D7.1 Preliminary LCA

FLEXBY

FLEXIBLE AND ADVANCED BIOFUEL TECHNOLOGY THROUGH AN INNOVATIVE MICROWAVE PYROLYSIS & HYDROGEN-FREE HYDRODEOXYGENATION PROCESS

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EXECUTIVE SUMMARY

This document corresponds to the technical report "*Preliminary LCA*" (Deliverable 7.1) and it presents the results of the preliminary Life Cycle Assessment (LCA) of the Flexby technology, conducted by **GD** with the support of the project consortium. The study follows the ISO 14040/44 standards and includes all key LCA components, from goal and scope definition to life cycle inventory and impact assessment. A sensitivity analysis was also carried out to explore alternative scenarios, alongside a proposal for future work toward the complete cradle-to-grave LCA of the Flexby system, scheduled for Month 48.

Several coordination meetings were held with project partners to define the Flexby product system and collect relevant process data. **FRIMA** contributed with information on the design and energy requirements of the microwave pyrolysis reactor. **CSIC** contributed with experimental data on conventional slow and flash pyrolysis product yields and energy inputs for different feedstock scenarios, as well as insights on biochar activation. **PMI** provided simulation outputs and energy and mass balances from process modelling in Aspen Plus and HYSYS. **IDE** offered insights on coordination with partners and potential process optimization. **A4F** supplied data related to microalgae cultivation, while **US** provided data on the upgrading of both liquid and gaseous pyrolysis fractions into final fuel and H_2-rich gas products. These collaborative efforts ensured data consistency and alignment across the LCA framework.

To ensure methodological robustness and comparability, **GD** also performed a state-of-the-art review of existing LCA studies related to pyrolysis-based and biomass-to-biofuel systems. This review helped address common challenges and informed key modelling decisions.

The resulting LCA models were built in openLCA, focusing on two feedstocks: **Feedstock 2** (microalgae-based wastewater residues) and **Feedstock 5** (dairy-based oily sludge). Multiple process scenarios were simulated to assess the environmental performance of the Flexby system against conventional pyrolysis technologies. Environmental impacts were calculated using the Environmental Footprint (EF) 3.1 method, with a focus on identifying key hotspots and understanding the relative sustainability of the Flexby approach.

1 INTRODUCTION

1.1 DESCRIPTION OF THE DOCUMENT AND PERSUE

This report, Deliverable 7.1, titled "Preliminary LCA," is submitted in month 12 of the FLEXBY project. It presents the initial life cycle assessment (LCA) of the Flexby technology at its early development stage. In particular, the report includes:

- A state-of-the-art review of LCA studies on similar technologies to support comparability,
- The goal and scope definition following ISO 14040/44 standards, the description of the system boundaries, functional units, and assumptions applied,
- The inventory data collection approach and modelling in openLCA software,
- The preliminary environmental impact results using the Environmental Footprint (EF) 3.1 method,
- A sensitivity and scenario analysis to assess key variables and technological choices,
- Recommendations for future work leading to the full LCA at project Month 48.

This document provides the foundation for guiding the ongoing development and optimization of the Flexby system from an environmental sustainability perspective.

1.2 WPS AND TASKS RELATED WITH THE DELIVERABLE

This deliverable refers to Task 7.1: Life Cycle Assessment (Task Leader: GD; Other partners: ALL) [M01-M48] included on WP7: Sustainability assessment.

Task 7.1:

The environmental performance of the Flexby system will be evaluated by conducting LCA by GD, in accordance with ISO standards 14040 and 14044. An inventory of Flexby biogenic emission flows will be firstly created, including: (1) emissions generated in the MW-pyrolysis and pyro-gas section; (2) avoided emissions from the biofuel production and H2-free HDO; and (3) negative emissions from use of bio-char. For quantification of *all emission streams, an assessment of underlying uncertainties will also be performed. Environmental impacts will then be studied by GD with the support of ALL partners at several midpoints as well as endpoint impact categories related to: 1) human health; 2) ecosystems; and 3) resource availability, following the Environmental Footprint methodology. Background data for the impact assessment will be taken from relevant databases such as ECOINVENT. Modelling to be conducted here (and during other WP tasks) will be conducted adopting open source LCA software. Information regarding biomass feedstocks and the subsequent processing steps will be collected and provided by the Flexby consortium. The LCA will include a hotspot analysis to identify optimisation potential. The biofuel products will be compared to conventional fossil fuel products in support of task T6.3 led by GALP.*

1.3 NOTE ON TERMINOLOGY

Throughout this document, the term **"conventional pyrolysis"** is used as a general term to distinguish processes based on traditional heating methods (such as electric furnaces) from the microwave-assisted (MW) pyrolysis system developed within Flexby. Under the term **"conventional"** for pyrolysis, both **slow pyrolysis** and **flash pyrolysis** are included, as they are carried in electric furnaces instead of a MW system. Specifically, **slow conventional pyrolysis** refers to a process conducted in an electric furnace with a heating rate of 25 °C/min, an operating temperature of 500 °C and a residence time of 60 minutes. **Flash conventional pyrolysis** refers to a process conducted in an electric furnace where the final operating temperature of 500 °C is reached within seconds, and a residence time of 10 minutes. Similarly, **"conventional drying"** refers to moisture removal processes performed in an electric oven. The residence time and quantity of feedstock processed were based on the results presented in Deliverable 2.1 and subsequently scaled up for modelling purposes to 100 kg of feedstock (prior to drying) processed per hour.

Conversely, **microwave pyrolysis** is assumed to operate in a MW system, at a temperature of 700 °C, in line with available literature data (Du et al., 2011) with a capacity of 2 kg of feedstock. The process simulation by PMI in D2.3 was carried out using 100 kg/h of feedstock and the LCA model reflects this using as reference a flow processing rate of 100 kg of feedstock per hour. However, as experimental tests on the microwave system have not yet been conducted, this terminology and associated operating conditions (e.g., temperature, residence time) may be refined as the project progresses and further experimental data becomes available.

2 Coordination Among Project Partners and General Requirements

GD organized several online meetings and updates with the technical partners involved in the project, specifically:

- **A4F**, to discuss the data collection required to model the microalgae cultivation process,
- **FRIMA,** to discuss the data collection required to model the construction phase of the microwave reactor,
- **CSIS**, to discuss the data collection required to model i) the drying process of the feedstock, ii) pyrolysis of dried feedstock, iii) physical activation of the biochar,
- **US**, to discuss the data collection required to model the iv) pyro-gas reforming, v) use of the reformed gas in SOFC cells, vi) hydrogen-free Hydrodeoxygenation of the pyro-liquid,
- **PMI**, to obtain simulation data for processes that have yet to happen,
- **IDE**, to help with the coordination between partners and provided feedback on potential process optimisation.

The collaboration and diverse expertise of the partners facilitated the exchange of essential data for the preliminary LCA, helping to define the initial model and identify key impact areas. Primary data was collected, when possible, but, due to the early stage of the project, simulations and assumptions were implemented when necessary. Each meeting will be summarized, focusing on the key data shared by the partners, which were instrumental in shaping the LCA's foundational analysis.

A4F-GD meeting

A4F successfully completed the cultivation of microalgae at lab scale as part of WP2. Therefore, they could provide primary data for their process at this scale. Additionally, **A4F** offered insights into how the process will be scaled to a higher TRL, which will be considered in the final LCA study to ensure an accurate assessment of the environmental impacts at later stages of development.

FRIMA-GD meeting

FRIMA provided data on the microwave design they are working on, including the expected lifetime of main components, electricity demand, cleaning procedures, and working hours within Flexby technology. However, since the design is not yet completed, specific information could not be obtained. As a result, it was decided to exclude the machinery stage from the current LCA and focus on energy requirements.

CSIC-GD meeting

CSIC is conducting lab-scale tests on the conventional drying of the feedstocks and conventional slow and flash pyrolysis, to evaluate the yields and compare their energy requirements with those of MW drying and pyrolysis. They played a key role in identifying the scenarios to be assessed. Feedstocks 2 and 5 were selected for consideration. Feedstock 5 was considered instead of Feedstock 6 (Feedstock 6 was used in the simulations presented in Deliverable 2.3, based on the tests in Deliverable 2.1, however **PMI** provided updated simulation data for Feedstock 5 as well for this task) due to its greater availability and its close similarity in origin, which made it a suitable alternative for maintaining consistency in the analysis. The composition of F5 varies and when characterized for Deliverable 2.1 it was similar to Feedstock 2, while in more recent samples it is closer to Feedstock 6. The work presented in this report is based on D2.1.

Feedstock 2 has been tested in both conventional slow and flash pyrolysis (see chapter 1.3 for details on terminology); Feedstock 5 has, so far, only undergone slow conventional pyrolysis. Since **CSIC** does not have access to the microwave system developed by **FRIMA** yet, it was decided to benchmark conventional pyrolysis against **PMI**'s simulations of MW pyrolysis energy requirements.

Additionally, **CSIC** provided data on other processes, including the transportation and storage of feedstocks, which are currently inefficient due to logistical constraints specific to this stage—issues that will not persist at the pilot scale. The biomass is associated with odorous substances due to the wastewater sludge, with Feedstock 5 being the most odorous. To address this, small quantities of biomass are transported, to maximize its use while mitigating social concerns related to odor dispersion. Regarding Feedstock 2, a discussion with **A4F** led to the decision to explore pre-drying options before shipping, to avoid transporting large amounts of water that also require refrigeration.

Finally, **CSIC** are not yet conducting the biochar activation process and therefore the energy requirements could not be considered here, instead the biochar, without further processing, is considered the product of pyrolysis.

US-GD meeting

US provided data on gas separation, WSG process and steam reforming for hydrogen-rich gas production, as well as H_2-free hydrodeoxygenation for biofuel production. They also shared information on the catalysts that will be implemented and the overall approach. However, since they will begin conducting tests at a later stage in the project, their data includes assumptions and literature-based estimates. Additionally, they helped define which data should be taken from **PMI**'s simulations of the process.

Regarding the battery cell, **US** clarified that, due to the composition of the gas streams, a SOFC cell will be used instead of a PEM cell. Under the current Flexby configuration, PEM cells are not a viable option because the pyrolysis gas, both before and after upgrading, contains CO. Given thermodynamic constraints, CO would poison the PEM anode, rendering the fuel cell inoperative. In contrast, SOFCs are more tolerant to a wider range of impurities and can efficiently handle the gas composition. Additionally, since some methane will remain in the upgraded pyrolysis gas, SOFCs can also utilize methane alongside hydrogen, further enhancing electricity production in the fuel cell.

PMI-GD meeting

PMI contributed to defining the Functional Unit of the LCA and provided key simulations for the study. They helped estimate the electricity required for microwave-based drying, pyrolysis, and further processing of bioliquid and biogas.They also addressed energy and physical property estimations for the gaseous fraction and the potential applications of the resulting biofuel.

