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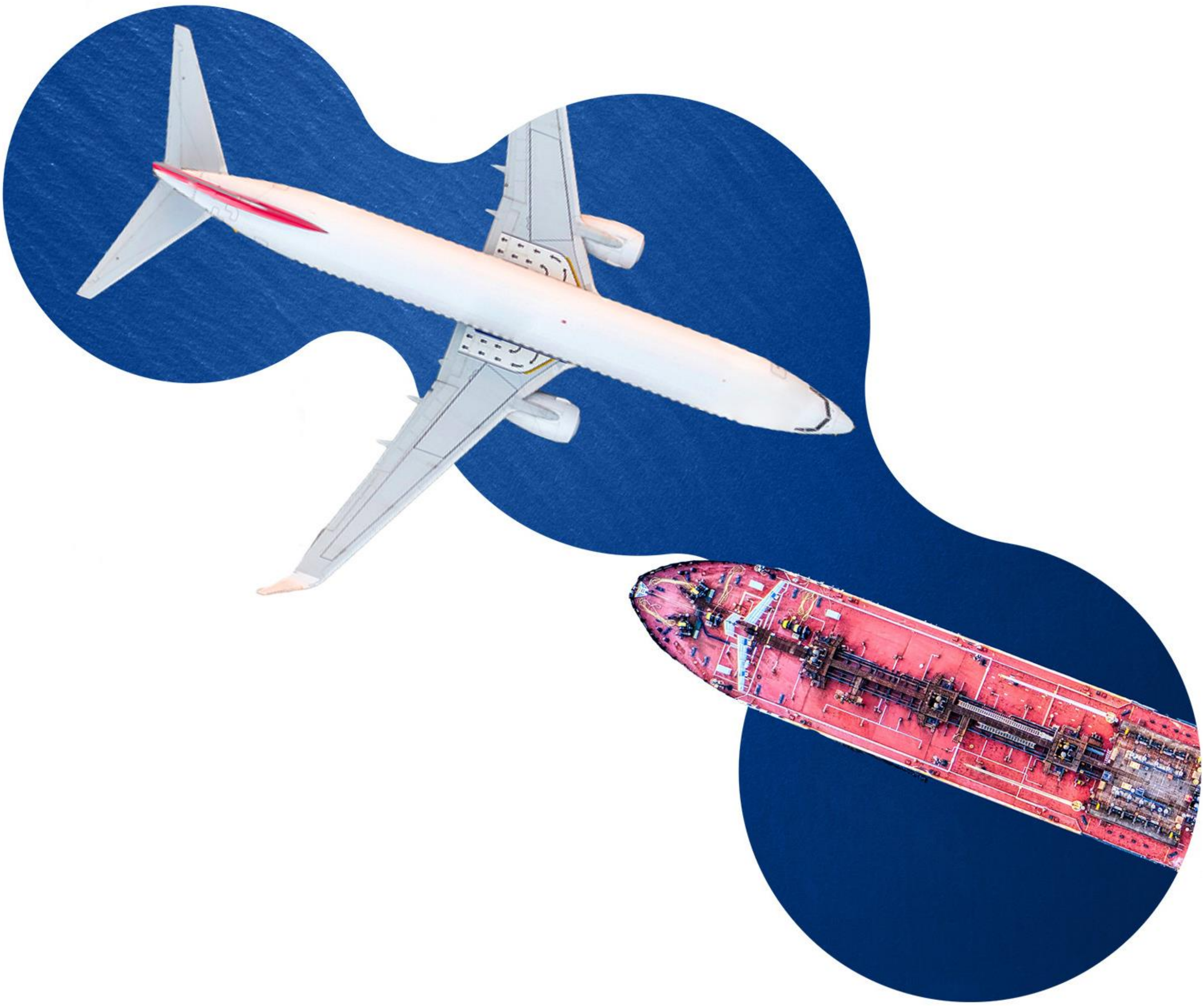
COCPIT

D1.1
Scenarios definition



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Statement of Originality

This deliverable contains original unpublished work except where clearly indicated otherwise. Acknowledgement of previously published material and of the work of others has been made through appropriate citation, quotation or both. This project has used a standard methodology already developed in BECOOL project (Grant Agreement number: 744821), following EU recommendations. Ad hoc modifications were added to comply with the Grant Agreement conditions for COCPIT (Grant Agreement number: 101122101).

Disclaimer of warranties

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Abbreviations

AD	Anaerobic Digestion	**LCA**	Life Cycle Assessment
AFDW	Ash Free Dry Weight	**MFSP**	Minimum Fuel Selling Price
AI	Artificial Intelligence	**MGY**	Million Gallons per Year
BDO	2,3-butanediol	**MSP**	Minimum Selling Price
CHP	Combined heat and power	**NREL**	USA National Renewable Energy Laboratory
CSTR	Continuous Stirred Tank Reactor	**OFMSW**	Organic Fraction of Municipal Solid Waste
D	Deliverable	**OPEX**	Operational Expenses
DAF	Dissolved Air Flotation	**PBR**	Photobioreactor
DF	Dark Fermentation	**PC**	Protein Concentrate
DSS	Decision Support System	**PFD**	Process Flow Diagram
DW	Dry Weight	**SAF**	Sustainable Aviation Fuels
EO	Expected Outcome	**s-LCA**	Social Life Cycle Assessment
EU	European Union	**SOTA**	State-of-the-art
FCI	Fixed Capital Investment	**STPV**	Semi-transparent photovoltaic
FFA	Free Fatty Acids	**T**	Task
GGE	Gasoline Gallon Equivalent	**TAG**	Triacylglycerols
GHG	Greenhouse Gas	**TEA**	Techno-economic Analysis
HEFA	Hydrotreated Esters and Fatty Acids	**VFA**	Volatile fatty acids
HTL	Hydrothermal Liquefaction	**WB**	Wet Base
HTL-AP	Hydrothermal Liquefaction Aqueous Phase	**WP**	Working Package
IL	Ionic Liquid	**WWT**	Waste Water Treatment
KPI	Key Performance Indicator	**WWTP**	Waste Water Treatment Plant
KSO	Key Specific Objective		

1 Executive Summary

Within pre-design and conception phase (WP1) stage, Task 1.5 aims to define the alternative scenarios, based on different parameters that can affect the outcome of techno-economic, environmental and social indicators. The main target is to specify the best possible combinations between these parameters and form the scenarios, which will be elaborated and optimised during the course of the COCPIT project. In deliverable D1.1, the fine-tuning and the definition on the 7 different prospective scenarios of SAF production are described based on the work and progress that has been made so far in the project.

The initial step was to specify the Europeans Union's (EU) goals for Sustainable Aviation Fuel's (SAF) production in the next decades in order to achieve being in compliance with the future projections and establishing a base case scenario. Based on this, the average annual capacity per plant in the year 2050 was estimated (Chapter 2). Different reports of the USA National Renewable Energy Laboratory (NREL) were used as benchmarks for the HTL and HEFA pathways analyzed in COCPIT, in order to obtain results that can be compared to the ones that will be produced later during project's implementation. The benchmarks' results were estimated by adapting the mass balances given in the reports to reflect the case for the corresponding quantity of the EU's goals. Techno-economic and environmental indicators were also provided (Chapter 3).

The idea of the COCPIT project for the different stages and a description of the novelties that will be applied were then described (Chapter 4). Within this context, all experimental partners were asked to fill out templates and tables regarding their experimental work to deconstruct the different stages and obtain a detailed understanding of the inputs, outputs and equipment units per stage (Chapter 5).

The main parameters for the scenarios definitions, namely i) centralized or decentralized, ii) solar irradiance, iii) carbon dioxide resources, iv) fermentable biogenic sources, v) symbiosis with wastewater treatment facility, vi) symbiosis with waste-to-energy plants and vii) symbiosis with sewage sludge valorisation process, were analysed in Chapter 6. An extensive literature review was conducted to break down and thoroughly acquaint each one of the evaluating parameters. This former work built such a deep understanding that allowed a mapping methodology to be developed and followed. Different maps and tools, each one concerning one of the parameters and providing information about specific locations within the European countries, were used to track down the best but feasible combinations of the parameters. That way the alternative scenarios were built, in order for them to be capable of supporting EU's goals and be subjected to future projections. Finally, in Chapter 7, the way where the scenarios will feed the Decision Support System (DSS) tool in order to help investors and end-users was presented.

This deliverable will help to constitute a database that will feed the DSS tool of COCPIT project. Different input parameters will be screened and varied within realistic ranges and combined together in order to train the AI tool with realistic data. The different data are illustrated and materialized, offering an inventory for specifying the first scenarios with a future potential to generate more scenarios under study. Different parameters are screened, and specific ranges are defined with real data at their minimum and maximum values to be a better and more precise input for the DSS tool. The seven scenarios that are presented in this deliverable aim to materialize some illustrative situations, while the real number of studied combinations will be a lot more. The experimental results from project partners will validate the developed inventory and feed the tool with realistic data. The DSS will compare and combine both physical and AI model results and will provide new parameter values & configurations based on the indexes of the performance to make predictions and offer suggestion on the possible scenarios.

2 Future demands for SAF

The ReFuelEU Aviation initiative suggests that 70% of jet fuel consumed by flights departing from EU airports should be sustainable aviation fuels (SAF) by 2050. Beginning in 2025, aviation fuel suppliers are mandated to guarantee that all fuel provided to aircraft operators at EU airports includes a gradually growing minimum percentage of SAF [1]. This requirement entails a minimum of 2% SAF in aviation fuel by 2025, increasing to 6% by 2030, 20% by 2035, 34% by 2040, 42% by 2045, and ultimately reaching 70% by 2050. Additionally, synthetic fuels are expected to comprise a progressively rising portion of the fuel blend, aiming to reach 35% by 2050 [2]. The total EU demand for aviation fuel is estimated to be 45 million t in 2050. With the proposed SAF blending mandate in place and by considering the total demand, approximately 31.5 million t of SAF would be required by 2050. It is also noted that 104 additional SAF production plants will be operated in the EU in the same timeframe. In order to be in compliance with this objective, a mean annual SAF production of 302.9 kt per plant will be adopted while compiling the scenarios [1].

