D7.2 First Social Evaluation and Economic report (S-LCA and LCC)

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 "*First Social Evaluation and Economic Report (S-LCA and LCC)*" (Deliverable 7.2) and presents the preliminary results of the Life Cycle Costing (LCC) and Social Life Cycle Assessment (S-LCA) of the FLEXBY system. The assessment was conducted by **GD** with the support of all project partners within WP7. The study follows established LCC principles, ISO 14040-44 for the LCI structure, as well as the UNEP-SETAC 2009/2020 S-LCA guidelines and aligns with the system boundaries defined in the preliminary environmental LCA with additional data considering machinery (Deliverable 7.1). Together, the LCC and S-LCA provide an early-stage, cradle-to-gate evaluation of FLEXBY's economic performance and potential social impacts, offering the foundation for the final integrated sustainability assessment at Month 48.

The LCC and S-LCA were developed using a harmonised process structure and shared data templates, drawing upon process simulations, partner-supplied equipment specifications, catalyst data, and experimental inputs available to date. The modelling work was carried out in openLCA, using ecoinvent v3.11 for the LCC background data, and the SOCA v4 database for the S-LCA background data.

Coordination with project partners played a central role in refining assumptions and collecting primary economic and social data. **IDE** provided insights on potential valorisation options for biochar and contributed to process alignment. **PMI** supplied preliminary CAPEX and OPEX estimates for the upgrading units, which were further refined through discussions with **US**, who contributed additional inputs on catalyst types, replacement rates, and equipment maintenance requirements. **FRIMA** provided detailed information on the design and component-level behaviour of the microwave pyrolysis unit, while **A4F** supplied cultivation and harvesting data from raceway pond operation, including social indicators related to worker safety and plant operation.

A state-of-the-art review of LCC and S-LCA work related to biofuel production, pyrolysis-based conversion chains, and microalgae systems supported the methodological choices. The review helped positioning FLEXBY system in the current context of similar system.

The preliminary LCC models were built for two feedstocks:

- Feedstock 2 – microalgae grown in municipal wastewater (with and without wastewater treatment services), and
- Feedstock 5 – dairy-based oily sludge obtained directly from a wastewater treatment plant.

The assessment considers the different products of the FLEXBY conversion routes: biofuel from the bioliquid fraction, electricity from the gaseous fraction of the bioliquid pathway, electricity from pyro-gas, and biochar production.

1 INTRODUCTION

1.1 DESCRIPTION OF THE DOCUMENT AND PERSUE

This report, Deliverable 7.2, titled "First Social Evaluation and Economic Report (S-LCA and LCC)", submitted in month 20 of the FLEXBY project, presents the initial life cycle costing (LCC) and social life cycle assessment (S-LCA) of the FLEXBY technology at its current stage of development. In particular, the report includes:

- An overview of state-of-the-art LCC and S-LCA studies for comparable biofuel and microalgae-based systems,
- The goal and scope definitions following established LCC principles and UNEP-SETAC S-LCA guidelines (2009/2020) and aligned with ISO 14040/44,
- The methodological framework, modelling assumptions, data sources, and system boundaries applied to the cradle-to-gate assessment,
- The preliminary LCC results for biofuel, gas fraction-derived electricity, and biochar pathways, including sensitivity analyses for different feedstocks and wastewater-treatment scenarios,
- The initial screening of social hotspots across relevant stakeholder groups using the SOCA database,
- Key data gaps and recommendations to support the final integrated sustainability assessment planned for Month 48.

This document forms the basis for guiding the continued refinement, optimisation, and sustainability integration of the FLEXBY system from both an economic and a social perspective.

1.2 WPS AND TASKS RELATED TO THE DELIVERABLE

This deliverable refers to **Task 7.2**: Life Cycle Costing (Task Leader: GD; Other partners: ALL) [M01-M44] and **Task 7.3**: Social Life Cycle Assessment, including gender issues (Leader: GD; Others: ALL [M01-M44] included on **WP7**: Sustainability assessment.

