels Standard (RFS) [130] and the European Renewable Energy Directive II [131], respectively. Compared to these values, and in accordance with the sustainability criteria thresholds used for the aforementioned standards (70% of GHG savings for the RED II [131] and a minimum of 50% for the U.S. RFS [132]) the BECCS scenario is way below the GHG emissions reduction targets, while the BE scenario only marginally .

Because of the absence of any study analysing the SAF production within BECCS, the results of both scenarios are compared against FT studies without CCS. In this sense, the GWP for the BE scenario is comparable with similar studies, since its value falls within the range of −1.60 and 18.20 CO_2eq/MJ determined by Wei et al. [25], while it is slightly higher than the value of 6 CO_2eq/MJ determined by de Jong et al. [32]. The low WtWa GHG emissions were explained by de Jong et al. [32] as the result of the self-sufficiency of the process in terms of energy and excess electricity production. In relation to the multi-functionality approach, de Jong et al. [32] found that the system expansion method tends to calculate lower WtWa GHG emissions when the substituted co-products have higher emission intensities than those of the system. This last statement has been also verified in the present work, since the emissions of the substituted fossil gasoline, diesel and electricity are greater than the carbon intensity of the studied system. Therefore, the fact that the displacement method estimates lower GHG emissions than those of the energy allocation method, and as recommended by other authors [32,36,133], the results of the energy allocation method are preferred and used for further analyses.

Further, Section S.7 of the Supplementary material provides information of the other environmental impact categories calculated by Recipe 2016 Midpoint (H). The fossil jet fuel environmental impacts are taken from the database provided by Ecoinvent3 and compared against the results of the BECCS and BE scenarios analysed by the energy allocation approach.



	BECCS	BE	BECCS	BE
	Energy Allocation		System Expansion	
Jet fuel combustion	4.35	4.35	4.35	4.35
Jet fuel distribution	0.69	0.69	0.69	0.69
CCS (includes operation and infrastructure of compression, T&S)	0.22	0.00	0.22	0.00
CO2 stored	-137.83	0.00	-137.83	0.00
Biorefinery	3.40	3.31	-7.17	-11.60
Transport of wood chips	1.29	1.26	2.22	2.22
Wood chips production from forest residues	6.04	5.89	10.36	10.36
Total GHG emissions	-121.83	15.51	-127.16	6.02
Fossil jet fuel (U.S. Renewable Fuels Standard)	89.00	89.00	89.00	89.00
Fossil jet fuel (European Renewable Energy Directive II)	94.00	94.00	94.00	94.00

Fig. 8. Global Warming impact for the BECCS and BE scenarios for displacement and energy allocation. The fossil jet fuel GWP is shown for comparisons.

4.3.1. Sensitivity analysis and uncertainty analysis

A parametric analysis has been conducted by varying the values of the carbon footprint of each life-cycle stage, as presented in Table 7. The ranges of variation for each variable have been roughly defined, either according to the evidence found in the literature or on reasonable assumptions.

As depicted in Fig. 9, the GWP of the system is very sensitive to the amount of CO_2 that is captured and stored. A 5% increase in the capture capacity of CO_2 has a positive impact on the total emissions of the plant and the GWP diminishes to −129.29 gCO_2e/MJ. On the other hand, a decrease of the capture level by 15% is translated to a higher GWP of −100.50 gCO_2e/MJ. The fact that even in the extreme negative case the GWP value is highly negative, it highlights the importance of storing permanently the captured CO_2 and provides certainty on the sustainability of FT-biofuels production. In addition, the FR chips production and their transport to the process plant cause relatively significant fluctuations in the GWP of the process. Therefore, ensuring short distance transport for the feedstock is of high importance for the sustainability of the system. Finally, the other process stages appear to have a negligible effect on the GWP.

4.3.2. Monte Carlo analysis

The obtained results for the uncertainty analysis of the BECCS scenario are reflected in the form of histogram in Fig. 10. The mean value and the GWP's obtained from the simulations is equal to −118.93 gCO_2e/MJ of SAF with a standard deviation of 6.17 gCO_2e/MJ of SAF. In addition, the project has 95% interval for the GWP to be between −131.26 and −106.60 gCO_2e/MJ. Hence, the Monte Carlo simulations