3 Base case scenario and first estimations

In order to establish the novelties and the contributions of COCPIT to the existing technologies of SAF production, it is important to determine the dynamics of the current situation in biofuel production industry through reliable, thorough and rigorous literature sources. The two pathways that are included in the COCPIT project are the Hydrothermal Liquefaction (HTL) and the Hydrotreated esters and Fatty Acids (HEFA). Two different reports that have been published from the USA National Renewable Energy Laboratory (NREL) have been chosen to be used as benchmarks for this processes, as trustworthy resources that provide useful information and quality data to build the base case scenarios. Both publications report process design, techno-economic evaluation, and sustainability metrics for the production of jet biofuels from microalgae cultivation by utilizing either HTL [3] or HEFA [4] pathway. Process flow diagrams, conditions, conversion yields and assumptions are adopted and adjusted to enable the estimations of the base case scenario performance in accordance with the EU demands. The cultivation of microalgae takes place in open pond reactors in both reports. This assumption is considered only for defining the benchmark results from the NREL reports and it will be later replaced by a photobioreactor operation, as this is the technology that will be implemented during the project. In Chapter 4, a definition/explanation of the process changes that COCPIT brings to this case study, will be described in detail.

3.1 HTL technology

HTL is a method for producing SAF that started to be evaluated in the literature during the first years of the 21st century. Figure 3.1 presents the process flow diagram of HTL from NREL report (2024) [3]. In this study, two scenarios are under evaluation, with their difference being on the inclusion of the protein extraction stage in the overall production process. Protein extraction is usually an important aspect that should be examined, as the content of nitrogen in the final fuel might affect the SAF's efficiency. The first scenario, which includes protein extraction, requires a biomass concentration up to 10 wt% solids for efficient protein extraction. The liquid stream is acidified to precipitate the solubilized protein, and then the stream is separated via filtration. The separated protein solids are spray dried to produce a dry protein powder, while the aqueous stream from the protein extraction process, containing soluble organics, is assumed to be recycled to the algae farm.

For the second scenario, in which the stream undergoes directly downstream conversion to fuels without protein extraction, 20 wt% solids concentration is assumed. Condensed-phase liquefaction then takes place through the effects of time, heat, and pressure and the resulting HTL products (biocrude, solid, aqueous, and gas) are separated. The aqueous phase is sent to an anaerobic digestion (AD) unit to generate biogas for process heating. In this scenario, the HTL aqueous phase is also recycled to the algae farm after being subjected to the AD. The gas stream from HTL is used for process heating, while the solid stream is subjected to acid digestion to recover phosphorus components from the ash. The acid digestate and the treated water from the anaerobic digestion unit are assumed to be recycled to the algae farm.

The HTL biocrude is upgraded via hydrotreating and hydrocracking to remove oxygen, nitrogen, and other heteroatoms. The upgraded oil is then fractionated via distillation to generate diesel-, jet-, and naphtha-range fuels. The present analysis maintains the use of off-site point-source CO_2 capture and pipeline transport but incorporates further granularity to reflect local point-source capture costs and energy demands. The model assumes that 80% of the reported annual emissions are available for transport. The transport model defines the most optimal route between the source and algae farm, preferentially using existing rights-of-way and other corridors and avoiding sensitive areas, off-limits areas, and urban areas, similar to what was defined in the land screening model of NREL report (2024) [3].

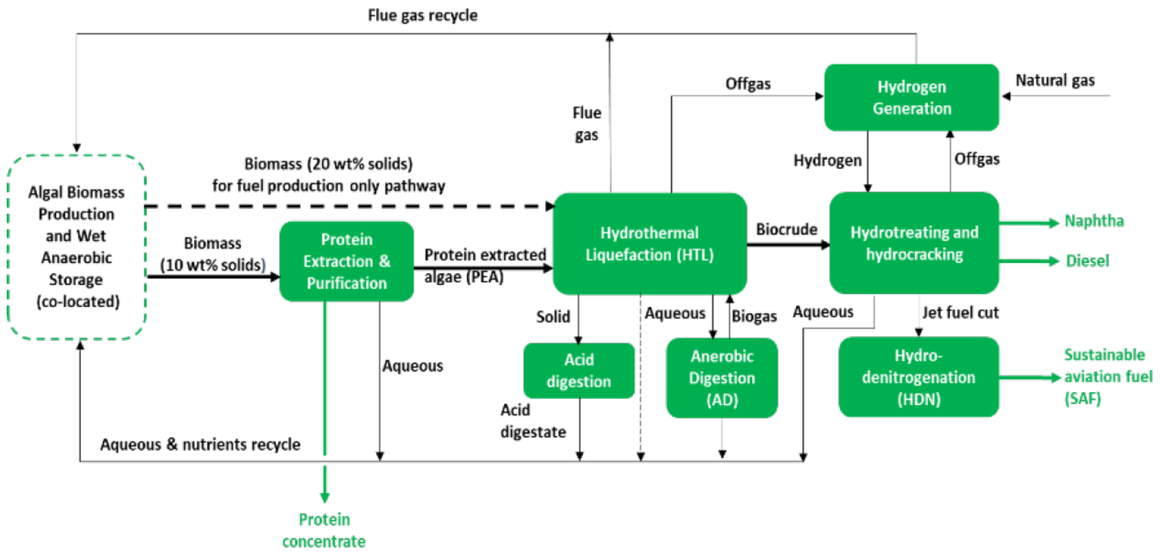


Figure 3.1 Base case of HTL process [3]

This study will be used as a benchmark for the conventional HTL process, on which the COCPIT project will create a beyond state-of-the-art study. As explained in Chapter 2, the European Union's goals for SAF for 2050, are estimated to reach 31.5 Mt produced from 104 plants, which results in an mean annual production capacity of 302.9 kt per plant. By setting this quantity as a target and using the different conversion yields that are given in NREL report (2024) between the different stages [3], the corresponding required quantity of the feedstock is estimated (1.6 million tons of algal biomass). Figure 3.2 presents this rationale into an illustrative block flow diagram, without considering protein extraction, where each process step has its own module presenting the sequence of the calculations. Those numbers will further be optimized when applying the innovations of COCPIT project.