IDE-GD meeting

Dedicated meetings were also held with **IDE**, who supported coordination efforts among partners involved in the task. The exchanges helped to align on data availability, clarify technical details, and communicate the structure and boundaries of the LCA model, helping shape the assumptions and focus areas of the preliminary study. **IDE** also provided input on potential process optimization strategies, particularly related to system efficiency improvements, which will be explored in future development phases.

3 State-of-the-Art

LCA is as a critical tool for evaluating the environmental performance of emerging technologies. In the context of Flexby, which integrates the use of two different feedstocks, microwave-assisted pyrolysis, gas reforming, hydrodeoxygenation (HDO), and biochar activation, the need for a robust and adaptive LCA methodology is particularly relevant given the novelty of the combined system.

In recent years, a growing body of research has focused on LCA applied to biomass-to-biodiesel pathways, including pyrolysis-based systems (Chamkalani et al., 2020; Elfallah et al., 2024; Ketzer et al., 2018; Ubando et al., 2019; Yu et al., 2022). Despite this expansion, there remains no consensus on how to conduct LCAs in a standardized and comparable manner across these technologies. Reviews have generally pointed out methodological inconsistencies, particularly in defining system boundaries, functional units, and allocation procedures. This lack of harmonization limits the comparability of results and reduces the usefulness of LCA as decision-making tool.

A key point of contention in the literature is the definition and application of functional units (FUs). Reviews consistently note a lack of consistency in FU choice, which can obscure interpretation and limit comparability across studies. While mass- or volume-based FUs are common, service- or energy-oriented units for biofuel systems are recommended, as they better reflect the function of the output and improve understandability (Chamkalani et al., 2020; Yu et al., 2022).

System boundary selection is another critical challenge in conducting meaningful LCAs for multifunctional systems. The literature includes both cradle-to-gate and cradle-to-grave perspectives but often lacks clarity in accounting for co-products such as biochar, syngas, or liquid fractions. Allocation methods vary widely; some studies use energy- or mass-based allocation, while others adopt System Boundary Expansion (SBE) to account for avoided burdens. Chamkalani et al. (2020) recommend SBE as the preferred strategy in multifunctional systems, as it provides more transparency and reflects system-level trade-offs more effectively. In the case of Flexby, both allocation and SBE approaches will be explored to model the environmental implications of valorising all output streams, including activated biochar (Ferrera-Lorenzo et al., 2014), thereby reducing environmental burden and increasing resource circularity. In this study, only physical allocation was considered.

Given this general lack of harmonization, Bradley et al. (2017) proposed to use a FU based on "the combustion of 1 MJ (LHV) of algal biofuel in a car engine," and System Boundaries which include upstream infrastructure construction, cultivation, conversion, and downstream combustion. While this approach suits light-duty fuels better, Flexby's final LCA will adapt, for the final, complete LCA study, a similar logic tailored to biofuels for heavy transport applications, ensuring consistency with ISO 14040/44 and RED standards.

Feedstock choice and variability also have significant implications for LCA outcomes. Algae-based biofuels have been extensively studied (Ağbulut et al., 2023) and while they offer promising integration with wastewater treatment and biogenic carbon uptake, they are typically associated with high energy and water demands during cultivation, potentially compromising the energy return on investment (EROI) of the system (Ketzer et al., 2018; Yu et al., 2022; Chamkalani et al., 2020). Flexby aims to mitigate these concerns by sourcing, at higher TRL, algae waste that naturally grows in wastewater, thereby eliminating the need for energy-intensive cultivation. The sludge feedstock derived from dairy wastewater also represents a valuable resource and must be carefully modelled due to its compositional variability and potential presence of contaminants. As Ubando et al. (2019) note, ash and residue disposal remain critical but underexplored issues in biofuel LCAs—an issue Flexby aims to overcome by valorising all fractions of the pyrolysis process.

Moreover, the literature emphasizes the energy intensity of thermochemical processes. Drying, in particular, has been identified as a major energy sink (Chamkalani et al., 2020), while catalyst deactivation—especially due to sulphur content in algal biomass—remains a known technical risk in reforming and upgrading stages (Yang, 2017). Flexby aims to overcome these challenges using a microwave drying and pyrolysis system instead of a conventional one, along with an integrated design that includes a combined reformer and water-gas shift reactor. Furthermore, the Hydrogen-free hydrodeoxygenation requires water injections, which might reduce the need for complete feedstock drying, reducing energy consumption at a critical stage. In addition, the project applies Multidisciplinary Design Optimisation to enhance overall system efficiency.

Overall, these innovations, while still under development, are expected to improve technological efficiency and environmental performance of the Flexby system.

Another notable gap in the literature is the limited inclusion of downstream upgrading processes—such as hydrodeoxygenation and product refining—in LCA studies. Most assessments focus on bio-oil production but stop short of evaluating the full environmental impacts of converting bio-oil into usable transport fuels (Yu et al., 2022). Flexby addresses this gap by aiming to include the entire chain from waste feedstock to final upgraded biofuels, allowing for a more comprehensive evaluation of sustainability performance in the final LCA study. While the current preliminary LCA adopts a gate-to-gate perspective, it already encompasses all operational phases, not just the pyrolysis, to provide a picture of energy requirements up to the production of the final biofuel.

Given this overview and the early stages of Flexby technology, this preliminary LCA does not aim to deliver definitive results. Instead, it is designed as a flexible and informative tool to guide decision-making during the design and optimization phases of the project. It will help identify environmental hotspots and support the development of mitigation strategies, ultimately feeding into a full cradle-to-grave Life Cycle Sustainability Assessment (LCSA) in Month 48.

4 Goal and scope

The goal of this preliminary LCA is to evaluate the potential environmental impacts associated with the operation phase of the Flexby technology. The assessment aims to identify key impact hotspots, compare conventional and microwave-assisted pyrolysis processes (see Table 2 for details on scenario) and inform future improvements as the technology advances. Given the early stage of development, the study focuses on a gate-to-gate system boundary, covering resource use, emissions, and energy requirements during operation. This scope allows for a consistent comparison between different scenarios and pyrolysis methods, while setting the basis for a more comprehensive assessment to be completed in later project stages.

4.1 Reasons, project goal and intended application

The preliminary LCA of the Flexby technology is conducted to provide an early assessment of its environmental performance, focusing specifically on the operational phase of the system. The study uses the Environmental Footprint (EF 3.1) method for impact calculation, with particular emphasis on climate change impacts, and is aligned with ISO 14040 and 14044 standards. This early-stage analysis evaluates emissions and resource use associated with microwave-assisted pyrolysis and the subsequent production of biofuels and H_2-rich gas, based on available experimental and simulated data. Although biochar is included in the system outline, its activation and end-use are not yet modelled and will be addressed in the final LCA. This early-stage analysis is intended to support technology development by identifying key environmental hotspots, critical assumptions, and opportunities for improvement, laying the groundwork for a more complete assessment at a later stage.

4.2 Intended audience

This preliminary LCA report (Deliverable 7.1) is intended primarily for internal use within the Flexby consortium. It serves as a basis for collaboration among partners by providing early insights into environmental impacts. The findings will support ongoing technology optimization and contribute to a shared understanding of sustainability challenges and opportunities within the project.

Additionally, as a public deliverable, this report may also serve as a useful reference for external technical stakeholders seeking insights related to LCA modelling of emerging biofuel technology, especially when involving pyrolysis systems. Given the methodological diversity currently present in the literature about similar systems (see chapter 3), this report therefore contributes to the broader scientific and technical discourse by offering a well-documented case study that can help inform future assessments.

4.3 Product system and function

The function of the Flexby system is to produce 1) advanced biofuel and 2) electricity from pyro-gas, using biogenic waste in the form of microalgae cultivated in domestic wastewater as well as oily sludge from wastewater treatment plant serving a dairy processing facility. As a by-product FLEXBY will produce biochar that will be re-use in different section of the process. Figure 1 provides an overview of the Flexby process.

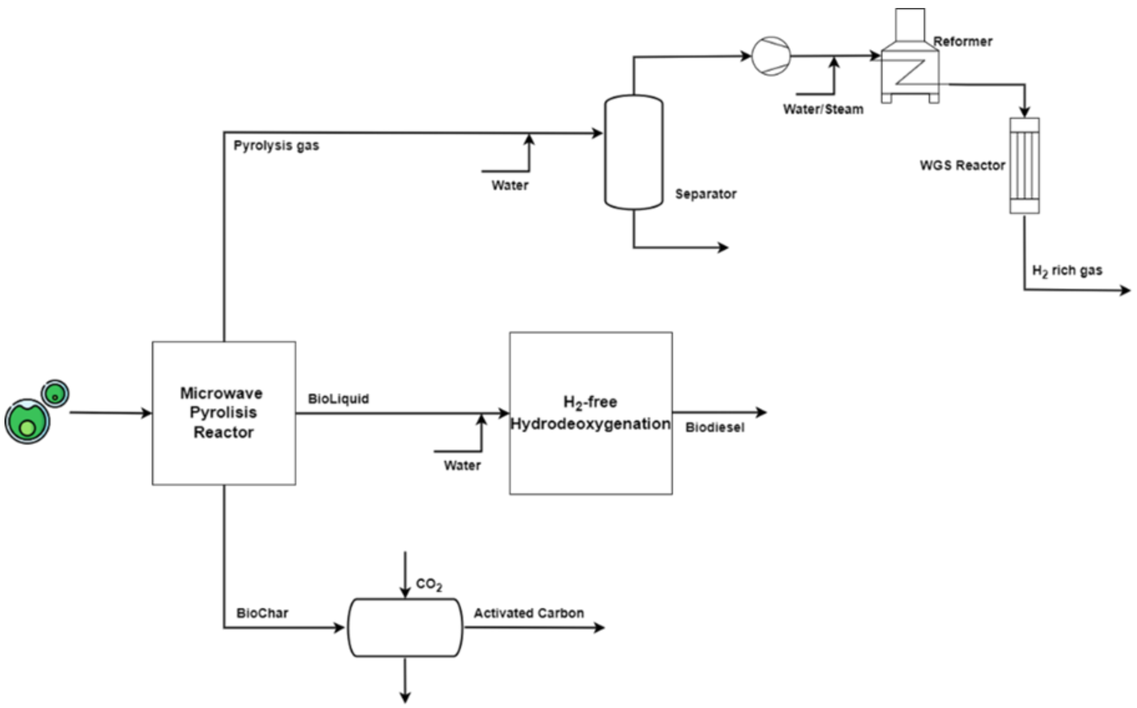


Figure 1: Block Flow Diagram of the Flexby process.

The feedstock is introduced into the MW pyrolysis reactor (with drying if required). The resulting three fractions are then collected and processed separately. The MW reactor operates at a maximum power of 3 kW and has a capacity of 2 kg of wet feedstock. The pre-design of the MW reactor, provided by **FRIMA**, is shown in Figure 2.