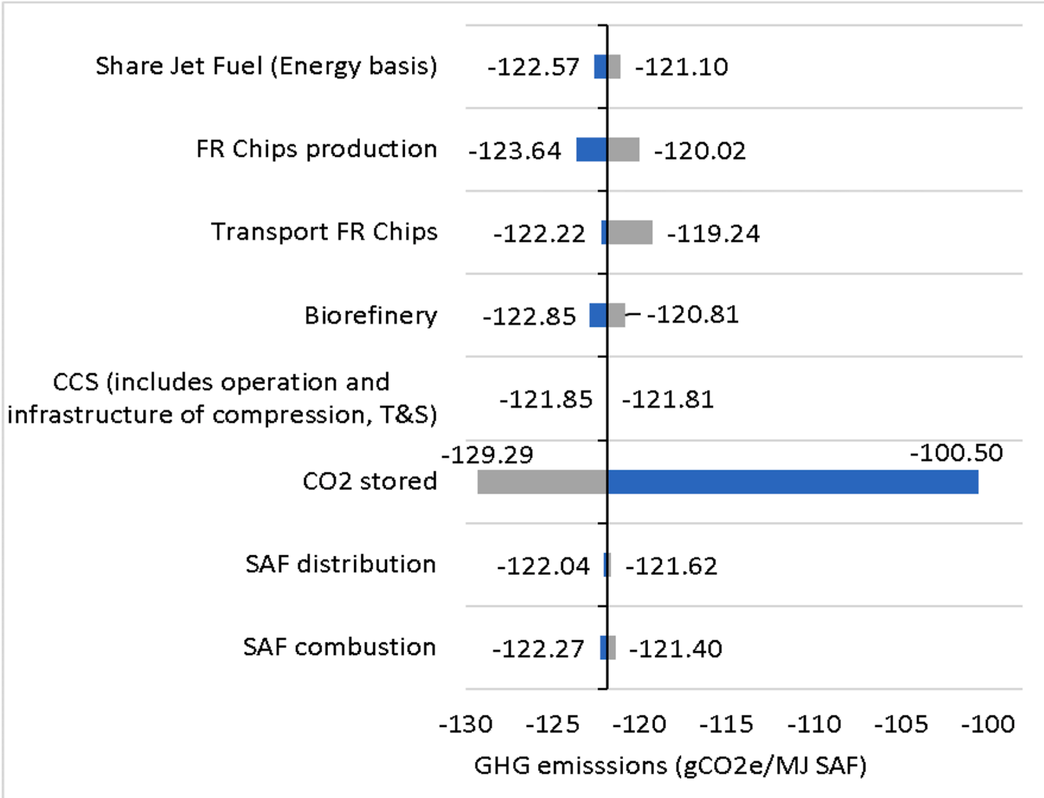


Fig. 9. Sensibility analysis on the Global Warming Potential.