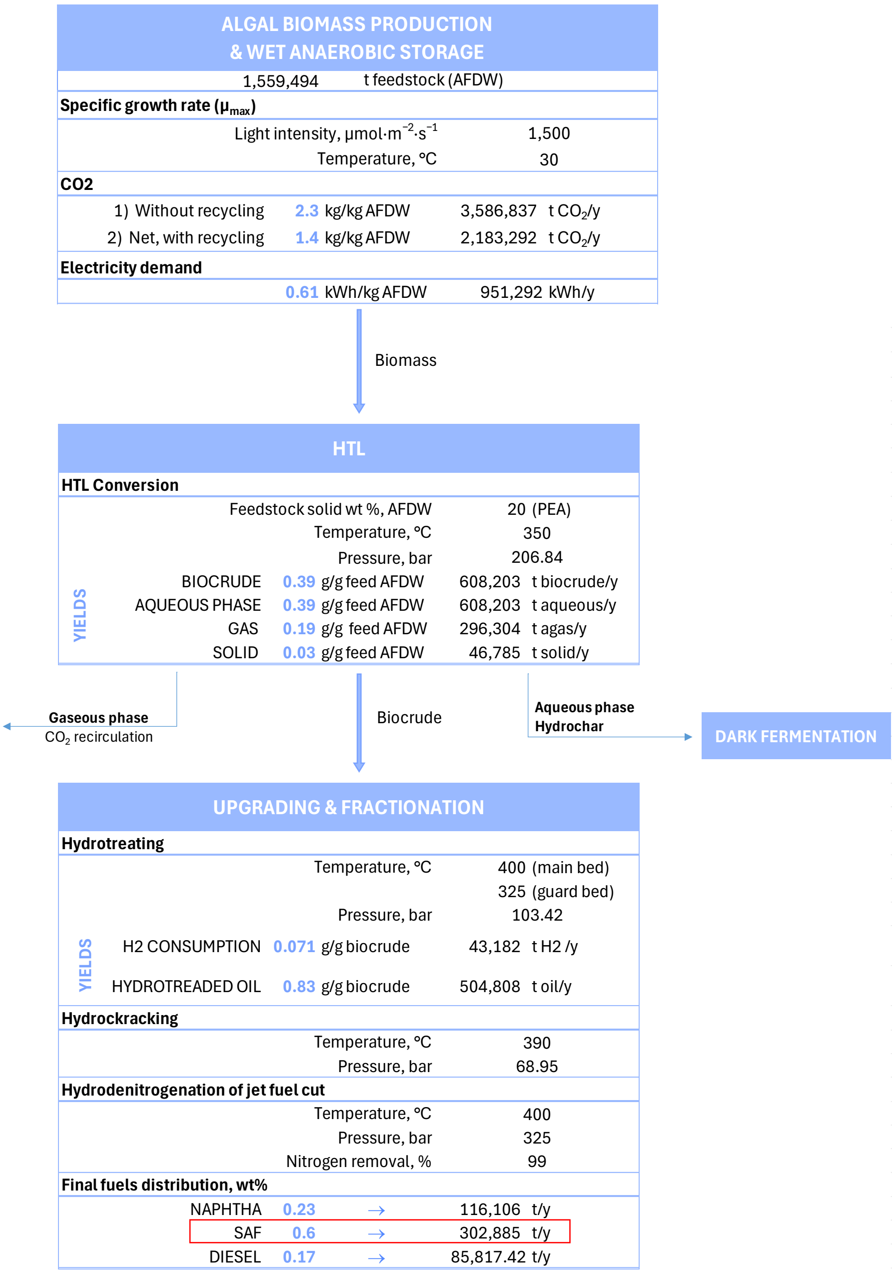


Figure 3.2 Block Flow Diagram of benchmark's HTL pathway aiming to 2050 EU goals

3.2 HEFA technology

The second pathway used in the COCPIT Project is HEFA. It is one of the most studied processes for producing SAF throughout the years. The design is based on a notional facility design, sized to produce 10 million gallons per year (MGY) containing an integrated system for algae cultivation, processing, and upgrading. Figure 3.3 displays the baseline algae production and processing pathway [4]. Algae are grown in open ponds, dewatered from 0.5 g/L to 200 g/L by settling, dissolved air flotation (DAF), and centrifugation. Biomass is diverted from cultivation to wet anaerobic storage during peak seasons and pulled from storage during low production seasons. Biomass is pretreated with dilute acid to hydrolyse carbohydrates to sugars and enable lipid extraction. Pretreated hydrolysate is separated into solid and liquid fraction, with the solid stream to be routed to lipid extraction and the liquid one to sugar fermentation. Regarding the fuel fermentation pathway, two different alternatives can be followed, either fermentation to carboxylic acid or 2,3-butanediol intermediates, which are then upgraded to final hydrocarbon fuel products through catalytic steps. For lipids extraction a CSTR and a centrifugal separator are used. The extracted lipids are further processed to produce hydrocarbon fuels derived from the FFAs and polyurethane derived from the TAGs. For the fuel production, algal lipids undergo hydroprocessing to produce renewable diesel fuel and then are subjected to a one-step deoxygenation and hydroisomerization. The final step for the fuel intermediate stream that results from the fermentation pathway and the FFAs is the conversion into renewable jet fuel, through hydrotreating. When the individual process of lipid conversion is taken into consideration, the renewable diesel blend-stock has a yield of 62.1% per wt of oil feed and naphtha 21.8% per wt of oil feed. The H_2 consumption for hydrotreating is 2.23% per wt of oil feed. Remnants, including lost solvent and unrecovered lipids, are sent to anaerobic digestion (AD) for energy and nutrient recycling. Energy recycling is accomplished by biogas combustion in a combined heat and power (CHP) system that was heat-integrated with the solvent recycle loop.

Similarly to HTL pathway, an illustrative block flow diagram is presented in Figure 3.4 expressing the estimations regarding SAF production based on EU demands assumption and the conversion yields derived from NREL (2023) report that utilizes the HEFA pathway [4].

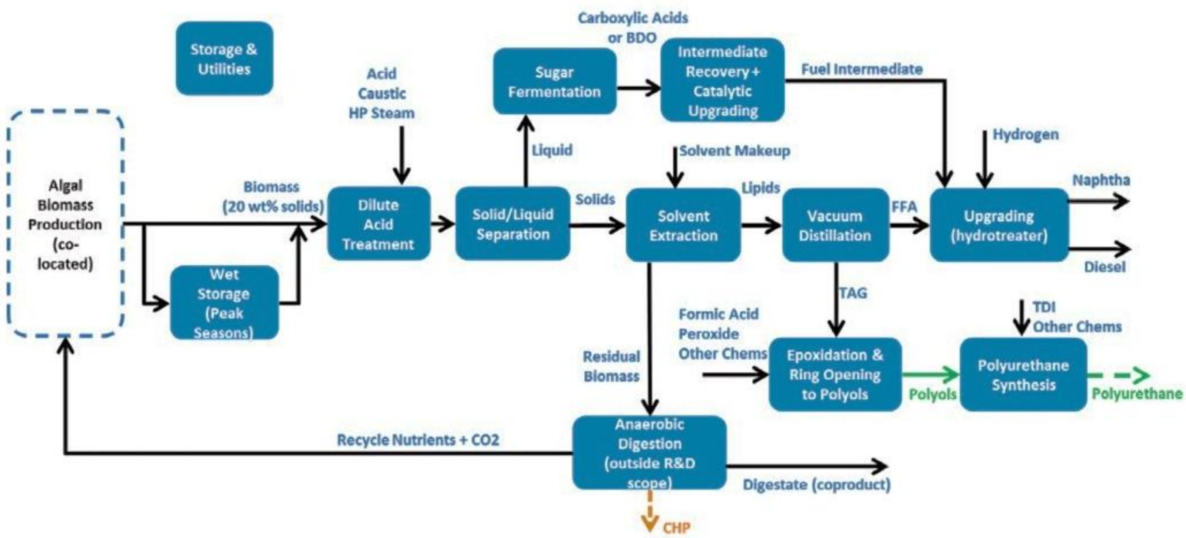


Figure 3.3 Base case of HEFA process [4]

This study will be the corresponding benchmark for the conventional HEFA process. More specifically, the sequence of calculations presented in Figure 3.4 is based on the European Union's goals for SAF (302.9 kt per plant) and the information (i.e. yields and mass balances) extracted from NREL (2023) report [4]. With each process step having its own module, the estimations start by targeting the desired SAF annual capacity. Two different pathways, sugars fermentation to acid/BDO and lipids extraction, are taken into account and by following each route, the quantity of intermediate products is calculated using the yield from lipids and BDO to fuel production [3, 5]. The scenario where acid is considered as intermediate product has also been studied giving approximately the same results as BDO pathway (data not shown). Finally, it is possible to estimate the required quantities of the feedstock (1.8 million t of AFDW algal biomass) as well as the raw materials based on the microalgae composition and the lipids loss during liquid-solids separation.

The estimated feedstock quantity required for the same biofuel production capacity through the HTL and HEFA by employing the technologies proposed by NREL reports are comparable, with a difference of approximately 14%.

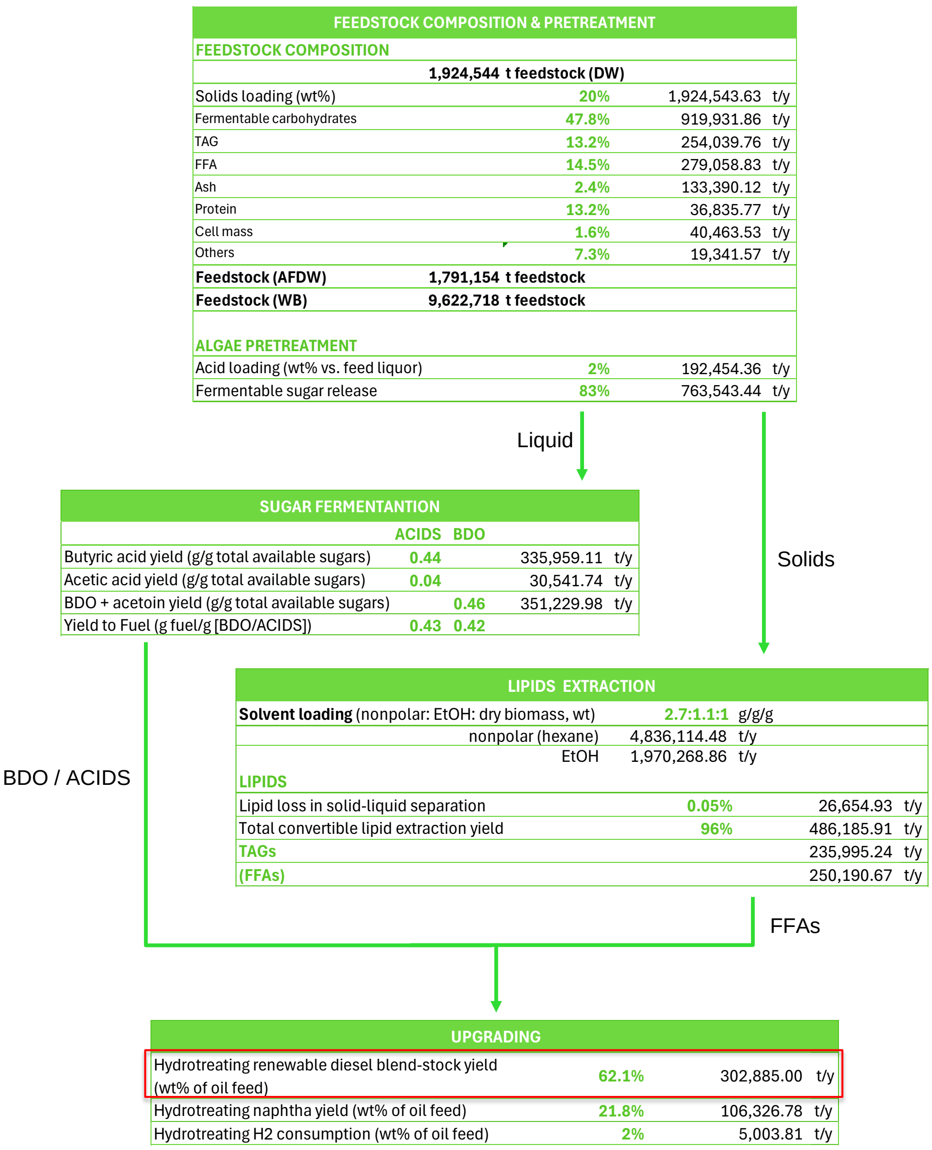


Figure 3.4 Block Flow Diagram of benchmark's HEFA pathway aiming to 2050 EU goals

3.3 Sustainability performance – State of the art

The different scenarios that will be built within COCPIT project will be the core for the sustainability assessment of the proposed innovations and the development of the AI tool. The essence of creating the alternative scenarios is to evaluate the influence of various parameters on the economic, environmental and social indicators. In this framework, the corresponding techno-economic and life cycle assessment results of the NREL reports that will be used as benchmarks for the process design, will also be an important source for comparison and evaluation of COCPIT's economic and environmental performance.