Task 7.2:

During this task, GD will address Life Cycle Costing (LCC) and an economic enabling evaluation at the micro-level. The LCC will ensure a general level assessment based on the actual costs of the biofuel production. It will be performed with respect to a long-term picture of the product line profitability. LCC will entail three steps: 1) Specification: using the market data from task 8.1, this step will list all required product characteristics and establish manufacturing and raw material costs alongside the expected performance; 2) Prototype Manufacture and Design: this step will allow estimating potential investment costs linked with the start of the production using data from task 5.3. Moreover, prototype production costs will be calculated at this point in order to give a more precise overview to decision-makers; and (3) Utilisation and Recycling costs: Every product produced is connected to waste disposal and utilisation costs. Both parameters will be summarised and added to the final part of the LCC. For costs over the life cycle, own data and data from generic databases and marketplaces will be used. The output of the action will be a comprehensive economic report which is open to ALL the continuous partner contributions and suggestions. It will be based on information related to more actual costs and might be subject to change.

Task 7.3:

GD will provide a comprehensive analysis of the requirements for European society to fully utilise and integrate the FLEXBY project technology and related products into various industrial and small-scale sectors. Extensive literature research will be conducted in order to collect the latest results of what potential social and political barriers and drivers exist. For completing supply chains, social LCA databases will be used. Results will be calculated and analysed, together with the identification of hot *spots. This task will also include gender issues, and FLEXBY through surveys, will analyse the factors that intersect with gender (income, age, travel patterns, geographic location and environmental attitudes). It will allow a better understanding of climate impacts and consequently contribute to environmental policies with optimised mitigation measures. Input from all the partners will be crucial for this task.*

2 Coordination Among Project Partners and General Requirements

For the preparation of this deliverable, **GD** consistently organised online meetings with the relevant technical partners involved at this stage, to ensure the prompt exchange of necessary data, particularly concerning costs and key indicators. In detail:

- **PMI**, to review their preliminary CAPEX estimates for upgrading two pyrolysis fractions (specifically bio-oil and gas fraction), followed by discussions on the corresponding OPEX.
- **A4F**, to discuss aspects related to the microalgae growth phase.
- **FRIMA**, to receive updates on the design of the microwave system.
- **US**, building on PMI's estimations, to further examine replacement costs and replacement rates of various components.
- **IDE**, to assess the fate of the biochar phase, explore potential optimisation pathways, as well as to support coordination among partners.

The collaboration and diverse expertise of the partners facilitated the exchange of essential data for the preliminary LCC and S-LCA, supporting the identification of key cost drivers and sustainability aspects. Primary data were collected whenever available; however, given the early stage of the project, simulations and well-grounded assumptions were applied, when necessary. Each meeting is summarised below, highlighting the most relevant inputs shared by the partners, which were instrumental in shaping the foundational analyses for both the LCC and the S-LCA.

<u>IDE-GD meeting</u>

IDE played an important role in supporting coordination among the partners, ensuring alignment of technical inputs relevant to both the LCC and S-LCA. A major point of discussion concerned the potential fate of the biochar, including whether it could be activated (chemically or physically, based on the tests conducted from **CSIC**) or alternatively valorised without activation in different sectors.

Although WP5 has not yet started, the meeting also included a preliminary discussion on potential optimisation pathways, exploring early opportunities to improve performance within the overall process.

PMI-GD meeting

The meetings with **PMI** were primarily focused on coordination, as several activities carried out by **PMI** and **GD** were closely aligned and needed to progress in parallel. A significant part of the discussions involved reviewing **PMI**'s initial CAPEX estimations for the components required to upgrade the bioliquid and gas fractions. These estimates were revisited to verify whether any updates or adjustments were necessary based on the latest technical inputs.

Following this, attention shifted to the OPEX considerations, where operational costs associated with the same upgrading processes were examined. This collaborative exchange ensured consistency between technical assumptions and the economic modelling required for the LCC.