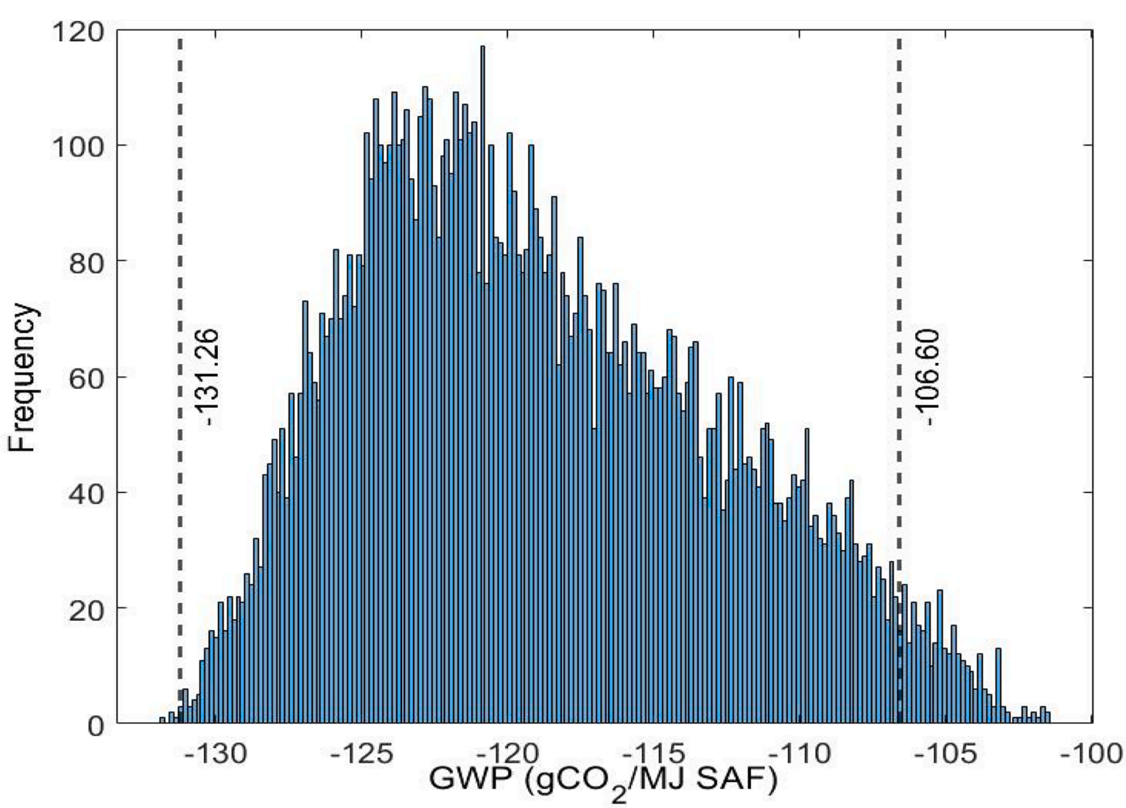


Fig. 10. Uncertainty analysis on the GWP for the BECCS scenario.

revealed that, despite the uncertainty of several parameters, proposed BECCS refinery would most problem achieve highly negative emissions in most cases.

5. Policy incentives assessment

This section intends to analyse the effect of existing renewable and potential, that would incentivise negative emissions, support schemes. Therefore, herein the effect of the Renewable Fuel Transport Obligation (RTFO) and the carbon price have been analysed.

The RTFO is a policy of the UK Government that intends to reduce GHG emissions in the transport sector by supporting the production and use of renewable fuels, while imposing an economic obligation to fossil fuel producers. Suppliers that produce more than 450,000 L per year are affected and should pay an amount of 0.50 to 0.80 £ per litre of fossil fuel supplied. On the other hand, this scheme rewards suppliers of sustainable renewable fuels, by granting them one Renewable Transport Fuel Certificates (RTFCs) per each litre of fuel produced. If the feedstock for the production of these renewable fuels are wastes or residues, dedicated energy crops, and/or material of non-biological origin, suppliers are awarded two RTFCs per litre delivered [134].

Concerning the aviation sector, fossil jet fuel does not have an obligation. However, producers of SAF are rewarded by certificates under the same criteria applied to road-mobile and NRMM [134]. Further, we consider herein the effect of receiving both single and double (as the feedstock is residue from sustainable forest management) certificates on the economic performance of the process. Since RTFCs can be traded among fuel suppliers [134], it is necessary to determine a price for the certificates in the market. Nevertheless, it is not easy to assign a price to the RTFCs because there is no data published by the government. In the market, an average peak price of 0.30 £/RTFC is provided; however, the prices used for the trading vary from 0.09 to 0.20 £/certificate [135]. As an example, if a price of 0.20 £/certificate is used SAF prices drop from 3.27 £/kg to 3.01 £/kg and 2.76 £/kg when one or two certificates are awarded respectively.

Another support action considered in this study is the price of CO_2, which is a decisive element for the feasibility of CCS projects in the coming years. Theoretically, the CO_2 price may have a double effect on the feasibility of this type of project, since not only additional revenues will be received by the storage of CO_2, but at the same time, the price of conventional jet fuel will be increased. As an example, Fig. 11 presents the effect of the CO_2 price with and without the effect of the RTFCs, over the MJSP. On considering a CO_2 price of 303.70 £/tonne CO_2, an emission factor of 5.21 kg CO_2/kg for the BECCS-derived SAF (according to the LCA results of −121.83 gCO_{2eq}/MJ), a conventional jet fuel gate price of 0.56 £/kg [136] and an emission factor of the conventional jet fuel of 3.74 kg CO_2/kg (87.5 gCO_{2eq}/MJ) [137], the MJSP of the SAF breaks even the price of the conventional jet fuel at a value of 1.70 £/kg. While, considering both, the CO_2 policy and the RTFCs at a price of 0.20 £/certificate, the MJSP breaks-even the price of the fossil jet fuel at a value of 1.60 and 1.49£/kg, at a CO_2 price of 275.17 and 246.64 £/tCO_2, for a single and double assignation of certificates per kg of SAF produced, respectively.