For the HTL pathway, the Minimum Fuel Selling Price (MFSP) is $8.69 per gasoline gallon equivalent (GGE) for fuel production alone for a capacity of 14.4 billion GGE/year, including SAF at 8.6 billion GGE/year [3]. This price can be further reduced with the inclusion of algal protein concentrate (PC) co-production to $3.72/GGE, even at a lower fuel production capacity of 7.7 billion GGE/year, with 4.6 billion GGE/year to be the SAF fraction. Environmental-wise GHG emissions from fuel and PC co-production, ranged with a weighted average of 61 g/MJ, in contrast to fuel-only production, which had an average of 85 g/MJ. GHG emissions for 1 t AFDW of algae as functional unit range from 0.94 t to 1.72 t, fossil energy consumption varies between 14,192 MJ and 23,789 MJ and freshwater consumption from 4,435 to 7,695 L per t AFDW.

Regarding the HEFA pathway the MFSPs of $5.99/GGE and $6.28/GGE were estimated for the acids' pathway and the BDO pathway, respectively [4].

4 Description of COCPIT process flow diagrams

The COCPIT project intends to deliver an innovative circular complete production chain of microalgae-based SAF through both pathways, HTL and HEFA. It aims not only to optimize the aforementioned processes, but also to introduce a state-of-the-art-technology at every processing stage, in order to ensure that it is as cost-effective and environmental-friendly as possible. The main stages of the process and how they differ from conventional biofuel production processes are described below. The main stages of the complete value chain are algae cultivation, lipid extraction and HEFA, HTL and biocrude upgrading, dark fermentation and fractionation of the final products (Figure 4.1).

4.1 Microalgae cultivation

At the microalgae cultivation stage, COCPIT utilizes the capabilities of the microalgae strain *Parachlorella kessleri*, which can store significant amounts of lipids (40%) and carbohydrates (30%) when nutrients are the limiting factor. The strain is cultivated in a thin film reactor to enhance photosynthesis. This reactor is covered with a semi-transparent photovoltaic (STPV) shell, generating electrical energy from the infrared portion of solar radiation. This innovation achieves at the same time the regulation of the temperature for the cultivation medium and the maximum solar energy absorption, leading to a dual benefit of generating biomass and electricity. The aim is to develop a high volumetric productivity photobioreactor with extrapolation to the pilot scale. Electricity from STPV panels is used to feed the system with power.

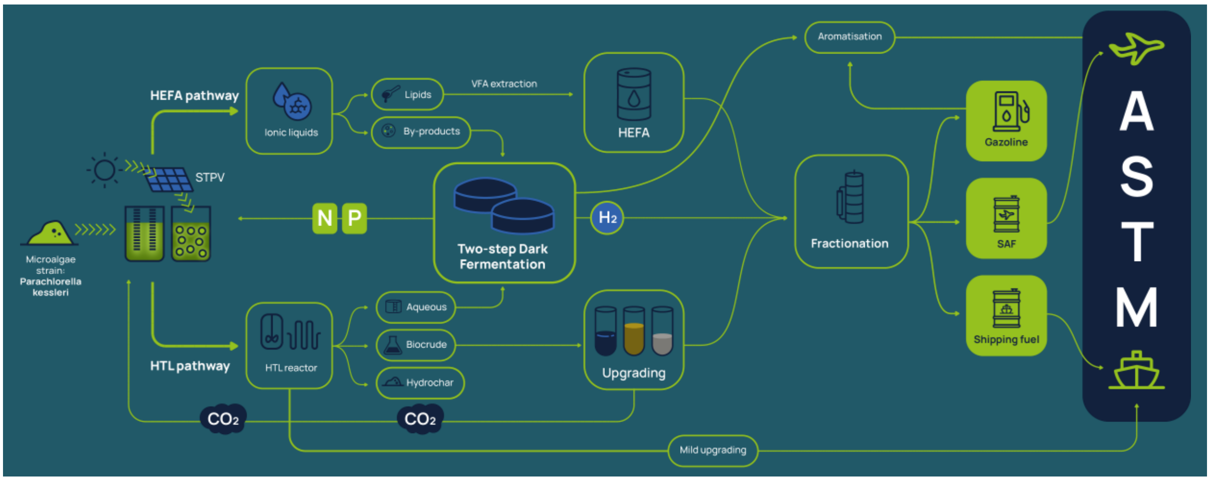


Figure 4.1 COCPIT concept at a glance

4.2 HTL pathway

Within the project, the first objective of the HTL pathway is the inclusion of the protein extraction stage under the boundaries of the study. Extracting proteins from algae before utilizing them in HTL serves two main purposes. The first one is the prevention of various issues associated with nitrogen in the fuel production chain. Moreover, it allows for a more efficient utilization of the proteins within the process by recirculating nitrogen effectively and generating hydrogen to feed HTL's biocrude upgrading, simultaneously.

For the transformation stage, COCPIT aims to design a combined CSTR-TR continuous HTL reactor tailored to the SAF production from microalgae, in order to deal with the main obstacle of HTL upscaling, i.e. clogging and biocrude separation. The improvement of the quality of microalgae biocrude faces challenges in achieving a significant reduction in nitrogen content to comply with transportation fuel standards and in minimizing the hydrogen needed in the process. Additionally, the production of fuel additives from volatile fatty acids (VFA) aims to increase the permissible proportion of SAF in aviation, which is currently restricted to 50% due to the absence of aromatics.

Moreover, exploring mild upgrading of HTL biocrude to create alternative maritime fuels is under evaluation to enhance process flexibility. After the end of HTL, biocrude hydrotreating takes place. COCPIT addresses the challenge of managing the high nitrogen content in SAF through an innovative catalytic hydrotreatment process, employing multi-stage processing and on-line product fractionation.

4.3 HEFA pathway

HEFA pathway starts with the separation of the lipids replacing the conventional organic solvents with ionic liquids (ILs), as they have a better ecologic profile and can make the process more afford-able and less prone to problems typically associated with conventional catalysts. Ionic liquids are entirely composed of ions, featuring large organic cations paired with organic or inorganic anions. Although some commercial ILs can extract 80-90% of lipids from wet and dry biomass, some ILs are toxic, so their presence in traces inhibits downstream processes like DF. In COCPIT project the innovative nature of this procedure stems from the use of perfectly biodegradable ILs. Lipid extraction is studied using two approaches: cell disruption and cell permeabilization. Since some ILs are toxic, the innovative nature of this procedure stems from the use of perfectly biodegradable ILs.

The transformation stage of HEFA includes hydrodeoxygenation, hydrocracking and hydroisomerazation. In this stage, use of ILs as catalysts is also explored to evaluate whether the process would be more affordable and less prone to problems typically associated with conventional catalysts (i.e. corrosion, poor selectivity, regeneration etc.).

Since HEFA consists of C8-C15 straight-chain hydrocarbons with no aromatic or cyclic components, it is limited to a maximum of 50% in blends with fossil fuels. COCPIT aims to overcome this limitation by producing fuels that allow for higher blending rates and aspirations. This is achieved by enhancing HEFA with neat aromatics. Therefore, the processing stream is being enriched with VFAs occurring from dark fermentation and will finally be submitted to aromatisation.

4.4 Dark Fermentation

In order to ensure process circularity, dark fermentation (DF) is employed, processing all by-products and serving multiple purposes. Following the pathways to produce SAF, two different types of microalgae residues will be available: (i) protein and carbohydrates (HEFA Pathway) and (ii) primarily proteins (HTL pathway). To boost the production of hydrogen (H_2) and VFAs, a two-step dark fermentation process is suggested. The first reactor focuses on H_2 generation, while a second reactor stabilizes the carbonaceous residue by producing methane. Trials are conducted involving the injection of the aqueous phase of HTL into both steps of the process, while H_2 and CH_4 are concentrated through water scrubbing. The water used for scrubbing, which is enriched with dissolved CO_2, is then utilized in the photobioreactor (PBR), after undergoing treatment with a ferric solution to precipitate sulfur. A similar method is employed to recover CO_2 from the gaseous phase of HTL. VFAs are extracted from the supernatant of the dark fermentation process, following the previously outlined procedure. The digestate, which contains residual carbon and is rich in organic nitrogen and phosphorus, is diluted and added to the feed of the PBR. The technique of electrocatalytic conversion will be applied in the COCPIT project as a treatment method for the HTL-AP before being recirculated to the PBR, as it has a high content of short-chain carboxylic acids and oxygenated aromatics.

Furthermore, COCPIT explores additional adaptive strategies by considering scenarios where other waste streams, such as brewery effluents, food waste and OFMSW are utilized for DF, and where microalgae cultivation utilizes nitrogen and phosphorus-rich wastewater and CO_2 streams. Additionally, the potential for symbiosis with other waste-to-energy processes is investigated, opening up new avenues for integration.

4.5 Fractionation and final fuels distribution

Fractional distillation is employed to process upgraded biocrudes, corresponding to the boiling range of transportation fuels as well as distillation residues, with special attention to jet-fuel and diesel. It is anticipated that 15-20% of the fractions will fall within the kerosene range, while diesel could constitute up to 40%. To enhance the kerosene content, the diesel fraction undergoes isomerization using an appropriate catalyst.

5 Process Design Templates

The first step to perform the detailed process design, the techno-economic evaluation and the Life Cycle Assessment in WP7 is to deconstruct and understand the different stages. In order to be able to create a complete process flow diagram and build the mass energy balances, specific input from each partner regarding their relevant stage under study is necessary. The main data required for this step are yields and productivity, the conditions like temperature and pressure, the quantities of utilities and raw materials as well as physical properties of the solvents per equipment unit.

For that reason, a template was prepared to gather all required information from the partners who are performing experimental works within the COCPIT Project. This template includes three different parts, i) basic information regarding the process stage and the partner in charge, ii) table including the request for inputs, outputs and conditions per equipment unit and iii) the creation of a block diagram of the different equipment units for the corresponding stage. Completed templates have been already gathered from the different partners and the data are a valuable input to get insights for the performance of the different stages (e.g. conversion yields, conditions, utilities etc.) and start the comparisons with the base cases from the literature. Figures 5.1 and 5.2 present an example of a filled-out template for the lipid extraction stage.