The operation phase of the unit is divided into 2 stages: the first stage is the drying process, hot air enters from the top and vapor is recovered to reduce the humidity of the feedstock; In the second stage, nitrogen is introduced (also from the top) to inert the environment before pyrolysis begins. The maximum temperature of the product reaches approximately 700°C, in line with literature data (Ferrera-Lorenzo et al., 2014).

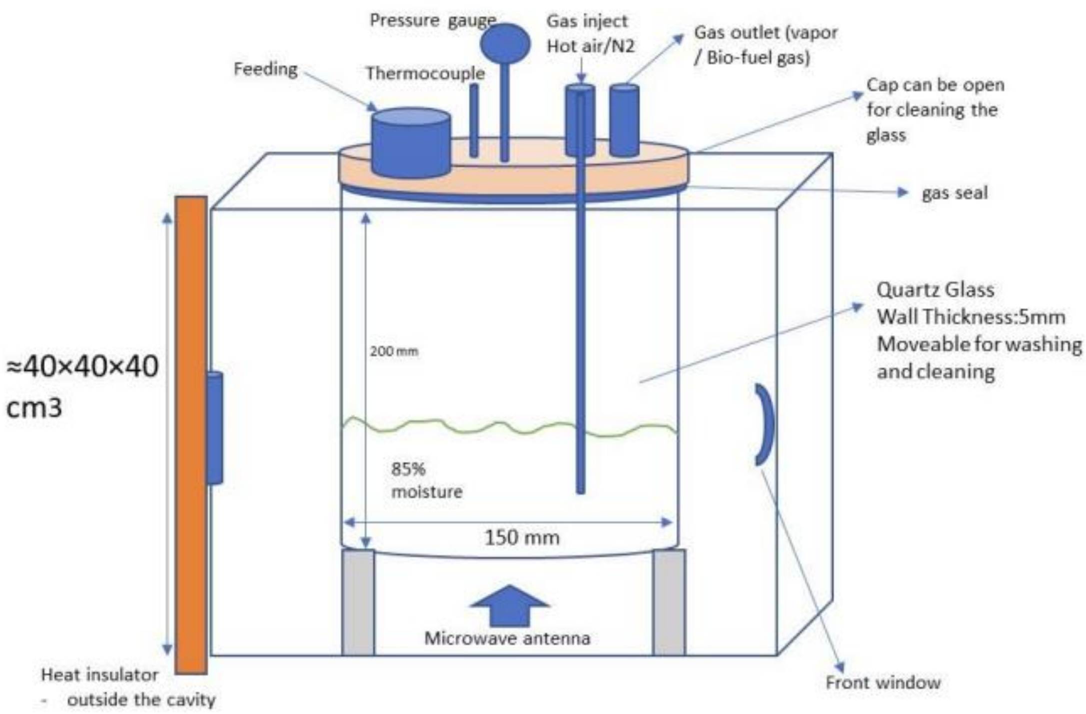


Figure 2: Pre-design of the Microwave Pyrolysis Reactor.

For the bioliquid pathway, H_2-free hydrodeoxygenation is a batch process working at approximately 150 bar and 250-300 °C, with a residence time ranging from 1 to 12 hours. The experimental tests of this unit will require 25 to 50 ml of the bio-liquid mixture, mixed with 40 mL of water.

The pyrolysis gas must be post-processed to obtain H_2-rich gas. The preliminary process scheme consists of:

- A separator to remove water from the gas mixture,
- A reforming unit, which enables the nearly complete conversion of methane into hydrogen, carbon monoxide, and carbon dioxide,

A water-gas shift (WGS) reactor, where water is added before the reaction to enhance hydrogen production. Pressures and temperatures have been selected based on literature data and industrial standards (Caballero et al., 2022; Saeidi et al., 2017). However, since the primary objective is hydrogen production for electric energy generation in a fuel cell, the reformer pressure is limited to 4 bar, aligning with the operating pressure required by fuel cells (Askaripour, 2019).

The final applications of the biochar fraction are still under investigation. It can be re-used directly (mixed with the feedstock to heat easier the process in the microwave) or it may be physically activated to obtain a porous carbonaceous material that can be used as support in the catalysts. The biochar could be used as soil amendment.

The lab-scale experimental tests will be conducted in batch mode. However, the pilot-scale plant, which will be installed at US facilities, will operate continuously. To ensure a stable flow of gas and liquid for post-processing, buffer units will be installed between the MW pyrolysis reactor and the rest of the process.

4.4 Functional unit

For the functional unit, the bioliquid fraction which after undergoing further purification steps, results in the advanced biofuel, is considered as the product of interest. Biochar and pyrogas are produced as valuable by-products. Hence, the following functional units are considered in relation to each product that is obtained from the product system in this study:

- 1 kWh of electricity produced from a solid-oxide fuel cell by utilizing the pyro-gas
- 1 kg of pyrolysis bioliquid that can be combusted for use in a transport vessel
- 1 kg of biochar produced

4.5 System boundaries

Based on insights from all meetings with partners, it was decided to proceed with gate-to-gate system boundary, focusing on the operation life cycle stage of Flexby. This approach allows for a detailed assessment of energy requirements and impact hotspots during operation while also enabling a comparison between conventional and MW pyrolysis systems. However, cradle-to-gate data are implemented for the electricity and water datasets.

By isolating this stage, we can better understand process efficiencies, emissions, and resource consumption, ensuring a solid evaluation of Flexby's operational phase performance. The operational stage—particularly pyrolysis, reforming, and hydrodeoxygenation—is recognized as energy-intensive, especially when dealing with chemically heterogeneous and high-moisture biomasses (Chamkalani et al., 2020; Yu et al., 2022). Moreover, most existing LCA studies on bio-oil production tend to stop at the pyrolysis stage and do not include subsequent upgrading steps into higher-value biofuels, which are critical to understanding the true sustainability of these systems (Yu et al., 2022; Elfallah et al., 2024). Flexby addresses this by including these post-processing stages already at the preliminary stage of the LCA.

4.6 Data requirements and data collection

Data for the LCA was collected through regular technical exchanges and coordination calls with project partners, during which process insights, operational conditions, and system configurations were discussed. To support consistent and structured data gathering, **GD** developed and distributed customized Excel templates tailored to each partner's scope of work (see Annex 1). These templates were organized by process stage and included dedicated sections for inputs, outputs, emissions, and resource use. While primary data was collected whenever available—especially from lab-scale tests—gaps were filled using simulations (mainly supported by **PMI**) and literature, particularly for technologies not yet implemented. The templates also included fields for processes not currently modelled in the preliminary LCA (e.g., machinery or end-of-life) to ensure completeness for the final assessment.

4.7 Data quality control

Data quality was not assessed for this task.

4.8 Allocation procedure

Allocation is applied to partition the flows of a process when this produces two or more products as output. The pyrolysis process has three output streams – the bioliquid, pyro-gas and the biochar. The three streams are all further processed into the final products of activated biochar, heavy transport biofuel and electricity. The quantitative reference amongst these is the biofuel, making the pyro-gas and activated biochar the by-products. A sensitivity study was performed to analyse the impacts of allocation choices on the results. Physical allocation was performed in this study, based on the physical property of mass, to allocate the impacts of pyrolysis to the three pyrolysis fractions. Economic allocation, physical allocation based on mass and energy values as well as system expansion will be included in the sensitivity analysis of allocation procedures in our future studies.

4.9 Assumptions

Given the early stage of the Flexby process, the preliminary LCA relies on a combination of primary data, simulations, and literature sources. When direct measurements or operational data were not available, assumptions were made based on analogous processes, expert input from partners, and process simulations. These assumptions are documented in detail for every process in the LCI section.

4.10 Calculation

The calculations are performed with the open-source software openLCA, v2.4.1, with ecoinvent v3.11 cutoff unit processes as background database.

4.10.1 Impact assessment methods and impact categories

The Life Cycle Impact Assessment (LCIA) method used will be Environmental Footprint v3.1 (EF v3.1). As of now, circularity and plastic littering will not be considered, as they are not deemed relevant to the product system in object.

Table 1 - Impact Categories and Reference Units of Method EF 3.1

Impact Category	Reference unit
Acidification	mol H^+ eq
Climate change	kg CO_2 eq
Climate change (biogenic)	kg CO_2 eq
Climate change (fossil)	kg CO_2 eq
Climate change (land use)	kg CO_2 eq
Ecotoxicity freshwater	CTUe
Ecotoxicity freshwater (inorganics)	CTUe
Ecotoxicity freshwater (organics)	CTUe
Eutrophication freshwater	kg P eq
Eutrophication marine	kg N eq
Eutrophication terrestrial	mol N eq
Human toxicity cancer	CTUh

Human toxicity cancer (inorganics)	CTUh
Human toxicity cancer (organics)	CTUh
Human toxicity non-cancer	CTUh
Human toxicity non-cancer (inorganics)	CTUh
Human toxicity non-cancer (organics)	CTUh
Ionising radiation (human health)	kBq U235 eq
Land use	dimensionless (pt)
Ozone depletion	kg CFC11 eq
Particulate matter	disease incidence
Photochemical ozone formation (human health)	kg NMVOC eq
Resource use fossils	MJ (net calorific)
Resource use minerals and metals	kg Sb eq
Water use	m^3 world eq

4.11 Interpretation of results and sensitivity analysis

To evaluate the results of the preliminary LCA, impact categories as stated in the section are considered, with emphasis on climate change. The results are used to identify environmental hotspots within the various processes, with a particular focus about energy requirements. In addition, scenario analysis is conducted to test the key assumptions that could significantly influence the outcomes (see chapter 1.3 for details on terminology). The tested scenarios include:

Table 2 - Definition of scenarios for sensitivity analysis

Scenario	Feedstock	Pyrolysis Details
S2.1	Microalgae	Dried using microwave technology and processed through microwave pyrolysis
S2.2	Microalgae	Conventionally dried and processed through conventional slow pyrolysis
S2.3	Microalgae	Traditionally dried and processed through conventional flash pyrolysis at moderate temperature
S5.1	Dairy-based oily sludge	Dried using microwave technology and processed through microwave pyrolysis
S5.2	Dairy-based oily sludge	Conventionally dried and processed through conventional slow pyrolysis

For the conventional slow and flash pyrolysis scenarios used to benchmark the Flexby microwave system, we selected the configurations that yielded the highest amounts of bio-oil and pyro-gas for the two feedstocks under consideration, based on **CSIC** tests, where multiple configurations were evaluated. The tables below present the three product fractions obtained from the microwave pyrolysis reactor for the two feedstocks (2 and 5), as derived from **PMI** simulations and reported in Deliverable 2.3 – *Requirement List for the TRL4 Flexby System*.