Since the cost of the RTFCs does not have a defined value, as it fluctuates in the market, Fig. 12 depicts the variation of the MJSP when double certificates are assigned per kg of SAF at different certificates and CO_2 prices. The first thing to notice is that the higher the price of the RTFCs and CO_2, the lower is the value of the MJSP. Similarly, the break-even line indicates that the cost of the SAF could only equal the price of the conventional jet fuel at a range of CO_2 prices between 189.60 and 303.70 £/tonne CO_2, in the price range of the RTFC's between 0 and 0.40 £/certificate. Therefore, the economic feasibility of sustainable fuels has a huge dependence on the incentive policies proposed by the government, which plays the main role for attaining the goal of decarbonizing the country by 2050.

6. Conclusions

This study has investigated the effect of incorporating CCS on a biorefinery that aims to produce jet fuel from forest residues. The biomass processing capacity of the plant is based on the estimated availability of forest residues in the United Kingdom. The purpose of the

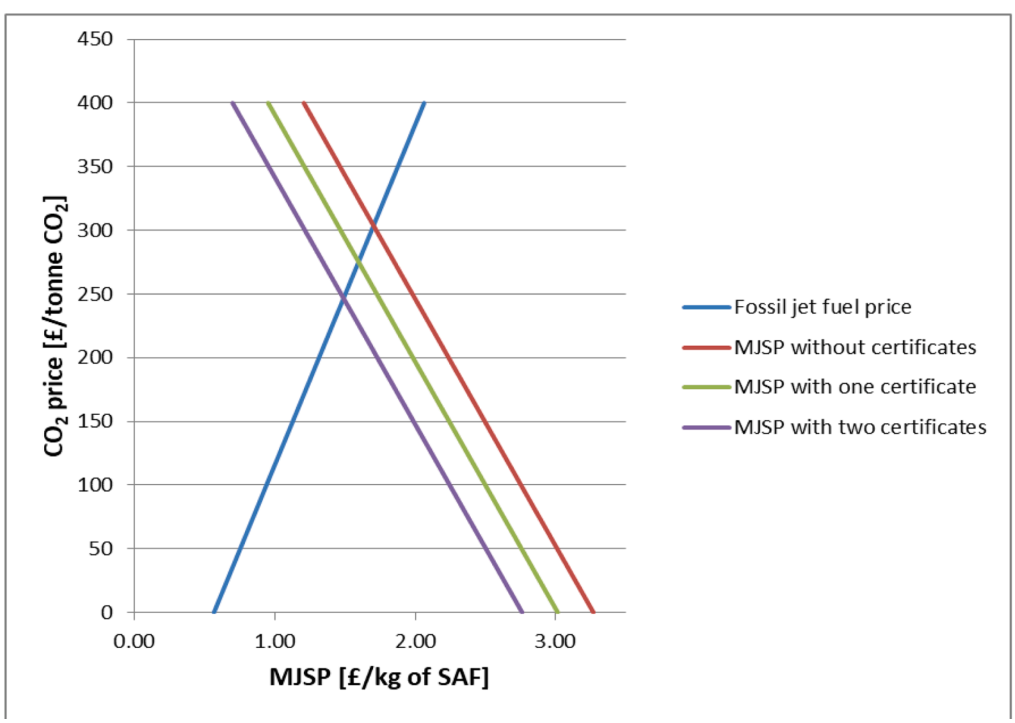


Fig. 11. MJSP and fossil jet fuel price as a function of CO_2 price and number of RTFC (RTFC=£0.2). Interception points indicate CO_2 prices at which MJSP breaks-even with fossil jet fuel price.

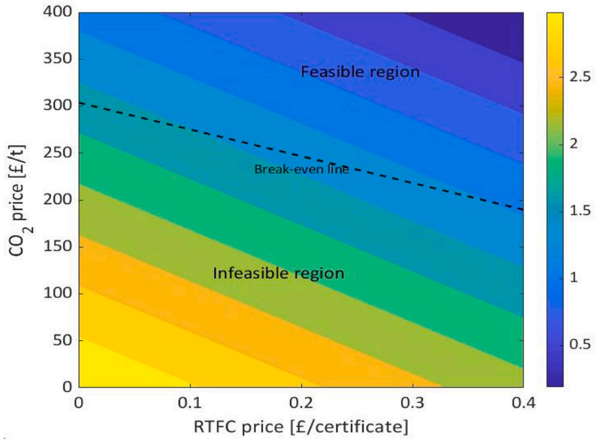


Fig. 12. Effect of the RTFCs and the CO_2 price on the MJSP. The break-even line indicates pair of CO_2 price and RTFC at which MJSP breaks-even with the fossil jet fuel price.