A4F-GD meeting

The discussion with **A4F** focused primarily on the costs associated with the microalgae growth phase. At this stage of the project, microalgae cultivation is performed specifically for FLEXBY, however, the objective of the project is to integrate the system into an urban wastewater treatment process, where the production of biofuel would valorise the algal biomass residue from urban wastewater treatment.

A4F also provided information on replacement rates of key components and other cost-related aspects required for the LCC analysis. In addition, they contributed with inputs for the S-LCA, including relevant social indicators and identification of stakeholders associated with processes. These included insights into activities conducted at their facility, such as employee safety training, the use of personal protective equipment (PPE), and other practices linked to worker well-being and operational safety.

FRIMA-GD meeting

FRIMA successfully submitted Deliverable 3.1, which presents the detailed design of the microwave machine. Building on this deliverable, subsequent meetings focused on gathering data essential for the LCC and S-LCA.

During these meetings, **FRIMA** provided information detailed related to the design, construction, and operational aspects of the microwave system, including costs, sourcing of components and the replacement rates of specific parts.

US-GD meeting

Since **US** will ultimately operate the machinery for upgrading the two pyrolysis fractions, the meeting with them focused on validating and refining the economic assumptions derived from **PMI**'s initial review. While **PMI**'s estimations primarily covered the initial capital expenditure, the discussion with **US** centred on identifying the components requiring replacement at rates different from the overall system lifespan, as well as determining the associated replacement costs.

US also provided insights regarding the catalyst they are designing (a topic they further elaborated in Deliverable 4.1). The meeting included a discussion of the costs associated with the catalyst and potential concerns related to the sourcing of rare metals, highlighting important considerations for both the LCC and S-LCA analyses.

3 State-of-the-Art

The progressive rise in global population, industrialisation, and urbanisation has intensified the demand for energy while accelerating greenhouse gas emissions from fossil fuel consumption. This dependence not only threatens long-term energy security but also exacerbates climate change and environmental degradation. Recent preliminary estimates from the Global Carbon Budget 2025 indicate that total anthropogenic CO_2 emissions (combining fossil fuel combustion and land-use change) are projected to reach approximately 42.2 Gt CO_2 in 2025, 1.1% more than 2024, marking another record high (Friedlingstein et al., 2025, preprint). Despite the ratification of the Paris Agreement, signed by over 190 countries and aimed at limiting global warming to well below 2 °C, observed emission trajectories remain significantly misaligned with pathways required for climate stabilisation. According to the Emissions Gap Report 2019, global greenhouse gas emissions must decline rapidly, with reductions of 7.6% per year in the decade 2020-2030 to remain on pathways consistent with limiting warming to 1.5 °C. This widening mitigation gap underscores the urgency of accelerating global low-carbon transitions.

The continued escalation of CO_2 emissions reflects a transgression of the planetary boundary for climate change, as defined by Earth System science. This boundary, conceptualised by Rockström et al. (2009), marks a critical threshold beyond which the risk of abrupt and irreversible system-level shifts increases substantially. Specifically, the climate boundary is described as maintaining atmospheric concentrations below 350 ppm CO_2 in order to preserve system resilience and ecological stability (Rockström et al., 2009). Current emission trajectories far surpass this boundary, intensifying risks of feedback and instability across climate and biosphere integrity domains (Drüke et al., 2024).

Consequently, these trends highlight the imperative for immediate and large-scale adoption of low-carbon technologies and policies. Failure to reverse current emission patterns threatens climate equilibrium and the adaptive capacity of both human and ecological systems, emphasising a pressing need for transformative interventions in global energy systems.