Table 3 - Products of the microwave pyrolysis of Feedstock 2 as simulated by ***PMI***

Pyrolysis Gas		Bio Liquid		Solid	
Component	Mass Flow (kg/h)	Component	Mass Flow (kg/h)	Component	Mass Flow (kg/h)
Hydrogen	0.1109	Pyrrole	1.3863	Char	2.1042
CO_2	1.5406	$C_8H_{14}O_4$	5.9794	Ash	3.5300
CO	0.5311	Toluene	0.0537		
Methane	0.1984				
Ammonia	0.3502				
Total	2.7311	Total	7.4194	Total	5.6442

Table 4 - Products of the microwave pyrolysis of Feedstock 5 as simulated by ***PMI***

Pyrolysis Gas		Bio Liquid		Solid	
Component	Mass Flow (kg/h)	Component	Mass Flow kg/h	Component	Mass Flow kg/h
Hydrogen	0.0329	Pyrrole	1.8359	Char	2.1068
CO2	1.2422	C8H14O4	4.8696	Ash	3.5800
CO	0.4611	Toluene	0.3331		
Methane	0.4046	Benzene	0.1641		
Ammonia	0.4676				
Total	2.6085	Total	7.2026	Total	5.6968

4.12 Limitations

Since the project development and Flexby technology are still in their early stages, data on machinery and end-of-life could not be collected for this preliminary LCA. Therefore, this study focuses on the resources and emissions of the operation phase, comparing simulations of Flexby technology with traditional alternatives.

4.13 Critical review

Not necessary for this study. However, the results are shared and discussed with the partners.

5 Life Cycle Inventory and modelling

The Life Cycle inventory (LCI) is an overview of all the unit processes that have been modelled based on the data provided in the previous section. The processes are modelled using the background database of ecoinvent 3.11 cut-off unit processes. This section provides a detailed overview of the data collection process, mapping of process data provided by the partners to the background database as well as process assumptions and limitations.

5.1 Data collection and data sources

Data collection for this study was carried out through close collaboration with project partners, ensuring access to relevant process information. Several meetings were held with each partner to discuss the necessary data and clarify key aspects of their processes. Where primary data was unavailable, assumptions and simulation results were used.

A key part of this effort was the development and provision of standardized data collection templates in Excel by **GD** (see Annex 1) which allowed partners to systematically report their data in a consistent and structured manner. These templates were shared with all partners, and further guidance was provided during the meetings to ensure accurate and complete data collection. The templates were customized for each partner, with separate sheets organized according to the specific processes and machinery they were responsible for. Although machinery and end-of-life stages were eventually excluded from the preliminary LCA, the templates were designed to capture relevant information for these aspects whenever available. This data has been stored for future use and will be incorporated into the final study when it will be possible to gather the details that will be available at later stages.

Data sources for the foreground model included primary data provided directly by the project partners, which was used whenever available, such as **A4F**'s lab-scale cultivation results was used for the harvesting of microalgae process described in section for scenarios **S2.1** and **S2.2**, further described in section 5.2.1 and **CSIC**'s pyrolysis test data was applied to the pyrolysis fractions of scenarios **S2.2**, **S2.3** and **S5.2**. In cases where primary data was unavailable, simulations and assumptions based on literature were utilized to fill in gaps. For example, **PMI**'s simulations were used to estimate energy requirements as well as flow rates for the MW pyrolysis system for feedstock 2 and feedstock 5 to benchmark Flexby technology against traditional ones. The data provided by **PMI** for the further processing of the pyrolysis products of feedstock 2 were applied to **S2.1**, **S2.2** and **S2.3**. Similarly, the processing of pyrolysis products with feedstock 5, was applied to scenarios **S5.1** and **S5.2**.

The background data for the study was sourced from ecoinvent 3.11 (cut-off version), which provided additional context for environmental impacts and resource consumption not covered by the project's primary data.

5.2 Process specific life cycle inventory

The product system has been organized according to the processes of the operational stage of Flexby. All processes within the foreground system can be identified in the database, according to the naming convention established in the foreground modelling process. Three pyrolysis technologies were explored, the conventional slow and flash pyrolysis methods, as well as the Flexby microwave pyrolysis.

The product system starts with the processes related to the feedstock, Feedstock 2, the microalgae, includes the growth and harvesting phases. Feedstocks 5, the wastewater sludge from dairy treatment plants, is taken directly from the wastewater treatment. The feedstock then undergoes drying at the **CSIC** facilities before pyrolysis. The products of pyrolysis, the bio-oil, pyro-gas and biochar each respectively undergo further processing into their final products. The idea was to benchmark the microwave pyrolysis against the conventional methods.

In the LCA model, 100 kg/h was assumed to be the flowrate of the starting feedstock, to be synchronous with the **PMI** deliverable. All electricity datasets were modelled using the electricity was modelled using the ecoinvent dataset ‘market for electricity – ES (ES stands for Spanish)’, expanded in Table 5, which comprises mainly of the ‘electricity voltage transformation from high to medium voltage - ES’ dataset, representing the Spanish electricity grid which is expanded in Table 6.

Table 5: Breakdown of the dataset ‘market for electricity – ES’ from ecoinvent 3.11 cut-off unit processes

Amount	Unit	Provider
0.00589003544699592	kWh	market for electricity, medium voltage - ES
0.999502691678668	kWh	electricity voltage transformation from high to medium voltage - ES
4,97E+09	kWh	electricity, from municipal waste incineration to generic market for electricity, medium voltage - ES
1.13E-7	kg	market for sulfur hexafluoride, liquid | sulfur hexafluoride, liquid | Cutoff, U - Europe
1,86E+06	km	market for transmission network, electricity, medium voltage | transmission network, electricity, medium voltage | Cutoff, U - Global
1.13E-7	kg	Suphur hexafluoride emission

Table 6: Breakdown of the dataset ‘electricity voltage transformation from high to medium voltage - ES’ from ecoinvent 3.11 cut-off unit processes

Amount	Unit	Provider
0.172448441923221	kWh	electricity production, wind, 1-3MW turbine, onshore - ES

0.0463592393722816	kWh	electricity production, nuclear, boiling water reactor - ES
0.00555359128171375	kWh	electricity production, natural gas, conventional power plant - ES
0.0152961553114214	kWh	heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014 - ES
0.0324533918650728	kWh	electricity production, oil - ES
0.0949246974411621	kWh	electricity production, wind, <1MW turbine, onshore - ES
0.00300696860083875	kWh	electricity, high voltage, import from MA - ES
4,58E+10	kWh	electricity production, wind, >3MW turbine, onshore - ES
0.0521325588223619	kWh	electricity, high voltage, import from FR - ES
1,43E+10	kWh	treatment of coal gas, in power plant - ES
0.185963129321026	kWh	electricity production, nuclear, pressure water reactor - ES
0.00471361885729601	kWh	treatment of blast furnace gas, in power plant - ES
0.043397481953478	kWh	market for electricity, high voltage - ES
0.0209372378402285	kWh	electricity, high voltage, import from PT - ES
0.00161321714902109	kWh	heat and power co-generation, biogas, gas engine - ES
0.0181738994444408	kWh	electricity production, hard coal - ES
0.0139331393034276	kWh	electricity production, hydro, pumped storage - ES
5,20E+09	kWh	electricity production, wind, 1-3MW turbine, offshore - ES
0.0470132255963422	kWh	electricity production, hydro, reservoir, non-alpine region - ES
0.0196847004387116	kWh	electricity production, solar thermal parabolic trough, 50 MW - ES

0.0912626921228027	kWh	electricity production, hydro, run-of-river - ES
4,44E+10	kWh	electricity production, solar tower power plant, 20 MW - ES
0.173433691619442	kWh	electricity production, natural gas, combined cycle power plant - ES
4,95E+05	km	market for transmission network, electricity, high voltage direct current aerial line - Europe
1,30E+04	km	market for transmission network, electricity, high voltage direct current land cable - Europe
1,02E+04	km	market for transmission network, electricity, high voltage direct current subsea cable | transmission network, electricity, high voltage direct current subsea cable | Cutoff, U - Europe

5.2.1 Microalgae growth and harvesting

The unit processes, representing the microalgae growth and harvesting, focus on the resource inputs, operational processes, and waste outputs associated with cultivating microalgae in wastewater. Primary data was provided for these processes by **A4F**, which provided mostly primary data, having carried out the cultivation as part of WP2.

The system under study is based on an open raceway pond operated in batch mode, where microalgae are grown using domestic wastewater as the primary nutrient source. While wastewater composition and algae productivity may vary seasonally, ongoing data collection aims to capture these fluctuations. Key inputs to the system are the wastewater, which provides both water and nutrients for algal growth, and sodium hydroxide, which is used in the harvesting process. The precise CO_2 uptake in the system by the microalgae, is not yet fully determined due to the open nature of the raceway. However, ongoing research aims to quantify this, and the findings will be incorporated into the final sustainability studies as a key element in quantifying the biogenic nature of the microalgae. Biomass is harvested after 3–4 days of growth using a settler for physical separation, with additional centrifugation. While centrifugation is not expected to be part of the full-scale process, it has been temporarily used for further dewatering.

The process generates two wastewater fractions: one left in the raceway after each batch to be reused, and another separated from the biomass during harvesting. This second wastewater stream is returned to a treatment plant for further processing.

5.2.2 Drying of feedstock

The feedstocks contain a high amount of water, the utility of which is being investigated in the Flexby system. For now, **CSIC** conducted the pyrolysis tests using a conventional setup, which required the water contained in the feedstock to be fully evaporated before the processing in the pyrolysis ovens. The drying process, carried out by **CSIC**, is hence the step before the conventional pyrolysis processes (slow and flash), removing moisture from the feedstock. This approach was also applied to the microwave system simulations, supporting a conservative estimate of energy requirements.

However, this remains under evaluation, as one of the Flexby's innovative aspects lies in its potential to utilize the water further in the system, since the hydrogen-free HDO needs water injections to operate. Further experimental work will clarify whether this optimization is feasible and can reduce or eliminate the need for energy-intensive drying, potentially lowering overall impacts.

The same procedure was followed for both Feedstock 2 and 5, except that Feedstock 5 especially, being wastewater sludge, is comprised of several odorous substances, which may require odour mitigation at a larger scale, which is not currently considered in the model. During sample drying, water is released along with a small part of volatile compounds suspected to cause odours. Using a material balance before and after sample drying, the percentage of weight loss is calculated, which is equal to the sample's moisture content. However, while it is estimated that emissions of light volatile compounds occur during this stage, their precise quantification and characterization were not possible.

Currently, drying is performed in lab-scale ovens, while in the Flexby pilot system, drying (in any extent that will be needed) will be integrated into the MW pyrolysis unit. While tests on MW drying are planned, initial energy consumption estimates have been simulated using design data from **FRIMA** and simulations by **PMI**, which will be benchmarked against the data from tests conducted by **CSIC**.

The LCI of the drying and deodorization process was modelled with inputs of 100 kg of feedstock and electricity for drying, considered to be 0.6424 kWh/kg of water evaporated. The outputs include the dry feedstock along with water and volatile organic compounds. The fractions for water, VOCs and dried feedstock can be found in the table below.