current study was to evaluate the techno-economic and environmental feasibility of SAF produced through gasification and FT via a BECCS scenario, and this was compared against the same pathway but without the sequestration of carbon dioxide. The CO_2 capture unit is inherent to the process regardless of the provision of permanent CO_2 storage or not and therefore adding the CCS section highly enhance the environmental feasibility of the process while minimally increasing the MJSP. In addition, the on-site generation of heat and electricity generation makes the BECCS-FT attractive since it covers the energy demand of both the CO_2 capture and the compression and hence avoiding the use of external energy loads that may be derived from fossil sources. The LCA results suggest that the BECCS configuration achieves highly negative emissions. The main outcomes of the present study can be summarised as follows:

- The results of the process modelling in Aspen Plus for the BECCS scenario has revealed that 26.26% of the carbon ends up in the products, 43.24% is wasted in the flue gases, and 30.50% is captured and permanently stored. The BE scenario has a similar carbon balance but in this case the CO_2 captured is released to the atmosphere.
- The energy balance of the BECCS and BE processes reveal that the electricity production is lower in the former, due to the energy penalty associated with the compression of CO_2. However, in terms of heating and cooling utilities, the requirements of both scenarios are quite similar. As a result, the overall energy efficiency of the BECCS scenario is 37.7%, which is only 2.57% lower than the efficiency of the BE scenario.
- The economic analysis revealed similar results for the CAPEX for both scenarios. For the BECCS scenario, the CAPEX only increases by 2% due to the cost of the CO_2 compression section. In addition, the addition of CCS increases the OPEX by 8.4%. The calculated MJSP are 3.27 £/kg and 3.03 £/kg, for the BECCS and the BE scenarios respectively. The gap between the MJSPs is about 7.34 %, and hence adding CCS does not have a significant effect on the economic viability of the project. Nevertheless, in both cases, the MJSPs are higher than the gate price of fossil jet fuel (0.56 £/kg [136]).
- The sensitivity analysis over the MJSP suggest that the BECCS process is CAPEX intensive (MJSP varies from 2.54 to 4.48 £/kg) and hence research and deployment of similar technologies is highly suggested as due to learning effects CAPEX reduction can be achieved. Another important cost factor is the feedstock price. Economies of scale may reduce the MJSP by 33% if the plant size increases to 100 dry-tonnes/h of feedstock. However, this strategy should be carefully analysed in the UK (and elsewhere) due to the restricted availability of FR.
- The GWP calculated for both BECCS and BE scenarios with the Energy Allocation approach, results in −121.83 gCO_2eq/MJ and 15.51 gCO_2eq/MJ, respectively. According to the sustainability criteria thresholds used for the different investigated standards (70% of GHG savings for the RED II [131] and a minimum of 50% for the U.S. RFS [130]), the BECCS scenario is well below these targets. This result is encouraging since it does not only reflect the potential of the BECSS in reducing the carbon footprint of the aviation sector, but also its suitability as a carbon dioxide removal strategy that could offset the GHG emissions of other sectors that are difficult to decarbonise such as heavy industries.
- The sensitivity analysis revealed that the GWP of the BECCS scenario is sensitive to the amount of CO_2 to be captured from the syngas, the emission intensity of the FR chips production and the feedstock transport. Despite all the uncertainties associated with the values adopted for the LCA, the Monte-Carlo analysis demonstrated that the SAF derived from the FT-BECCS configuration would most probably always have a negative GWP, and therefore will act as a CDR technology.

The study demonstrates the importance of coupling the production of value-added products such as jet fuel with CCS since such strategies can achieve negative emissions and facilitate the deployment of next generation CCS/CDR technologies. The current results add to a growing body of literature on the BECCS process configurations, and more studies should be developed to create a robust database to encourage further development and deployment. Similarly, studies that analyse other environmental impacts are highly recommended for a complete environmental evaluation of the BECCS configuration.

CRediT authorship contribution statement

Maria Fernanda Rojas Michaga: Conceptualization, Formal analysis, Investigation, Methodology, Software, Validation, Writing – original draft. **Stavros Michailos:** Conceptualization, Methodology, Software, Validation, Writing – review & editing. **Muhammad Akram:** Methodology, Validation, Writing – review & editing. **Evelyn Cardozo:** Methodology, Software, Writing – review & editing. **Kevin J. Hughes:** Resources, Supervision, Writing – review & editing. **Derek Ingham:** Project administration, Resources, Supervision, Writing – review & editing. **Mohamed Pourkashanian:** Resources, Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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