The transportation sector remains one of the largest contributors to greenhouse gas emissions, accounting for around 15% of global emissions (IPCC, 2023). To mitigate such emissions and achieve sustainable energy goals, renewable biofuels such as bioethanol and biodiesel have gained attention as viable alternatives. However, first-generation biofuels derived from food-based feedstocks have raised serious socio-economic and ethical debates over food security, leading to the advancement of second-generation biofuels based on lignocellulosic biomass (Naik et al., 2010; Ahmed er al., 2021). According to a Deloitte 2022 study, the sectoral contribution of biofuels to the EU27 economy with a direct Gross Domestic Product (GDP) impact of 2,304 M€ and an indirect at 6 621 M€ with a total 8,925 M€, with most of the contribution arising from the operation and maintenance phase (JRC, 2023; Deloitte, 2022). Despite improvements in conversion technologies and biomass utilisation, second-generation biofuels still face challenges related to feedstock availability, logistics, and seasonal dependency, limiting their scalability and economic feasibility (Sims et al., 2010).

Third- and fourth-generation biofuels, particularly those derived from microalgae, offer a promising pathway toward overcoming these limitations (Dutta et al., 2014, Mat Aron., et al, 2020). Microalgae are photosynthetic microorganisms capable of converting CO_2 and solar energy into biomass rich in lipids, carbohydrates, and proteins, which are suitable for diverse biofuel pathways (Brennan & Owende, 2010). Their cultivation does not compete with agricultural food production as they can grow in non-arable lands and saline water or even wastewater. Moreover, microalgae exhibit rapid growth rates and high areal productivities exceeding those of terrestrial biofuel crops (Chisti, 2007; Singh & Gu, 2010). They also demonstrate relevant CO_2 uptake capacity, with several studies highlighting their potential for significant carbon mitigation, even from an LCA perspective (Wang et al., 2008, Lardon et al., 2009).

The use of waste residues, as in FLEXBY, to replace fossil fuels can reduce reliance on imported fossil fuels and the geopolitical vulnerabilities associated with oil and gas distribution. It can also reduce the number of accidents and supply chain vulnerabilities present along fossil fuel supply chains. The flexible feedstock options in the project rely on waste residue or feedstock that does not compete with food resources. The FLEXBY process can employ dairy sludge, which would otherwise be anaerobically digested/incinerated, or microalgae biomass after growth in wastewater, which would additionally serve the function of wastewater treatment (Amaro et al., 2023) and carbon capture during the growth phase. This has been demonstrated in the EU project

Sabana and is in practice by the plant operated by Aqualia with different species of microalgae (SABANA, 2020)

The sustainability of microalgae biofuel production depends on several factors including the cultivation method, harvesting and dewatering, drying, nutrient inputs and conversion process (Lardon et al., 2009). Life cycle assessment studies indicate that co-locating algal cultivation with industrial facilities or wastewater treatment plants can significantly reduce greenhouse gas emissions and improve wastewater quality (Collotta et al., 2016). See also Deliverable 7.1.

From an economic perspective, the limited LCC studies available show a high degree of variability, mirroring the methodological diversity reported in D7.1 (titled *Preliminary LCA*) about LCA state-of-the-Art. This inconsistency originates from differences in cultivation systems, productivity assumptions, reactor design, dewatering strategies, conversion technologies, and allocation approaches. Nonetheless, LCC and TEA on similar systems highlight that there is growing evidence that with the right combination of cultivation strategy, process design, and by-product valorisation, the concept remains worth pursuing. The comprehensive review *"Microalgal biorefineries: a systematic review of technological trade-offs and innovation pathways"* (2025) demonstrates that there exist realistic, evidence-based configurations combining advanced cultivation strategies, energy-efficient harvesting and dewatering, bioproduct recovery, and valorisation of co-products that could substantially improve both economic viability and sustainability of microalgal biorefineries, thereby keeping the concept relevant and promising for future circular-bioeconomy.

Although capital expenditure and operational costs remain considerable, significant cost reductions can be achieved by optimising cultivation in wastewater and by valorising side-products, as in the case of FLEXBY, given that it allows for offsetting the biomass production costs, which is a hotspot in microalgae biorefineries (SABANA 2020, Mehariya et al., 2021, Rafa et al., 2021, Sivaramakrishnan et al., 2023, Geng et al., 2025). Furthermore, the policy framework, such as subsidies, renewable energy targets, and research incentives, plays a critical role in determining the financial viability of microalgae biofuels, with localised factors like labour costs and resource access influencing competitive advantage over conventional fuels (Roles and al., 2021).