Table 5.1 Lipid extraction mass and energy balances per equipment unit

Mass and energy balances per equipment unit					
Equipment unit 1 (mixing 1)			Equipment unit 2 (cooling)		
	Value	*Unit*		*Value*	*Unit*
Inputs			Inputs		
microalgae mass (main product	2.77	kg/kg product	microalgae mass (main pr	2.77	kg/kg product
water of microalgae	17.64	kg/kg product	water of microalgae	17.64	kg/kg product
Ionic Liquids	27.78	kg/kg product	Ionic Liquids	27.78	kg/kg product
Outputs			Outputs		
microalgae mass (main product	2.77	kg/kg product	microalgae mass (main pr	2.77	kg/kg product
water of microalgae	17.64	kg/kg product	water of microalgae	17.64	kg/kg product
Ionic Liquids	27.78	kg/kg product	Ionic Liquids	27.78	kg/kg product
Utilities			Utilities		
Electricity	14.4	kWh/kg product	Electricity	0	kWh/kg product
Water	4400	kg/kg product			

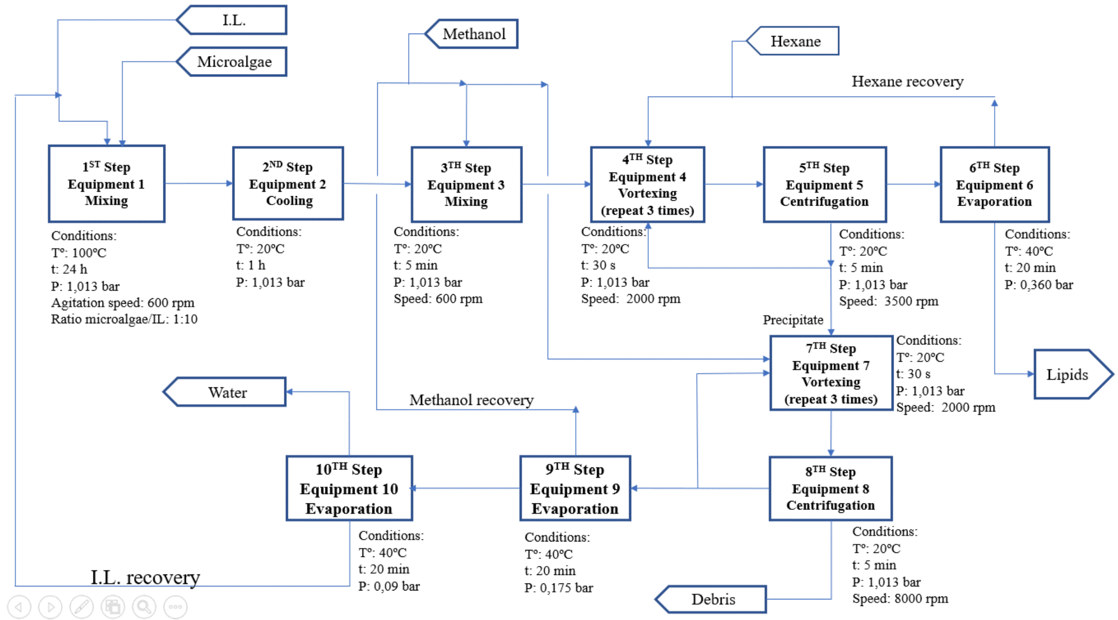


Figure 5.1 Lipid extraction process flow diagram

6 Scenarios development

The alternative scenarios that are going to be evaluated within the COCPIT project are defined though a variety of parameters, which play a vital role in the optimization of the process. These parameters include: i) the location of microalgae cultivation site (integrated with the biofuel producing plant or external resources providing plants or decentralized), ii) the efficiency of the solar irradiance of the country for microalgae cultivation, iii) the coupling of the HTL of sewage sludge with cultivated microalgae and whether it is possible for the cultivation site or the biofuel plant to be coupled with a iv) carbon dioxide providing plant, v) a wastewater treatment facility, vi) a ferment-able biogenic source and vii) a waste-to-energy plant depending on their corresponding needs. In sections 6.1-6.6, the different considerations will be explained based on an extended literature re-view for evaluating the different parameters under study.

6.1 Integrated vs decentralized

One key aspect is evaluating whether an integrated or decentralized approach should be followed. On centralized biorefineries the cultivation, pre-production processes (lipid/protein extraction exc.) and the process for the final conversion to SAF and co-products (e.g. shipping fuel) are carried out in the same place. For the decentralized configuration, the microalgae cultivation is located in a different area than the one of the SAF production plant [6].

An integrated scenario seems to be ideal, not only from an economic but also from an environmental point of view. This involves integrating microalgal production within industrial sites, utilizing nutrient-rich flue gas and utilizing wastewater to produce biomass that meets growing energy demands. This method also offers the added benefits of wastewater treatment and emission control. In a centralized system, the capacity at each stage is interdependent, which can hinder the development of large-scale biorefineries. Conversely, decentralized production requires harvested algae to be collected, transported, and processed in various locations for extracting algal crude, biofuel residue, and nutrient-rich digestate. This decentralized method generates considerable localized waste. Additionally, because dried microalgae biomass can decompose and degrade through natural chemical reactions, it must be quickly transported to biofuel production facilities, making transportation time-sensitive and introducing uncertainty [6, 7, 8, 9]. The complexity of this selection will be further evaluated within the different scenarios.

6.2 Solar resources

Regarding solar resources, geographical areas with high irradiances throughout the year and moderate temperatures are optimal for microalgae cultivation. Based on the average amount of sunlight hours per day (10-12h), and the mean solar irradiance ranging from 400 $\mu mol \cdot m^{-2}s^{-1}$ (winter time) to 1,800 $\mu mol \cdot m^{-2}s^{-1}$ (summer time), southern Spain and southern Portugal are considered especially suitable for outdoor cultivation [10]. Cultures of *P. kessleri* reached saturation already at 250 $\mu mol \cdot m^{-2}s^{-1}$, and the growth did not further improve by cultivation at 500 $\mu mol \cdot m^{-2}s^{-1}$ [11]. For the large-scale production of lipid-enriched biomass, the minimum mean light intensity for production of reserve lipids is about 150 $\mu mol \cdot m^{-2}s^{-1}$ [12]. In order to define the most appropriate locations for microalgae cultivation, in the perspective of solar irradiance, the yearly photovoltaic production and yearly in-plane irradiation values from the European commission’s photovoltaic geographical information system were used.

6.3 Carbon dioxide resources

According to the most recent EUROSTAT data for the year 2021, total carbon dioxide emissions, including both biogenic and non-biogenic type, in Europe reached about 2.5 billion tons [13]. Currently, it is important environmental-wise to recirculate the non-biogenic type, but in the future the production of SAF might demand only on biogenic sources. Therefore, the possibility to evaluate the CO_2 resources as a study variable will be included during the project.

According to statistics, the emitted biogenic CO2 can range between 154 and 250 million t of CO2 per year. There is uncertainty about total biogenic emissions across Europe, as many countries do not separate them from total CO2 emissions. Individual values for produced biogenic carbon dioxide were gathered from literature for countries such as Sweden, Germany and Finland, while for the remaining European countries, biogenic emissions have been estimated according to the country-specific emissions provided (Figure 6.1). For most countries, the majority of biogenic CO2 is pro-duced by the paper, wood or pulp industries, waste management industries or power plants. Other possible sources are industries producing biogas, biomethane and bioethanol, cement and lime (combustion-related emissions), chemicals and food and beverages. For the same sectors, it is im-portant to define the deployment uptake of the carbon, e.g. the capturable quantity of CO2, as the exploitation of biogenic carbon dioxide sources is highly dependent on the location and in what per-centage the CO2 is accessible. This an important aspect that will be taken under consideration, as along with the prediction of the future biogenic availability per sector, meaning weather they tend to increase or decrease (Table 6.1)[14].