Table 7: Fractions of feedstock, water and volatile organic compounds (VOC) for 100 kg of feed

Feedstock	Dry feedstock (*kg*)	Water + VOC (*kg*)	Electricity (*kWh*)
2 (microalgae)	15.79	84.21	54.104925
5 (dairy sludge)	15.51	84.49	54.284825

5.2.3 Pyrolysis

CSIC is conducting lab-scale tests on both conventional slow and flash pyrolysis to provide a benchmark for MW pyrolysis, that will be the focal point of the Flexby technology. These tests help estimate yields and energy consumption for comparison. The performance of the MW pyrolysis, instead, is being simulated by **PMI** to estimate energy consumption and product yields.

The yields for pyrolysis for feedstock 2 and 5, considering the data from CSIC for slow and flash pyrolysis processes as well as the microwave pyrolysis data obtained from simulations conducted by **PMI** are provided in the table below. The biofuel fraction is the most valuable of the three. In the next sections, the processing of the different fractions and their modelling is described.

The energy requirements vary for the different pyrolysis technologies. The energy requirement for the microwave pyrolysis was estimated by **PMI** to be between 2.3 -3.6 kWh/kg depending on the feedstock.

Table 8: Energy requirements in kWh/kg of feedstock

Technology	Energy requirement (kWh/kg)	Source

Slow Pyrolysis	5.5	Estimated with data from CSIC assuming no optimization
Flash Pyrolysis	4.15	Estimated with data from CSIC assuming no optimization
Microwave Pyrolysis	2.3 – 3.5	PMI Deliverable 2.3

For reference, see the scenario definitions in Table 2.

Table 9: Percentage (%) yields of the bio-oil, biochar and pyro-gas fractions respectively for each scenario

	S2.1	S2.2	S2.3	S5.1	S5.2
Bio-oil Yield (%)	47	54	54	45.6	54
Pyro-gas Yield (%)	17.3	21	24	16.5	24
Biochar Yield (%)	35.7	25	22	36	22

5.2.4 Biogas processing: Separation from ammonia, WGS, and steam reforming

US is responsible for developing the pyro-gas processing stage, which includes ammonia and water separation, steam reforming, and the WGS reaction. Although experimental work has not yet started, we defined the expected configuration through technical discussions with them. Therefore, the LCI at this stage is mainly based on assumptions and process simulations provided by **PMI** (reflected in Deliverable 2.3).

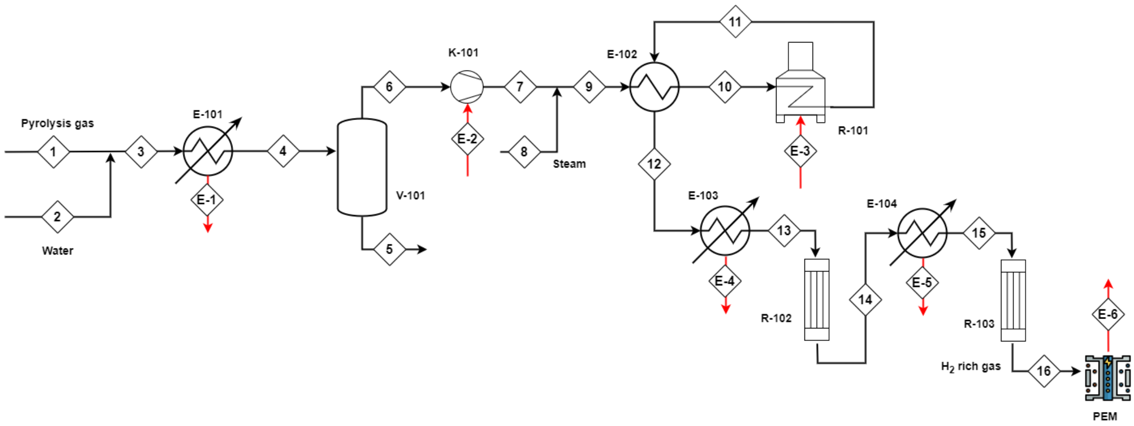


*Figure 3: Process Flow Diagram (PFD) of pyrolysis gas post-processing (**PMI**)*

The flow diagram in Figure 3, taken from D2.3, shows that after pyrolysis, the pyrolysis gas (stream 1) is initially mixed with water (stream 2) to reduce its temperature from 700 °C to 70 °C. The stream is then further cooled to 30 °C in heat exchanger E-101, allowing for the separation of water and ammonia (stream 5) in separator V-101. The resulting gas stream (stream 6) is compressed in compressor K-101 to reach the operating pressure of the reformer, equal to 4 bar (R-101). Before entering the reformer, steam (stream 8) is added, and the mixture passes through a process-to-process heat exchanger (E-102), which utilizes the heat from the reformer product (stream 11) to preheat the inlet mixture (stream 10).

The reformed gas (stream 11) is subsequently cooled to 250 °C using water (heat exchanger E-103) to reach the required temperature for the first adiabatic water-gas shift (WGS) reactor (R-102). The gas product (stream 14) is further cooled to 250 °C before entering the second adiabatic WGS reactor (R-103). The current design includes separation through cooling and condensation, followed by reforming and WGS using nickel- and iron-based catalysts. A combined reformer-WGS reactor is foreseen in the future configuration. Finally, the hydrogen-rich stream (stream 16) is directed to a solid-oxide fuel cell (SOFC) for electric energy generation.

The temperatures and pressures of the various streams were provided by PMI and shown in Table 10.

Table 10: Input parameters for pyrolysis gas post-processing Aspen HYSYS simulation

Stream number	Temperature [°C]	Pressure [bar]

1	700	2
2	30	2
3	70	-
4	30	-
5	-	
7	-	4
10	500	-
13	250	-
15	250	-

5.2.5 Bioliquid processing: H_2-free hydrodeoxygenation

Bioliquid processing through H_2-free hydrodeoxygenation (HDO) is another stage assigned to **US** within the Flexby project, to reduce the oxygen content of the bioliquid fraction. Hydrodeoxygenation is an emerging technology designed to drastically lower the energy requirements by using water as the main reactant (Jin et al., 2021). Optimizing this process involves adjusting conditions to maximize efficiency without relying on external hydrogen sources. For this catalyst selection support is a key factor. Also optimizing temperature, pressure, and space velocity is essential given that these parameters significantly influence the reaction kinetics and product selectivity (Jin et al., 2021, Zhu et al., 2015).

Although this process has not yet been experimentally implemented, its modelling has been developed through close collaboration with **US**, drawing on design discussions and simulations carried out by **PMI,** the work is represented in the flow diagram in Figure 4. At this stage, the system boundaries and assumptions reflect the projected configuration for the semi-pilot setup, with updates expected once experimental data becomes available.

From Figure 4 taken from D2.3, continuing with the bioliquid output of pyrolysis, the bio-liquid recovered from the MW pyrolysis reactor (stream 17) is first mixed with water (stream 18) to cool down the mixture. The resulting stream (19) is further cooled to 60 °C in heat exchanger E-105 with cooling water. The condensed stream (20) is then pressurized to 16 bar by pump P-101 to reach the hydrodeoxygenation (HDO) operating pressure, producing stream 21. The HDO product (stream 22) is subsequently flashed (via a valve and heat exchanger E-106) to separate the gas phase (stream 25) from the refined bio-oil (stream 26).

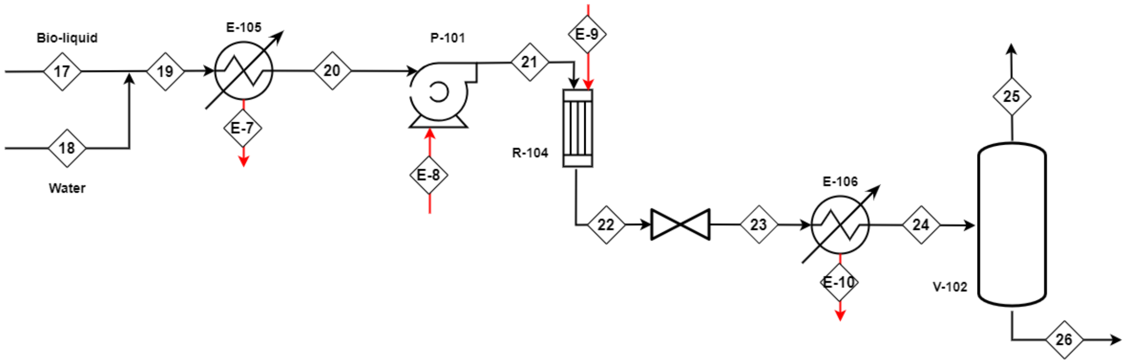


Figure 4: Flow diagram of bio-liquid processing

Table 11 presents the fixed input parameters used in the simulation to model the process system.

Table 11 - Input parameters for bio-liquid refining Aspen HYSYS simulation

Stream number	Temperature [°C]	Pressure [bar]
17	700	2
18	30	2
20	60	-
21	-	16
22	250	-
23	-	2
24	50	-

5.2.6 Biochar processing: Biochar activation

Carbon activation is a process that will be carried out by **CSIC** using physical activation with CO_2 on a carbon bed. This process is essential to valorise the biochar by enhancing its surface area and porosity, making it suitable for applications such as adsorption, as a catalyst support or as soil amendment. Although this step has not yet been implemented, its modelling is currently based on assumptions and literature data provided by **CSIC**. The activation is expected to take place in a dedicated oven.

5.2.7 Comparative Analysis Parameterization

The scenarios in the sensitivity studies are set up based on the process details described in the previous sections and a large part of the assumptions were taken from the PMI deliverable. Table 12 shows all the parameters used to model the different scenarios. The naming of the parameters follows the structure of 'process_flow_unit', except for the parameters that start with 'flexby' and have stream numbers referring to energy or flowrates, these parameters are meant to reflect the data obtained from the **PMI** deliverable, D2.3.