From a social perspective, the development of microalgae-based biofuel industries can support rural and local economic growth through job creation in cultivation, harvesting, processing, and value-added manufacturing. Such projects can diversify local economies and enhance community resilience, offering more equitable socio-economic opportunities in line with the UN SDGs. From feedstock production to machinery production and operation, FLEXBY has immense job creation potential. EurObserv-ER reported 149,700 direct and indirect jobs in biofuels in the EU 27 in 2022, up slightly from 148,300 in 2021 (JRC 2023; EurObserv-ER 2022). This was projected by IRENA to continue into 2023 (IRENA, 2024).

Reviews of social sustainability in bioenergy systems show that microalgae initiatives can contribute positively to employment and community development, although social aspects are still less frequently assessed compared with environmental and economic dimensions (Murphy, F., 2024). At the same time, broader S-LCA applications in bioenergy further underline the variability of social risks (such as labour rights, governance, and health and safety) across regions and value chains, stressing the need for context-specific evaluation (Ugolini et al., 2025).

Recent research underscores the importance of integrating socio-economic considerations into early-stage assessments of microalgae biorefineries. Pérez López et al. demonstrate that life cycle costing (LCC) can be systematically combined with screening-level Social Life Cycle Assessment (S-LCA) to identify potential social hotspots and opportunities in emerging technologies before they reach commercial maturity. This integrated approach enables developers and policymakers to better understand how cost structures, labour intensity, technological choices, and supply-chain configurations influence social performance, serving as a meaningful approach for guiding sustainable scale-up of algae-based biofuel systems.

4 Policy frameworks and incentives related to biofuels from Microalgae

The European policy landscape surrounding advanced biofuels is currently shaped mostly by the revised EU Renewable Energy Directive (RED III), which forms the core regulatory driver for the sector. RED III significantly increases the Union's climate and energy ambition by raising the binding target for renewable energy consumption to 42.5% by 2030, with an aspirational level of 45%. Within the transport sector, member states must meet either a 14.5% reduction in greenhouse gas (GHG) intensity of transport fuels or achieve a minimum 29% share of renewable energy in final transport energy consumption by 2030.

These requirements place advanced biofuels (particularly those derived from non-food, non-land-competitive feedstocks such as microalgae or other feedstock of non-biological origin) at the centre of national compliance strategies, as they are among the few fuel categories that can deliver significant GHG reductions without competing with agricultural resources. To enable this transition, the directive sets a binding 5.5% sub-target for advanced biofuels listed in Annex IX Part A by 2030. Both FLEXBY feedstock (a) Algae cultivated on land in ponds or photobioreactors, and (f) Animal manure and sewage sludge are included in Annex IX Part A.

Complementing RED III, the EU has introduced sector-specific measures that further stimulate demand for advanced biofuels. Under the ReFuelEU Aviation Regulation, fuel suppliers at EU airports must provide a steadily increasing share of sustainable aviation fuels, including advanced biofuels. Likewise, the FuelEU Maritime Regulation imposes progressively stricter limits on the greenhouse-gas intensity of marine fuels. Together, these instruments create additional, long-term market pull for advanced biofuels across two of the most difficult-to-decarbonise transport sectors.

Beyond regulatory compliance, broader sustainability considerations also draw from established international frameworks. The Roundtable on Sustainable Biomaterials (RSB) provides a comprehensive set of principles and criteria, including social impact screening tools that are widely used in bioenergy projects. These frameworks guide the assessment of social co-benefits such as employment generation and improvements in quality of life resulting from enhanced air quality. The latter is a particularly important aspect for biofuels that replace fossil-derived heating oils or lignite-based heat and power systems, which are significant sources of particulate matter (PM), sulphur oxides (SOx), and nitrogen oxides (NOx).