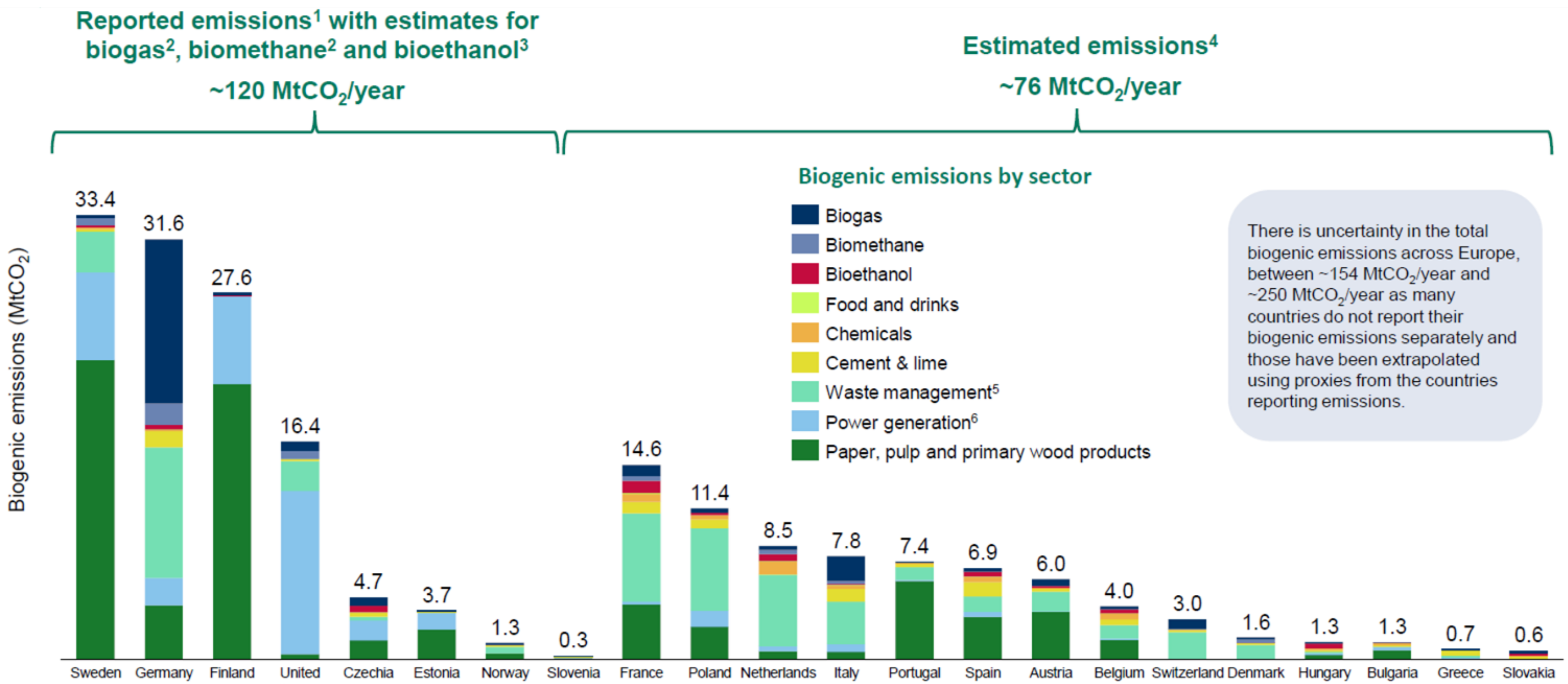


Figure 6.1 Biogenic CO_2 emissions in the EU per country and per sector [14]

Table 6.1 Biogenic CO_2 emissions in the EU and its deployment uptake [14]

Sector	Number of facilities in Europe	Average CO_2 emissions per plant ($MtCO_2$/year)	Average biogenic CO_2 emissions per plant ($MtCO_2$/year)	Total biogenic CO_2 emissions per sector (MtCO2/year)	Current share of European biogenic CO_2 (%)	Fraction of CO_2 in flue gases (%)	Low carbon capture deployment uptake (%)	High carbon capture deployment uptake (%)	Likelihood for deploying CO_2 capture based on technical aspects	Future sector trend will CO_2 emissions increase or decrease
Paper, pulp and primary wood products	614	0.74	0.68	417.52	39.0%	14-30	50%	80%	High potential for large plants located in suitable locations	Remain same
Power generation	Few pure biomass plants	0.36	Almost full emissions for those burning biomass		17.4%	10-12 (biomass fired)	50%	80%	Medium depends on location and asset lifetime	Very uncertain, likely an overall reduction in emissions and also growth in BECCS
Waste management	925	0.3	0.18	166.5	23.1%	6-12	25%	50%	Medium depends on location and asset lifetime	Growth particularly of waste to energy plants
Food and drink	212	0.13	0.00042	0.08904	0.1%	99	33%	66%	Sites relatively small and dispersed	Steady growth
Cement	829	0.74	0.05	41.45	4.1%	18 (kiln flue gas) 20-30 (pre calciner)	50%	80%	High potential for CO_2 capture to remove process emissions	Similar size
Biomethane production	729	0.006	0.006	4.374	0.2%	96	33%	66%	CO_2 already separated but unlikely to be used for CCU due to scale	Rapid growth
Biogas production	17.779	0.001	0.001	0.017779	10.1%	25-50	25%	50%	Low Many small scale plants	Growth
Bioethanol	146	0.12	0.06	8.76	2.2%	99	33%	66%	High Already captured for other uses	Potential growth but uncertain given gasoline demand reduction and further ethanol import potential

The estimated accessible EU's potential for biogenic CO2 in year 2050 is around 21-63 Mt, with an estimated maximum potential of 200 Mt. The extended use of biomass and biomass-derived products in existing industries might lead to higher biogenic emissions. This includes a greater reliance on solid biomass for industrial fuel switching and its increased application in the chemical industry. However, for the sectors of maritime, road and chemicals' industry fuels there are no policy drivers yet. The EU's CO2 outlook remains uncertain due to reduced gasoline demand and imports. Addi-ionally, biogenic CO2 emissions may rise from gasification-based fuel production for aviation and road transport. Further scaling up of biogas and biomethane production could also enhance supply [14].

The amount of biogenic CO_2 that will be produced in the future remains highly uncertain. The high uncertainty around this subject occurs from the appliance of different methods in the biofuel production industry, as well as the low future potential of capturable CO_2. According to literature, energy-related emissions are expected to significantly decrease over time, while new green industries depend on the availability of concentrated CO_2. Dechema's analysis of chemicals and fuels concluded that the available CO_2 would be sufficient to meet the maximum future demand for chemical production. Nevertheless, to achieve the net zero scenarios outlined by the IPCC, approximately 1,500 Mt of CO_2 equivalents will still need to be counterbalanced and permanently sequestered through technological or biological methods. [15, 16, 17, 18, 19]. Figure 6.2 presents the comparison of CO_2 supply and demand until 2050. The restriction of fossil CO_2 utilisation will convert CO_2 to a valuable feedstock for new green industries.

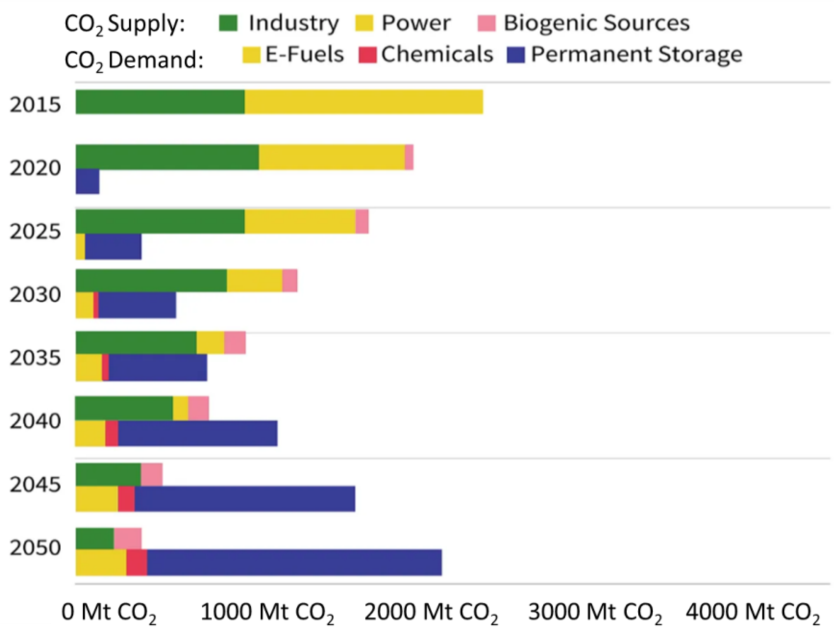


Figure 6.2 Projected supply and demand of CO_2 [15, 16, 17, 18]

6.4 Fermentable biogenic sources

There were many articles in the literature that suggested many different materials as fermentable biogenic sources, including municipal waste, waste of animal origin as well as industrial waste and effluents. These sources can be converted into hydrogen based on their sugars' content [20]. Regarding volatile fatty acids, some appropriate VFA producing sources utilize different types of waste. It is suggested that during selecting sources, sustainable and renewable feedstocks that are less competitive with food sources are the primary choices [21]. Brewery wastewater and brewery spent grains seems to be a good fermentable source, while literature indicated that raw ryegrass, wine vinasse and food waste should be taken into consideration as promising sources. All these mentioned sources of fermentable biogenic sources will be included in the developed scenarios.

6.5 Wastewater treatment for nitrogen and phosphorus recovery

The symbiosis of the microalgae cultivation with a wastewater facility is undoubtedly beneficial. There is advanced wastewater treatment as algae purifies the wastewater by using up its nutrients content for its growth. Moreover, it is economically sustainable, as most local manufacturers generate wastewater in large amounts which can be utilized free of charge and last but not least wastewater treatment plants usually produce CO_2 that can be used in microalgae production. Some obstacles that should be considered are the ability of the species to adapt in very high nutrient conditions and the fact that temperature, pH and content of heavy metals and pathogens in the wastewater can defect the development of algae and consequently lead to an increase in energy consumption and operating cost [6, 10, 22]. During scenarios definition, these aspects will be taken into account as case studies.

6.6 Symbiosis with waste-to-energy plants and sewage sludge valorisation process

Regarding symbiosis with waste-to-energy plants and sewage sludge valorisation process, there can be an overlapping or co-existence between these two scenarios and the aforementioned ones. Waste-to-energy facilities such as incinerators, anaerobic digesters, and bioethanol production sites are considered as sources of CO_2, but in this section, what is evaluated is the symbiosis of waste-to-energy plants and sewage sludge valorisation process that are going to be used in the biofuel producing plant rather than in cultivation stage. For instance, in the case of an incinerator, exploring heat recovery to fuel the centralised process could be evaluated to improve the system's energy efficiency. Likewise, the possibility of transforming process wastes streams into a two-stage process to produce H_2, VFA and CH_4 in an anaerobic digester is also being evaluated. Regarding symbiosis with sewage sludge, data from the NextGenRoadFuel project is being collected to model the utilization of nitrogen (N) and phosphorus (P) rich hydrothermal liquefaction (HTL) effluents for microalgae cultivation, as well as to explore the integration of HTL and upgrading steps into a unified process.

6.7 Maps combining strategy and scenarios definition

As the parameters that have been analysed in the previous sections can be combined in many different ways, it has been decided that the most efficient way to define the scenarios that will be analysed in the project is to adopt a map-combining approach (Figure 6.3). During this approach, different maps are tracked, each one concerning one of the parameters that are under evaluation, and the specific scenarios are developed based on the values that have been connected to these parameters.