Table 12: Parameters and values used in the sensitivity study to compare S2.1, S2.2, S2.3, S5.1 and S5.2

Parameter	S2.1	S2.2	S2.3	S5.1	S5.2
Feedstock options (feedstock amount = 100 kg)					
feedstock_2_microalgae (1 or 0)	1.0	1.0	1.0	0.0	0.0
feedstock_2_microalgae_kg	100.0	100.0	100.0	100.0	100.0
feedstock_5_dairy_based_oily_sludge (1 or 0)	0.0	0.0	0.0	1.0	1.0
feedstock_5_dairy_based_oily_sludge_kg	100.0	100.0	100.0	100.0	100.0
Drying and deodourization					
deodourization_electricity_kWh	0.0	0.0	0.0	0.0	0.0
drying_electricity_kWh_per_kg_water	0.642	0.642	0.642	0.642	0.642
drying_sludge_2_fraction	0.158	0.158	0.158	0	0
drying_sludge_5_fraction	0	0	0.155	0.155	0.155
drying_vocs_fraction_feedstock_2	0.0	0.0	0.0	0.0	0.0
drying_vocs_fraction_feedstock_5	0.0	0.0	0.0	0.0	0.0
drying_water_fraction_feedstock_2	0.842	0.842	0.842	0	0
drying_water_fraction_feedstock_5	0.845	0.845	0.845	0.845	0.845
Drying_sludge_kg	15.8	15.8	15.8	15.5	15.5
Feedstock options (feedstock amount = 100 kg)					
feedstock_2_microalgae (1 or 0)	1.0	1.0	1.0	0.0	0.0
feedstock_2_microalgae_kg	100.0	100.0	100.0	100.0	100.0
feedstock_5_dairy_based_oily_sludge (1 or 0)	0.0	0.0	0.0	1.0	1.0
feedstock_5_dairy_based_oily_sludge_kg	100.0	100.0	100.0	100.0	100.0

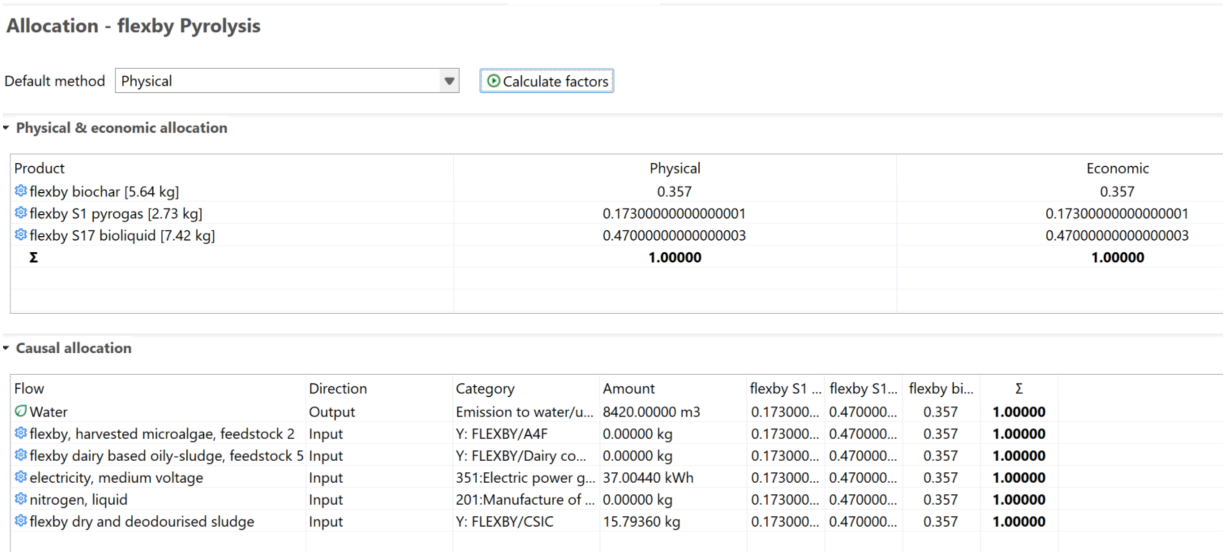
PMI D2.3 - Parameters for energy uptake and release					
flexby_E101_E1_kW	1.16	1.16	1.16	1.15	1.15
flexby_E103_E4_kW	0.68	0.68	0.68	0.76	0.76
flexby_E104_E5_kW	0.27	0.27	0.27	0.31	-0.31
flexby_E105_E7_kW	4.06	4.06	4.06	3.92	3.92
flexby_E106_E10_kW	1.31	1.31	1.31	1.33	1.33
flexby_K101_E2_kW	0.09	0.09	0.09	0.06	0.06
flexby_P101_E8_kW	0.01	0.01	0.01	0.01	0.01
flexby_PEM_E6_kW	3.66	3.66	3.66	4.15	4.15
flexby_R101_E3	1.64	1.64	1.64	2.45	2.45
flexby_R104_E9_kW	14.04	14.04	14.04	11.75	11.75
PMI Parameters for mass flowrates					
flexby_S01_pyrogas_kg	2.73	2.73	2.73	2.61	2.61
flexby_S02_kg	5.9	5.9	5.9	16.0	16.0
flexby_S03_kg	8.63	8.63	8.63	18.61	18.61
flexby_S04_kg	8.63	8.63	8.63	18.61	18.61
flexby_S05_ammonia_kg	6.25	6.25	6.25	16.48	16.48
flexby_S06_kg	2.38	2.38	2.38	2.13	2.13
flexby_S07_kg	2.38	2.38	2.38	2.13	2.13
flexby_S08_kg	0.67	0.67	0.67	1.36	1.36
flexby_S09_kg	3.05	3.05	3.05	3.49	3.49
flexby_S10_kg	3.05	3.05	3.05	3.49	3.49
flexby_S11_kg	3.05	3.05	3.05	3.49	3.49
flexby_S12_kg	3.05	3.05	3.05	3.49	3.49
flexby_S13_kg	3.05	3.05	3.05	3.49	3.49
flexby_S14_kg	3.05	3.05	3.05	3.49	3.49
flexby_S15_kg	3.05	3.05	3.05	3.49	3.49
flexby_S16_kg	3.05	3.05	3.05	2.13	2.13
flexby_S17_bioliquid_kg	7.42	7.42	7.42	7.23	7.23
flexby_S18_kg	1.24	1.24	1.24	1.1	1.1

flexby_S19_kg	8.66	8.66	8.66	8.24	8.24
flexby_S20_kg	8.66	8.66	8.66	8.24	8.24
flexby_S21_kg	8.66	8.66	8.66	8.23	8.23
flexby_S22_kg	8.66	8.66	8.66	8.23	8.23
flexby_S23_kg	8.66	8.66	8.66	8.23	8.23
flexby_S24_kg	8.66	8.66	8.66	8.23	8.23
flexby_S25_kg	3.74	3.74	3.74	3.1	3.1
flexby_S26_kg	4.92	4.92	4.92	5.13	5.13
Adiabatic WGS Process					
WGS_carbon_dioxide_kg	2.78	2.78	2.78	2.78	2.78
Pyrolysis					
pyrolysis_biochar_fraction	0.357	0.25	0.22	0.36	0.22
pyrolysis_bioliquid_fraction	0.47	0.54	0.54	0.456	0.54
pyrolysis_electricity_kWh_per_kg	2.34	5.5	4.15	3.65	5.5
pyrolysis_nitrogen_kg	0.0	0.0	0.0	0.0	0.0
pyrolysis_pyrogas_fraction	0.173	0.21	0.24	0.36	0.22
pyrolysis_water_m3	8420.0	8420.0	8420.0	8420.0	8420.0
Ammonia valorization *(excluded due to data uncertainty)*					
ammonia_valorization_energy_kWh	0.0	0.0	0.0	0.0	0.0
ammonia_valorized_kg	0.0	0.0	0.0	0.0	0.0
Biochar activation *(excluded due to data uncertainty)*					
biochar_activation_activated_biochar_kg	0.0	0.0	0.0	0.0	0.0
biochar_activation_co2_flow_kg	0.0	0.0	0.0	0.0	0.0
biochar_activation_electricity_kWh	0.0	0.0	0.0	0.0	0.0

6 Results and interpretation

The results are presented for the three products of the Flexby system separately. The results are allocated to the three streams, at the pyrolysis process, based on the masses of the fractions produced from pyrolysis as shown in Table 9. This section details the potential environmental impacts of the bioliquid, pyro-gas and biochar fractions respectively in the different scenarios considered. For reference, see the scenario definitions in Table 2.

The pyrolysis process requirements are allocated to the bioliquid fraction based on the ratio of the mass of bioliquid produced to the total mass as shown in Figure 5. And from here on, the mass-fraction allocated pyrolysis results, as well as the post-pyrolysis process results are reported separately for each fraction in the following sections.


Allocation - flexby Pyrolysis

Default method Physical Calculate factors

Physical & economic allocation

Product	Physical	Economic
flexby biochar [5.64 kg]	0.357	0.357
flexby S1 pyrogas [2.73 kg]	0.17300000000000001	0.17300000000000001
flexby S17 bioliquid [7.42 kg]	0.47000000000000003	0.47000000000000003
Σ	**1.00000**	**1.00000**

Causal allocation

Flow	Direction	Category	Amount	flexby S1 ...	flexby S1...	flexby bi...	Σ
Water	Output	Emission to water/u...	8420.00000 m3	0.173000...	0.470000...	0.357	**1.00000**
flexby, harvested microalgae, feedstock 2	Input	Y: FLEXBY/A4F	0.00000 kg	0.173000...	0.470000...	0.357	**1.00000**
flexby dairy based oily-sludge, feedstock 5	Input	Y: FLEXBY/Dairy co...	0.00000 kg	0.173000...	0.470000...	0.357	**1.00000**
electricity, medium voltage	Input	351:Electric power g...	37.00440 kWh	0.173000...	0.470000...	0.357	**1.00000**
nitrogen, liquid	Input	201:Manufacture of ...	0.00000 kg	0.173000...	0.470000...	0.357	**1.00000**
flexby dry and deodourised sludge	Input	Y: FLEXBY/CSIC	15.79360 kg	0.173000...	0.470000...	0.357	**1.00000**

Figure 5: Allocation of inputs to the three pyrolysis fractions based on mass

Section 6.1 reports the results of pyrolysis attributed to bioliquid pathway and the post processing up to the flashing of the bioliquid to produce the refined bioliquid. Section 6.1 reports the results of pyrolysis allocated to the pyro-gas and the post-pyrolysis, processing up to production of electrical energy. Section 6.3 only includes the pyrolysis impacts allocated to biochar production as further processing data was unavailable.

6.1 Bioliquid pathway

Overall, the microwave pyrolysis process corresponding to both feedstock 2 and 5, shows lower impacts than the conventional processes, for the production of refined biofuel.

Table 13 shows the potential environmental impacts, allocated to the production of 1 kg of bioliquid, calculated with the Environmental Footprint v3.1. method. The results show

S2.1 has the lowest potential impacts amongst the 5 scenarios followed by **S5.2** in most of the impact categories, except water use, where **S5.1** has the lowest potential impacts, Human toxicity: non-carcinogenic – organics where **S5.1** and **S5.2** show the lowest potential impacts, and Photochemical oxidant formation: human health where **S5.1** and **S5.2** show the lowest potential impacts. **S2.2** shows the highest impacts for most of the impact categories. Overall, the microwave pyrolysis process corresponding to both feedstock 2 and 5, shows lower impacts than the conventional processes, for the production of refined biofuel.