Air quality improvements form a key element of the social sustainability dimension in the project's assessment. Evidence from previous studies, including reviews by Tomlins (2021), Sippula et al. (2019), and Williams et al. (2018), indicates that replacing fossil fuels with biomass-derived fuels generally results in reduced emissions of PM, NOx, and SOx, depending on combustion characteristics and fuel upgrading. The "better air quality" indicator used in the sustainability assessment therefore not only captures direct emission reductions but also reflects wider societal benefits associated with transitioning to cleaner energy systems. Evaluation of data from experiments on fuel testing later stages of FLEXBY, would inform this indicator.

Internationally, policy support for microalgae-based fuels is growing, particularly through research and innovation programmes. In the United States, the Department of Energy and the National Renewable Energy Laboratory (NREL) prioritise algae-based conversion pathways through dedicated initiatives and techno-economic studies (NREL, 2025). In India, the government promotes advanced and third-generation biofuels through national biofuel policies and targeted support programmes (VekPolicy, 2025).

Overall, these policies create a favourable environment for microalgae and sludge-derived fuels, positioning them as key contributors to the EU Green Deal objectives.

5 Life Cycle Costing and Social LCA

5.1 Goal and scope

This preliminary Social Life Cycle Assessment (S-LCA) and Life Cycle Costing (LCC) study aims to provide an early-stage understanding of the project's potential social impacts and cost implications from its cradle-to-gate life cycle. These assessments serve as a foundation for the more detailed, comprehensive evaluation to be carried out at the end of the project. At this stage, the goal is to position the project within the current state of the art, identify strengths and areas for improvement, and begin screening relevant social and economic hotspots that may influence design and strategic choices moving forward. The scope is intentionally exploratory, focusing on key life-cycle stages and dominant cost drivers to support informed decision-making as the project progresses. Initially, all stakeholders are considered for the social hotspot screening.

5.1.1 Reasons, project goal and intended application

The preliminary LCC of the FLEXBY technology, following an attributional life cycle assessment approach, is conducted to provide an early estimation of its economic performance, focusing on the cradle-to-gate phase of the integrated demonstrator. This assessment includes the raw materials costs, energy costs, capital costs of the machinery required for the microalgae cultivation, microwave-assisted pyrolysis, reforming, and upgrading, as well as the costs of replacement parts over the system's lifetime. Decommissioning costs are not yet considered at this stage and will be addressed in the final LCC when more reliable component-specific data becomes available (D7.3 to be delivered in M44).

The analysis follows established life-cycle costing principles and is aligned with the system boundaries and assumptions defined in the preliminary LCA to ensure methodological consistency; however, some extensions have been made to the model presented in D7.1. Based on available experimental and simulated data, the study quantifies the main cost contributions associated with electricity and materials use, equipment operation, and component replacement across the key FLEXBY process steps. As an early-stage assessment, its purpose is to identify major cost hotspots, critical assumptions, and parameters driving economic performance, thereby supporting technology optimisation and preparing the ground for a more comprehensive and integrated sustainability evaluation later in the project.

5.1.2 Intended audience

This preliminary report is intended primarily for internal use within the FLEXBY consortium. Its main purpose is to provide an early economic perspective on the FLEXBY system, laying down data collection requirements, supporting collaborative work between partners by highlighting key cost drivers, identifying potential optimisation opportunities, and guiding further development of the technology. By translating the technical and environmental insights from earlier project stages into a lifecycle-based cost framework, this report contributes to a shared understanding of the economic feasibility and challenges associated with the FLEXBY process.

As a public deliverable, the report may also serve as a useful reference for external technical stakeholders interested in the cost analysis of emerging biofuel technologies, particularly those involving pyrolysis-based conversion routes. Given the methodological diversity and limited availability of LCC and S-LCA studies for similar systems, this document provides a transparent and well-documented case study that can support the broader scientific and industrial community. In doing so, it helps advance current discourse on lifecycle costing approaches for innovative biorefinery configurations and contributes to the foundation for future assessments.