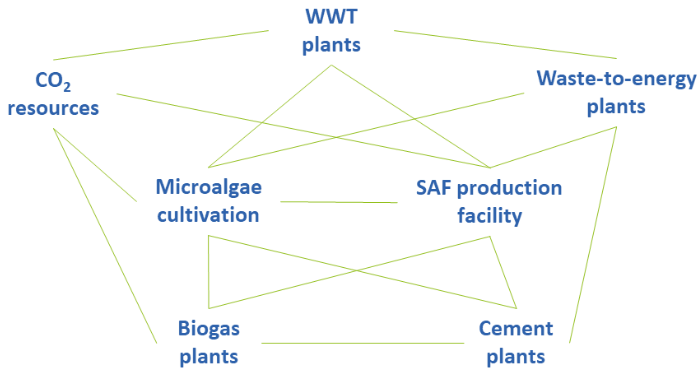
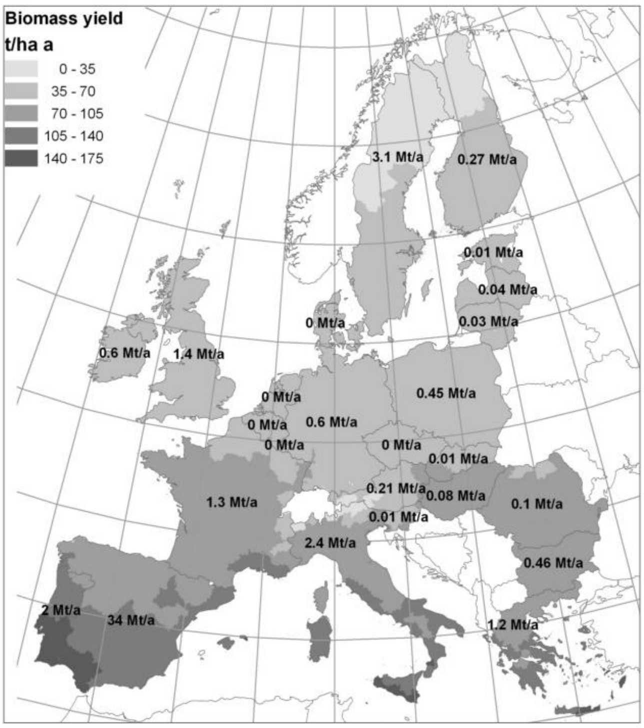


Table 6.2 Illustration of map combining strategy

The first map used presents the microalgae biomass resource potential for each EU's country in $Mt \cdot y^{-1}$ and the mean biomass yield in $t \cdot ha^{-1}\, y^{-1}$ along with a corresponding table of the microalgae biomass yield potential of the top 10 European countries [23]. With this data available and by keeping in mind the EU's goals for the year 2050, it became possible to select the dominant countries, which can support the desired quantity of SAF production per plant. Other maps used for scenarios definition include biogenic and non-biogenic CO_2 availability [14], WWT [24] and waste-to-energy [25] plants in EU, as well as OFMSW and brewery industries as fermentable biogenic sources [26]. These maps along with values for yearly in-plane irradiation from the European commission's photovoltaic geographical information system [27] were exploited to identify the most appropriate and realistic possible combinations of the parameters for the alternative scenarios, building as elaborated below.



* = Biomass is given as dry matter; the mean biomass yield is calculated for the total country area.

Figure 6.3 Map showing the microalgae biomass resource potential [23]

Table 6.3 Microalgae biomass yield potential of the top 10 European countries [23]

Country	Available areas considering restrictions to* LU km²	LU + Slope km²	LU + Slope + PA km²	Yield potential Mean yield** $t\ ha^{-1}\ a^{-1}$	Potential $kt\ a^{-1}$***
Spain	11,284	3,182	2,679	126	33,867
Sweden	10,524	3,568	2,263	22	3,092
Italy	8,583	373	255	102	2,438
Portugal	1,240	288	185	109	2,016
United Kingdom	4,002	747	386	35	1,352
France	8,408	322	145	88	1,268
Greece	1,991	158	127	104	1,203
Cyprus	141	84	75	149	1,109
Ireland	340	116	99	60	587
Germany	495	201	97	60	581
EU-27	54,926	10,136	6,655	78	49,171

* = LU: land use, PA: protected areas
** = mean yield calculated for available areas only
*** = kilotons per year

The experimental results will play a crucial role in further elaboration of the scenarios. It is important to highlight that the proposed scenarios outlined in this deliverable represent the main core. The scope of the project extends beyond these initial scenarios, thus more alternative approaches and strategies will be evaluated comprehensively during the first screenings of the equations and the DSS tool. For example, a future idea that is planned to be applied within the project is to evaluate the integration of the biocrude derived from HTL in existing refineries, under an economic and environmental point of view. The aim of assessing this scenario is to investigate the potential of minimising the equipment cost and the way of potentially converting existing fossil fuel production plants into SAF production plants. Moreover, the CO2 supply will be assessed not only based on the type of source, but also considering the vari-ous costs associated with CO2 (e.g., capture, transportation, etc.). These costs will be crucial and will vary de-pending on the required volume. This approach of setting the initial scenarios and then further expand them serves the dynamic potential of the DSS tool, ensuring a thorough examination of possible outcomes and implications.

The 7 alternative scenarios are presented and summed up in Table 6.4. The maps' combing strategy has been followed in order for the most appropriate and as realistic as possible combinations of the parameters to be tracked down. The following sub-sections provide the description for each scenario.

6.7.1 Scenario 3

The definition of the scenarios, should include a stand-alone scenario, which would implement COCPIT's novelties but would not exploit any external inputs regarding the parameters that are under evaluation. As this is a more pessimistic scenario, the microalgae cultivation is decentralized from the SAF producing plant and is based in France because it is an average country in terms of solar irradiance and microalgae yield potential with 6,768 $\mu mol \cdot m^{-2}\ s^{-1}$ and 88 $t \cdot ha^{-1} y^{-1}$, respectively. This should clarify whether the "beyond the state-of-the-art" technologies applied in the project are indeed optimizing the conventional processes for SAF production.

6.7.2 Scenarios 1&2

Apart from that, two best-case scenarios are built with all desired resources available and their difference relying on the one being decentralized and the other integrated to define the importance on transportation of feedstock, raw materials and utilities environmental- and economic-wise, as well as its hazards and risks. For the carbon dioxide supplement, the industry from which the biggest quantities of biogenic CO_2 are produced in the EU is selected. The most efficient source of hydrogen and VFA's is applied. The location of the plant is in Spain, one of the best EU countries for adequate solar irradiance with 9,417 $\mu mol \cdot m^{-2} s^{-1}$ [27]. Spain also has the higher yield potential of 126 $t \cdot ha^{-1} a^{-1}$ among the EU's countries [23]. In the aspect of biogenic CO_2 supply, Spain's main biogenic CO_2 emissions come from pulp, paper and wood products industry with the produced annual quantity to be 3.18 Mt CO_2 [14]. Regarding the symbiosis with a waste-to-energy plant, in Spain there are 12 such plants treating 3.01 Mt of waste in total [25]. The OFMSW is set as a fermentable biogenic source as an abundant waste stream (6.8 million t in 2021) with high carbohydrate content (45.8% fermentable sugars) [26].

6.7.3 Scenario 4

In this scenario biogenic and non-biogenic CO_2 emissions from biogas production are used as a source for microalgae cultivation. As in Germany a great percentage of biogenic CO_2 comes from biogas production, this scenario is located there. Germany's biogenic emissions from the biogas sector are estimated around 12.18 Mt of CO_2 per year [14]. Moreover, Germany is also selected as the top country in the brewery sector, so brewery effluents were chosen as a fermentable biogenic source. Germany is a mediocre country regarding its solar irradiance its yield potential with 5,663 $\mu mol \cdot m^{-2} s^{-1}$ and 60 $t \cdot ha^{-1} y^{-1}$, respectively [23,27].

6.7.4 Scenario 5

This scenario is located in Poland. Poland is a country with medium solar irradiance of 5,931 $\mu mol \cdot m^{-2} s^{-1}$, but one of the biggest EU's CO_2 emitters, for example 7.37 Mt of CO_2 were produced in Poland in 2021 from cement industry alone [27, 13]. Apart from that, great quantities of carbohydrates can be derived from OFMSW [26]. Poland is a pessimistic choice in the aspect of biomass production as it could only yield around 45 $t \cdot ha^{-1} y^{-1}$ [23].

6.7.5 Scenario 6

Italy, where this scenario is based on, is one of the most applicable countries in the aspect of solar irradiance with 7,503 $\mu mol \cdot m^{-2} s^{-1}$ [27]. Italy also has a great yield potential for biomass production of 122 $t \cdot ha^{-1} y^{-1}$ [23]. In this scenario wastewater treatment is applied and it is considered that not only the microalgae culture is integrated with the WWTP, but also with the SAF production plant. The iron and steel industry were chosen for non-biogenic CO_2 supply, as in Italy 1.51 Mt of CO_2 were produced in 2021 from this industry [13].

6.7.6 Scenario 7

As this scenario includes a waste to energy plant, it is considered that this could be a biogas-producing plant having a dual role as CO_2 source. As Sweden is the country with the biggest quantity of reported biogenic CO_2 emissions with 6.68 Mt of CO_2 per year [14] coming from the power generating sector, it was chosen for this scenario. This scenario includes symbiosis with sewage sludge, so it might be better to be formed as an integrated scenario. As Sweden has lower solar irradiance 4,848 ($\mu mol \cdot m^{-2} s^{-1}$) and lower yield potential (22 $t \cdot ha^{-1} y^{-1}$), this scenario will be defining the importance and contribution of the other parameters applied in this scenario to the final outcome and results [23,27].