*Table 13: LCIA results with the EF 3.1 method comparing the scenarios **S2.1**, **S2.2**, **S2.3**, **S5.1**, **S5.2** for the production of 1 kg of bioliquid*

Impact categories	Unit	**S2.1**	**S2.2**	**S2.3**	**S5.1**	**S5.2**
Acidification	mol H+-Eq	9.40E-03	1.19E-02	1.05E-02	1.03E-02	1.09E-02
Climate change	kg CO2-Eq	2.32E+00	2.94E+00	2.58E+00	2.55E+00	2.69E+00
Climate change: biogenic	kg CO2-Eq	5.56E-03	7.02E-03	6.16E-03	6.10E-03	6.42E-03
Climate change: fossil	kg CO2-Eq	2.28E+00	2.89E+00	2.54E+00	2.51E+00	2.64E+00
Climate change: land use and land use change	kg CO2-Eq	3.15E-02	3.98E-02	3.50E-02	3.46E-02	3.64E-02
Ecotoxicity: freshwater	CTUe	2.77E+00	3.57E+00	3.11E+00	3.06E+00	3.25E+00
Ecotoxicity: freshwater, inorganics	CTUe	2.63E+00	3.39E+00	2.96E+00	2.90E+00	3.09E+00
Ecotoxicity: freshwater, organics	CTUe	1.39E-01	1.76E-01	1.54E-01	1.53E-01	1.61E-01
Energy resources: non-renewable	MJ, net calorific value	7.55E+01	9.54E+01	8.38E+01	8.29E+01	8.73E+01
Eutrophication: freshwater	kg P-Eq	3.20E-04	4.10E-04	3.60E-04	3.50E-04	3.70E-04
Eutrophication: marine	kg N-Eq	2.12E-03	2.68E-03	2.35E-03	2.33E-03	2.45E-03
Eutrophication: terrestrial	mol N-Eq	2.19E-02	2.77E-02	2.43E-02	2.40E-02	2.53E-02
Human toxicity: carcinogenic	CTUh	5.45E-10	6.83E-10	6.04E-10	5.85E-10	6.18E-10
Human toxicity: carcinogenic, inorganics	CTUh	1.54E-10	2.01E-10	1.75E-10	1.71E-10	1.83E-10
Human toxicity: carcinogenic, organics	CTUh	3.91E-10	4.82E-10	4.29E-10	4.14E-10	4.34E-10
Human toxicity: non-carcinogenic	CTUh	1.87E-08	2.24E-08	2.03E-08	1.86E-08	1.96E-08
Human toxicity: non-carcinogenic, inorganics	CTUh	1.10E-08	1.46E-08	1.26E-08	1.23E-08	1.33E-08

Human toxicity: non-carcinogenic, organics	CTUh	7.61E-09	7.83E-09	7.71E-09	6.27E-09	6.33E-09
Ionising radiation: human health	kBq U235-Eq	2.71E+00	3.42E+00	3.00E+00	2.98E+00	3.13E+00
Land use	dimensionless	9.73E+00	1.23E+01	1.08E+01	1.07E+01	1.13E+01
Material resources: metals/minerals	kg Sb-Eq	6.43E-06	8.92E-06	7.62E-06	7.28E-06	8.08E-06
Ozone depletion	kg CFC-11-Eq	3.80E-08	4.87E-08	4.26E-08	4.19E-08	4.45E-08
Particulate matter formation	disease incidence	5.70E-08	7.22E-08	6.33E-08	6.26E-08	6.60E-08
Photochemical oxidant formation: human health	kg NMVOC-Eq	5.13E-02	5.34E-02	5.22E-02	4.32E-02	4.37E-02
Water use	m3 world Eq deprived	3.45E+05	3.00E+05	3.00E+05	3.40E+05	2.87E+05

The results are influenced by the energy requirements especially for the drying and pyrolysis processes. Pyrolysis fractions and their mass influence the allocation of impacts between the three fractions based on their mass, since physical allocation was chosen. The bioliquid fraction has the highest mass amongst the three, from Table 9. The drying energy requirement is very high in all scenarios, requiring about 52 kWh of electricity to evaporate about 84 kg of water. It is further influenced by the energy requirements of the pyrolysis process for all three fractions, followed by the high energy requirements of the hydrodeoxygenation process in the bioliquid production pathway. When focussing on the climate change impacts of the Feedstock 2 scenarios, the pyrolysis contributes 42% of the results in **S2.3**, 44% in **S2.1** and 49% in **S2.2**. The drying energy requirements contribute to 34%, 30.3% and 34.5% in **S2.1**, **S2.2** and **S2.3** respectively. For Feedstock 5, The pyrolysis results contribute 42.2% and 51% in **S5.1** and **S5.2** respectively to the overall impacts. The drying process contributes 39.47% and 31.63% in scenarios **S5.1** and **S5.2** respectively. And the Hydrodeoxygenation process contributes 18.25 and 17.23% respectively to **S5.1** and **S5.2**.

6.2 Pyro-gas pathway

Table 14 shows the potential environmental impacts, allocated to production of 1 kWh of electricity with the pyro-gas pathway, calculated with the Environmental Footprint v3.1.

method. The results show that **S2.1** has the lowest potential impacts amongst the scenarios, followed by **S5.1,** in most of the impact categories, *Climate change: land use and land use change* and the category of *water-use* where **S5.1** and **S5.2** have the lowest potential impacts. Overall, the microwave pyrolysis process corresponding to both feedstock 2 and 5, shows lower impacts than the conventional processes for thy pyro-gas fraction as well.

*Table 14: LCIA results with the EF 3.1 method comparing the scenarios **S2.1**, **S2.2**, **S2.3**, **S5.1**, **S5.2** for the production of 1 kWh of electricity with the pyro-gas pathway*

Impact categories	Unit	**S2.1**	**S2.2**	**S2.3**	**S5.1**	**S5.2**
Acidification	mol H+-Eq	4.12E-03	6.08E-03	5.24E-03	4.52E-03	5.49E-03
Climate change	kg CO2-Eq	1.78E+00	2.26E+00	2.06E+00	1.81E+00	2.04E+00
Climate change: biogenic	kg CO2-Eq	2.49E-03	3.63E-03	3.15E-03	2.59E-03	3.15E-03
Climate change: fossil	kg CO2-Eq	1.01E+00	1.48E+00	1.28E+00	1.12E+00	1.35E+00
Climate change: land use and land use change	kg CO2-Eq	7.73E-01	7.79E-01	7.76E-01	6.84E-01	6.87E-01
Ecotoxicity: freshwater	CTUe	1.26E+00	1.87E+00	1.61E+00	1.38E+00	1.68E+00
Ecotoxicity: freshwater, inorganics	CTUe	1.20E+00	1.78E+00	1.53E+00	1.32E+00	1.60E+00
Ecotoxicity: freshwater, organics	CTUe	5.98E-02	8.85E-02	7.62E-02	6.53E-02	7.95E-02
Energy resources: non-renewable	MJ, net calorific value	3.20E+01	4.75E+01	4.09E+01	3.49E+01	4.25E+01
Eutrophication: freshwater	kg P-Eq	1.40E-04	2.10E-04	1.80E-04	1.60E-04	1.90E-04
Eutrophication: marine	kg N-Eq	9.10E-04	1.35E-03	1.16E-03	9.90E-04	1.21E-03
Eutrophication: terrestrial	mol N-Eq	9.38E-03	1.39E-02	1.20E-02	1.02E-02	1.25E-02
Human toxicity: carcinogenic	CTUh	2.22E-10	3.27E-10	2.82E-10	2.45E-10	2.96E-10
Human toxicity: carcinogenic, inorganics	CTUh	7.33E-11	1.08E-10	9.34E-11	8.04E-11	9.77E-11

Human toxicity: carcinogenic, organics	CTUh	1.49E-10	2.19E-10	1.89E-10	1.64E-10	1.99E-10
Human toxicity: non-carcinogenic	CTUh	5.72E-09	8.47E-09	7.29E-09	6.26E-09	7.62E-09
Human toxicity: non-carcinogenic, inorganics	CTUh	5.39E-09	7.97E-09	6.87E-09	5.90E-09	7.17E-09
Human toxicity: non-carcinogenic, organics	CTUh	3.33E-10	4.93E-10	4.25E-10	3.63E-10	4.42E-10
Ionising radiation: human health	kBq U235-Eq	1.12E+00	1.68E+00	1.44E+0 0	1.20E+0 0	1.47E+00
Land use	dimensionless	4.11E+00	6.12E+00	5.26E+0 0	4.44E+0 0	5.43E+00
Material resources: metals/minerals	kg Sb-Eq	3.54E-06	5.27E-06	4.53E-06	3.80E-06	4.66E-06
Ozone depletion	kg CFC-11-Eq	1.83E-08	2.65E-08	2.30E-08	2.08E-08	2.49E-08
Particulate matter formation	disease incidence	2.55E-08	3.73E-08	3.23E-08	2.85E-08	3.43E-08
Photochemical oxidant formation: human health	kg NMVOC-Eq	3.45E-03	5.09E-03	4.39E-03	3.78E-03	4.59E-03
Water use	m3 world Eq deprived	1.71E+05	1.71E+05	1.71E+0 5	1.47E+0 5	1.47E+05

The pyro-gas mass is higher than that of the biochar in scenarios **S2.3** and **S5.2**. In these two scenarios the pyrolysis impacts attributed to this fraction, are higher than biochar but lower than the bioliquid fractions.

When focussing on the climate change impacts, for Feedstock 2, the pyrolysis process contributes 19 %, 33.95 % and 26.12 % respectively in **S2.1**, **S2.2** and **S2.3**. The drying and deodorization contributes 29.15 %, 21.16 % and 21.57 % respectively in **S2.1**, **S2.2** and **S2.3**. The carbon dioxide emissions before entering the fuel cell contributed 0.759 kg eq. of CO2 (these are assumed to be the same in all scenarios, which is unlikely but this is the value used until further data is available). These emissions may be excluding in sensitivity studies using a different impact assessment method, but need to be considered when using the EF3.1 method. They contribute a very large 42.6 %, 37.53 % and 43.7% respectively for **S2.1**, **S2.2** and **S2.3**.

For Feedstock 5, the pyrolysis process contributes 33 % and 30 % respectively in **S5.1** and **S5.2**. The drying and deodorization contributes 16.16 % and 19.6 % respectively in **S5.1** and **S2.3**. The biogenic carbon dioxide emissions before the fuel cell contribute 50.33 % and 37.3 % respectively for **S5.1** and **S5.2**.

6.3 Biochar pathway

Table 15 shows the potential environmental impacts, allocated to production of 1 kg of biochar, calculated with the Environmental Footprint v3.1. method. The biochar will further undergo activation and has the potential to be reused within the system as well as be used as soil amendment. As the rest of the pathway is incomplete, the results only account for the pyrolysis. The potential environmental impacts for the microwave pyrolysis scenarios, are lower than the others in all the impact categories, with **S2.1** having the lowest impacts. **S5.1** having the lowest potential impacts here and **S5.2** having the worst potential impacts.