Table 6.4 Proposed alternative scenarios of COCPIT project based on maps combining strategy

	Country	Integrated vs Decentralized	CO2 resources	Solar irradiance		Wastewater treatment	Symbiosis with waste-to-energy plants	Fermentable biogenic sources	Symbiosis with sewage sludge
				($kWh \cdot m^{-2}$)	($\mu mol \cdot m^{-2} s^{-1}$)				
Scenario 1	**Spain**	**Integrated**	**Biogenic** (paper pulp and wood industry)	**2,047**	**9,417**	✓	✓	**OFMSW**	✓
Scenario 2	**Spain**	**Decentralized**	**Biogenic** (paper pulp and wood industry)	**2,047**	**9,417**	✓	✓	**OFMSW**	✓
Scenario 3	**France**	**Decentralized**	✗ **(ambient)**	**1,471**	**6,768**	✗	✗	✗	✗
Scenario 4	**Germany**	**Decentralized**	**Biogas**	**1,231**	**5,663**	✗	✗	**Brewery** (Wastewater and brewery spent grains)	✗
Scenario 5	**Poland**	**Decentralized**	**Non biogenic** (Cement industry)	**1,289**	**5,931**	✗	✗	**OFMSW**	✗
Scenario 6	**Italy**	**Integrated**	**Non biogenic** (Steel industry)	**1,631**	**7,503**	✓	✗	✗	✗
Scenario 7	**Sweden**	**Integrated**	**Biogenic** (power generating)	**1,054**	**4,848**	✗	✓	✗	✓

7 Relation of the alternative scenarios with COCPIT decision tool

7.1 Design, functionality and overview of the Decision Support System (DSS)

The main objective of the COCPIT decision support tool is to assist investors, end-users, and biofuel producers in selecting, forecasting, and efficiently operating within various conversion pathways based on different scenarios, considering current or future uncertain parameters. The tool's users are divided into two categories: investors and operational users. Investors, seeking new opportunities or upgrades to existing investments, analyse the state of underlying processes, assess suitable conversion pathways in defined scenarios, and predict optimal pathways. Operational users, on the other hand, focus on optimizing pathways for efficient operation of processes, considering current and future parameters, aiming to enhance resource and operational efficiency by reducing operational expenses (OPEX), maximizing by-product recovery, minimizing energy consumption, environmental impact and raw material loss. Both user groups play a multifaceted role in evaluating the sustainability status (e.g. GHG savings) and profitability risk of alternative SAF production routes. The tool integrates process data, including operational data from SAF production processes via microalgae conversion, and domain knowledge, such as methodologies, equations, and interpreted data used in assessments. More specifically:

- Process design to develop alternative process flow sheets for SAF production via microalgae conversion
- Estimation of material and energy balances as well as sizing of unit operations at different plant capacities
- Optimization of a specific unit operation
- Estimation of TEA (e.g. MSP, FCI etc.), LCA (e.g. Global Warming Potential) and s-LCA indicators
- Evaluation of process profitability risk assessment via Monte-Carlo simulations.

Additionally, the tool will access fixed parameters according to literature and databases such as solar radiance in each region and the ability to determine CO_2 resource parameters based on sustainability indexes, facilitating informed decision-making for sustainable SAF biofuel production. The entire methodology will be fed by the different prospective scenarios that have been defined in Chapter 6 and the quantification of each parameter.

7.2 User Inputs and Output Parameters of the Decision Support System (DSS)

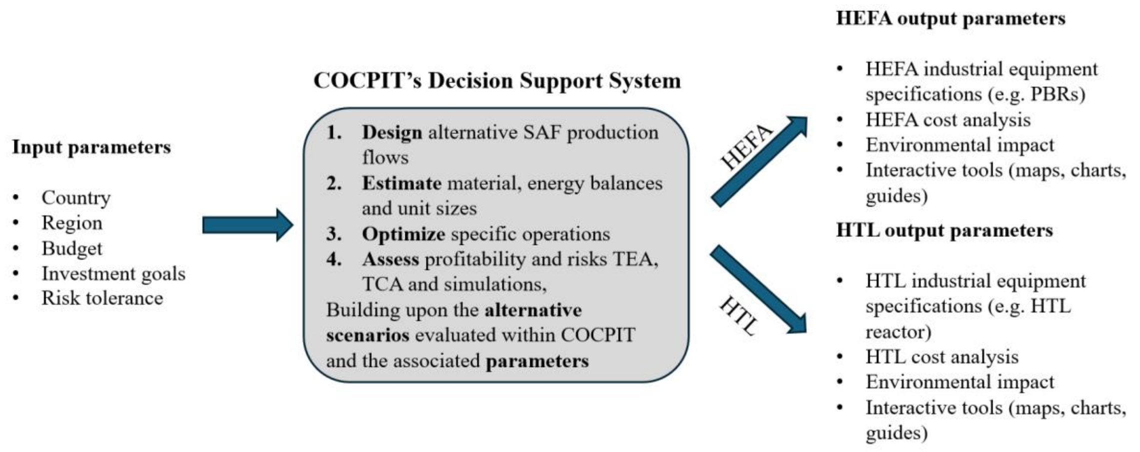


Figure 7.1 DSS tool concept

As depicted in Figure 7.1, user input will encompass critical factors such as the selection of the country and area for potential investment, production capacity, and investment budget. For example, an investor based in Europe may input parameters such as available land area in Spain, production capacity of 10,000 litres per month, and a budget of €1 million.

Output parameters will include detailed information on equipment elements, investment costs, operational costs, revenues, and environmental considerations, which will be monetized to integrate into the overall investment cost. For instance, output parameters may include the cost breakdown of photobioreactors, harvesting equipment, and processing facilities, along with estimated revenues and carbon footprint assessments. The DSS tool will offer outputs tailored to each method (HTL vs HEFA), unless the user specifies a preference, while all other parameters will be handled within the system. For example, if a user expresses interest in HTL technology, the DSS tool will provide detailed projections on equipment costs, energy requirements, and environmental impacts specific to this method. Process simulations will underpin the calculation of output parameters, ensuring accuracy and reliability. For instance, simulations will model the growth rates of microalgae, energy consumption during cultivation, and the efficiency of biofuel extraction processes.

A more detailed workflow highlighting the inputs and functions is presented in the next diagram.

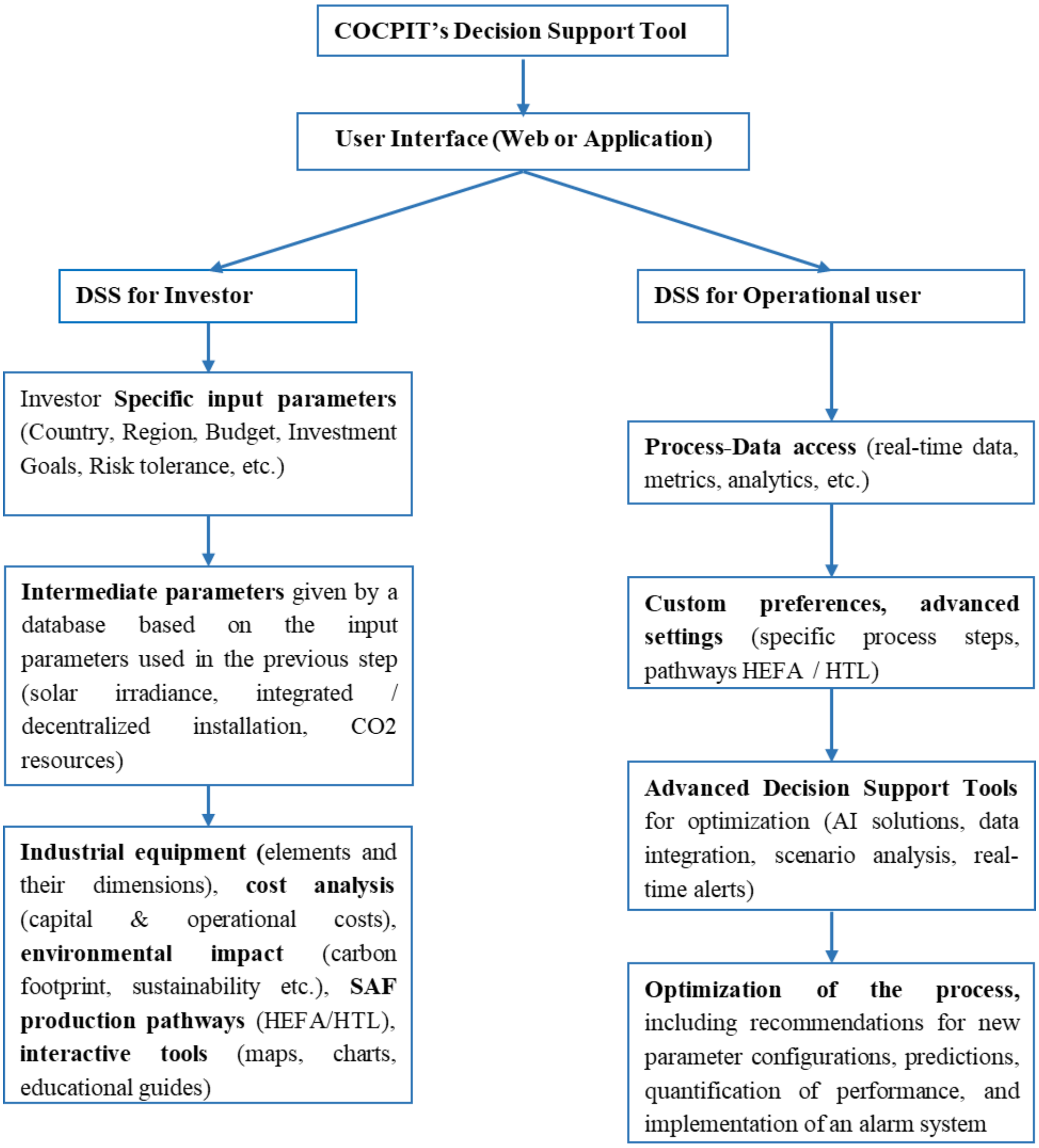


Figure 7.2 DSS tool workflow

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