*Table 15: LCIA results with the EF 3.1 method comparing the scenarios **S2.1**, **S2.2**, **S2.3**, **S5.1**, **S5.2** for the production of 1 kg of biochar (further processing has not been included)*

Impact categories	Unit	**S2.1**	**S2.2**	**S2.3**	**S5.1**	**S5.2**
Acidification	mol H+-Eq	4.80E-03	1.06E-02	1.02E-02	5.90E-03	1.22E-02
Climate change	kg CO2-Eq	1.17E+00	2.59E+00	2.50E+00	1.44E+00	2.97E+00
Climate change: biogenic	kg CO2-Eq	2.79E-03	6.17E-03	5.95E-03	3.43E-03	7.07E-03
Climate change: fossil	kg CO2-Eq	1.16E+00	2.55E+00	2.46E+00	1.42E+00	2.92E+00
Climate change: land use and land use change	kg CO2-Eq	1.58E-02	3.50E-02	3.37E-02	1.94E-02	4.01E-02
Ecotoxicity: freshwater	CTUe	1.48E+00	3.27E+00	3.16E+00	1.82E+00	3.75E+00
Ecotoxicity: freshwater, inorganics	CTUe	1.41E+00	3.12E+00	3.01E+00	1.73E+00	3.57E+00
Ecotoxicity: freshwater, organics	CTUe	7.02E-02	1.55E-01	1.50E-01	8.62E-02	1.78E-01
Energy resources: non-renewable	MJ, net calorific value	3.79E+01	8.37E+01	8.08E+01	4.66E+01	9.59E+01
Eutrophication: freshwater	kg P-Eq	1.70E-04	3.70E-04	3.60E-04	2.10E-04	4.20E-04
Eutrophication: marine	kg N-Eq	1.07E-03	2.36E-03	2.28E-03	1.31E-03	2.71E-03
Eutrophication: terrestrial	mol N-Eq	1.10E-02	2.44E-02	2.35E-02	1.36E-02	2.79E-02
Human toxicity: carcinogenic	CTUh	2.58E-10	5.70E-10	5.49E-10	3.17E-10	6.52E-10

Human toxicity: carcinogenic, inorganics	CTUh	8.59E-11	1.90E-10	1.83E-10	1.06E-10	2.17E-10
Human toxicity: carcinogenic, organics	CTUh	1.72E-10	3.80E-10	3.66E-10	2.11E-10	4.35E-10
Human toxicity: non-carcinogenic	CTUh	6.72E-09	1.49E-08	1.43E-08	8.26E-09	1.70E-08
Human toxicity: non-carcinogenic, inorganics	CTUh	6.33E-09	1.40E-08	1.35E-08	7.78E-09	1.60E-08
Human toxicity: non-carcinogenic, organics	CTUh	3.92E-10	8.66E-10	8.36E-10	4.82E-10	9.92E-10
Ionising radiation: human health	kBq U235-Eq	1.36E+00	3.00E+00	2.90E+00	1.67E+00	3.44E+00
Land use	dimensionless	4.92E+00	1.09E+01	1.05E+01	6.05E+00	1.25E+01
Material resources: metals/minerals	kg Sb-Eq	4.25E-06	9.40E-06	9.07E-06	5.23E-06	1.08E-05
Ozone depletion	kg CFC-11-Eq	2.01E-08	4.43E-08	4.28E-08	2.47E-08	5.08E-08
Particulate matter formation	disease incidence	2.89E-08	6.40E-08	6.17E-08	3.56E-08	7.32E-08
Photochemical oxidant formation: human health	kg NMVOC-Eq	4.02E-03	8.89E-03	8.58E-03	4.95E-03	1.02E-02
Water use	m3 world Eq deprived	2.29E+05	3.27E+05	3.72E+05	2.32E+05	3.80E+05

The biochar fraction has a higher mass than the pyro-gas and bioliquid in **S2.1**, **S2.2**, and **S5.1**. The pyrolysis impacts allocated to the biochar is higher than the pyro-gas (but lower than the bioliquid fraction) in these scenarios. All impacts for the climate change result of this fraction stem from pyrolysis and drying.

7 Conclusions

The current study is based on a non-optimised system where energy releases are not yet reused within the system, but future work aims to integrate energy recovery strategies, which are expected to reduce the overall energy demands of the system, potentially reducing, consequently, its environmental impacts as well.

Despite the non-optimised status of the Flexby system at the time of the study, **S2.1 and S5.1** using the microwave pyrolysis for Feedstock 2 and Feedstock 5**,** shows promising improvements to the existing conventional slow and flash pyrolysis processes of the feedstocks (**S2.2**, **S2.3** and **S5.2**) for all three fractions as shown in Table 13, Table 14 and Table 15. Potential impacts stem from the high energy requirements of the pyrolysis process, drying of the wet feedstocks for all fractions, the hydrogen-free HDO process for the bioliquid, and the carbon dioxide release from the water-gas-shift process, before the fuel cell for the pyro-gas. The results are also influenced by the masses of the fractions produced from pyrolysis.

From the technological standpoint, several advancements are expected as the system evolves. **A4F** may not cultivate microalgae specifically for Flexby but instead use them as a by-product from wastewater treatment, moreover, the plan is to build a facility when the microalgae growth is close to their processing, which would make possible to reuse the residual CO_2 produced during the processing of the pyrolysis products further contributing to resource efficiency and circularity.

The potential to utilize the water further in the system is being tested experimentally, since the hydrogen-free HDO needs water injections to operate. Further experimental work will clarify whether this optimization is feasible. But if successful, it would reduce or eliminate the need for the energy-intensive drying process, potentially lowering overall impacts.

Additionally, valorisation of ammonia recovered from the pyro-gas stream is under evaluation, contributing to improved nitrogen recovery and reduced emissions. A combined reformer–WGS reactor is planned in future configurations to enhance process integration and reduce complexity.

The reuse of waste heat from the SOFC is also being considered to improve energy efficiency across several stages. Additionally, the Flexby plant is designed to rely on renewable energy — particularly photovoltaic electricity — to minimize environmental impacts and strengthen sustainability.

8 From the preliminary LCA to the final sustainability study

This preliminary study serves as an initial assessment of Flexby technology, aiming to identify impact hotspots and potential optimizations. However, its scope is limited by the fact that the project is still in its early development stages. The LCA of Flexby is an ongoing effort that will continue throughout the project's duration, with the final study set to be published in Month 48, as part of the comprehensive Life Cycle Sustainability Assessment (LCSA). Therefore, the methodology of the sustainability assessment will evolve alongside the technological development of the project, as explored in the previous chapter. This iterative process will allow for a progressive refinement of assumptions and datasets, ensuring that the model remains aligned with ongoing improvements in the technology.

An ex-ante LCA will be conducted to evaluate future scale-up scenarios, leveraging higher-TRL data as it becomes available to benchmark and refine our scaling methods. Concurrently, we will investigate coproduct allocation and multifunctionality via System Boundary Expansion (SBE). The impact results depend on many parameters, often estimated rather than experimentally measured, so applying a statistical uncertainty analysis (e.g. Monte Carlo or sensitivity analysis) will significantly enhance the robustness of our sustainability assessment.

Ultimately, the final and complete LCA will adopt a cradle-to-grave approach, ensuring that every phase of the system's lifecycle is accounted for, from raw material extraction to end-of-life disposal or recycling, encompassing critical factors such as transportation, machinery development and use, and EoL management.

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Annex 1

Component Manufacturing			
Componennt identification [1]	Microwave cavity		
Provider/manufacturer [2]			
Location [3]			
Quantitative reference and unit [4]	e.g. 1 unit		
Contact person [5] Address Telephone e-mail		Date of completion [6]	
		Time period [7]	
Lifetime of machinary or plant (7a)			
Component data sheet [8]	Create and attach a separate sheet i.e.component data sheet if available		

Material composition	Amount	Unit [10]	Data source [11]	Costs [12]	Origin [13]	Comments [14]
Energy source incl. efficiency [15]						
Material Input [16]						
Manufacturing processes (16a)						
Service Inputs [17]						

Packaging						
Product per unit/box [27]		Comments [14]				
Unit [28]						
Components/materials [29]	Amount	Unit [10]	Costs [12]	Destination [30]	Comments [14]	

Transport [31]					
Materials, Supplies and Waste [32]	Distance (km) [33]	Means of transport [34]	Capacity (tonnes) [35]	Actual load (tonnes) [36]	Empty return (Yes/No) [37]

Internal transport [38]			
Means of transport [39]	Total amount of input transported	Fuel type [41]	Total consumption of fuel [42]

Component replacement and maintainance					
Replacement (number of times) per lifetime of project [43]	(fill replacement data here)				
Materials, Supplies and Waste for maintainance[43]	amount	unit[10]	data source[11]	origin[13]	comments [14]

End of Life (Would also apply to the replaced component)					
Materials, Supplies and Waste [32]	Distance (km) [33]	Treatment process options [34]	Capacity (tonnes) [35]		

Figure 6 - Example of Excel template for data collection of machinery components.

Process	Biochar activation		
Process identification [1]			
Process operator [2]			
Location [3]			
Quantitative reference and unit [4]	amount of biochar activated		
Contact person [5] Address Telephone e-mail		Date of completion [6]	
		Time period [7]	
Process flowsheet [8]	Create and attach a separate sheet i.e."process flow chart"		

Inputs [9]	Amount	Unit [10]	Data source [11]	Costs (12)	Origin [13]	Comments [14]
Energy source incl. efficiency [15]						
electricity	z	kg	Primary data		Spain	
Material Inputs [16]						
CO2	x	kg	Primary data		Spain	
Service Inputs [17]						

Outputs [18]	Amount	Unit [10]	Data source [11]	Costs (12)	Destination [13]	Comments [14]
Product(s) [19]						
Emissions to air [20]						
Emissions to water [21]						
Emissions to soil [22]						

Waste							
Process waste [23]	Amount	Unit [10]	Stage[24]	Costs(12)	Way of disposal [25]	Percentage[26]	Comments [14]

Packaging						
Product per unit/box [27]		Comments [14]				
Unit [28]						
Components/materials [29]	Amount	Unit [10]	Costs (12)	Destination [30]	Comments [14]	

Transport [31]					
Materials, Supplies and Waste [32]	Distance (km) [33]	Means of transport [34]	Capacity (tonnes) [35]	Actual load (tonnes) [36]	Empty return (Yes/No) [37]

Internal transport [38]			
Means of transport [39]	Total amount of input transported (tonnes) [40]	Fuel type [41]	Total consumption of fuel [42]

Figure 7 - Example of Excel template for the data collection of processes.

Each partner involved in data collection received a tailored Excel file designed specifically for their respective tasks. These files included multiple sheets organized by processes and machinery, allowing for structured and consistent data input. In addition to the data entry templates, each Excel file featured an introductory sheet with the legend of the sheets, a guidance sheet with instructions, sheets with flowcharts to support process visualization, and additional sheets customized to the specific needs of each partner's contribution.