5.1.3 Product system and function

The function of the FLEXBY system is to produce 1) advanced biofuel;2) electricity from pyro-gas; and 3) produce biochar from biogenic waste streams, specifically microalgae cultivated in domestic wastewater and oily sludge generated by a wastewater treatment plant serving a dairy processing facility. There is also a fourth function that is not currently assessed in detail but may undergo experiments in the near future, which is the wastewater treatment by the microalgae during cultivation.

The FLEXBY technology life cycle starts with the microalgae production at wastewater treatment facilities, overseen by **A4F** in Lisbon, where two raceway ponds were installed and operated. The raceways were fed with secondary effluent and operated in batch mode without prior microalgae inoculation, allowing native (autochthonous) species to develop naturally. The process also shows a potential for wastewater treatment.

This is followed by dewatering of the microalgae, internal transportation of algal biomass, lipid extraction, transportation to the transportation to the CSIC at Asturias facilities in Northern Spain, for microwave pyrolysis and then the processing of the outputs of pyrolysis at the facilities of **US**. As of November 2025, the processes are operated in batch mode; however, Figure 1 illustrates the FLEXBY process as an integrated continuous system, beginning with the microwave pyrolysis of the microalgae.

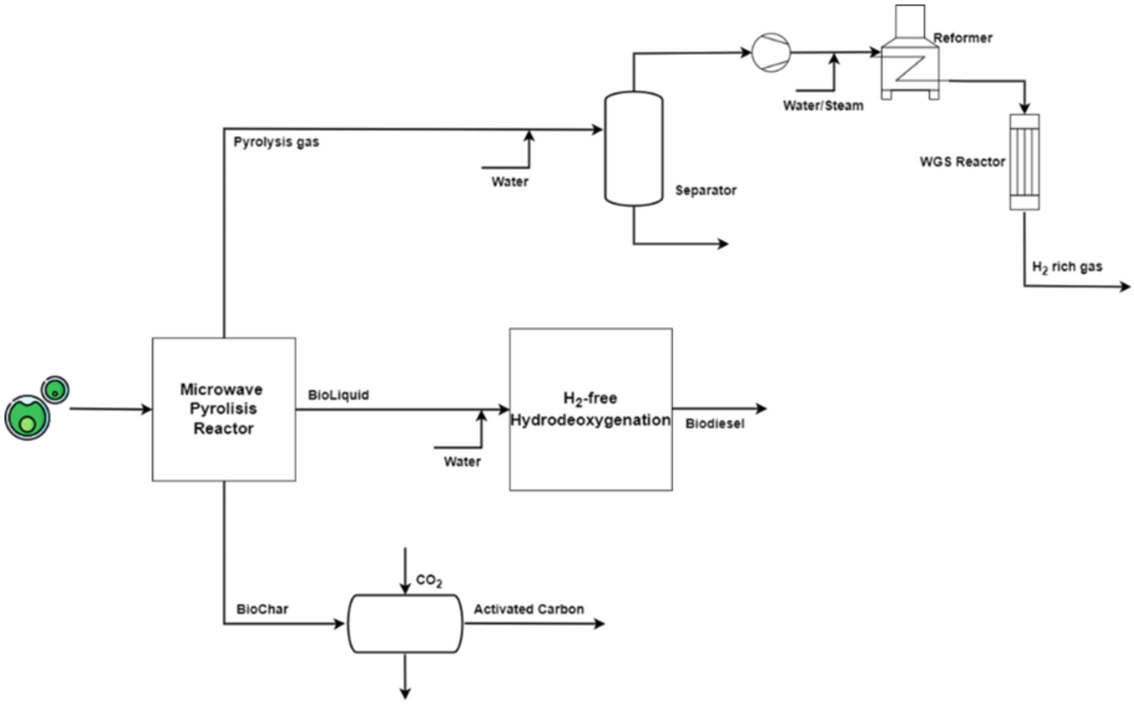

Figure 1: Block Flow Diagram of the FLEXBY process.

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 vapour 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).

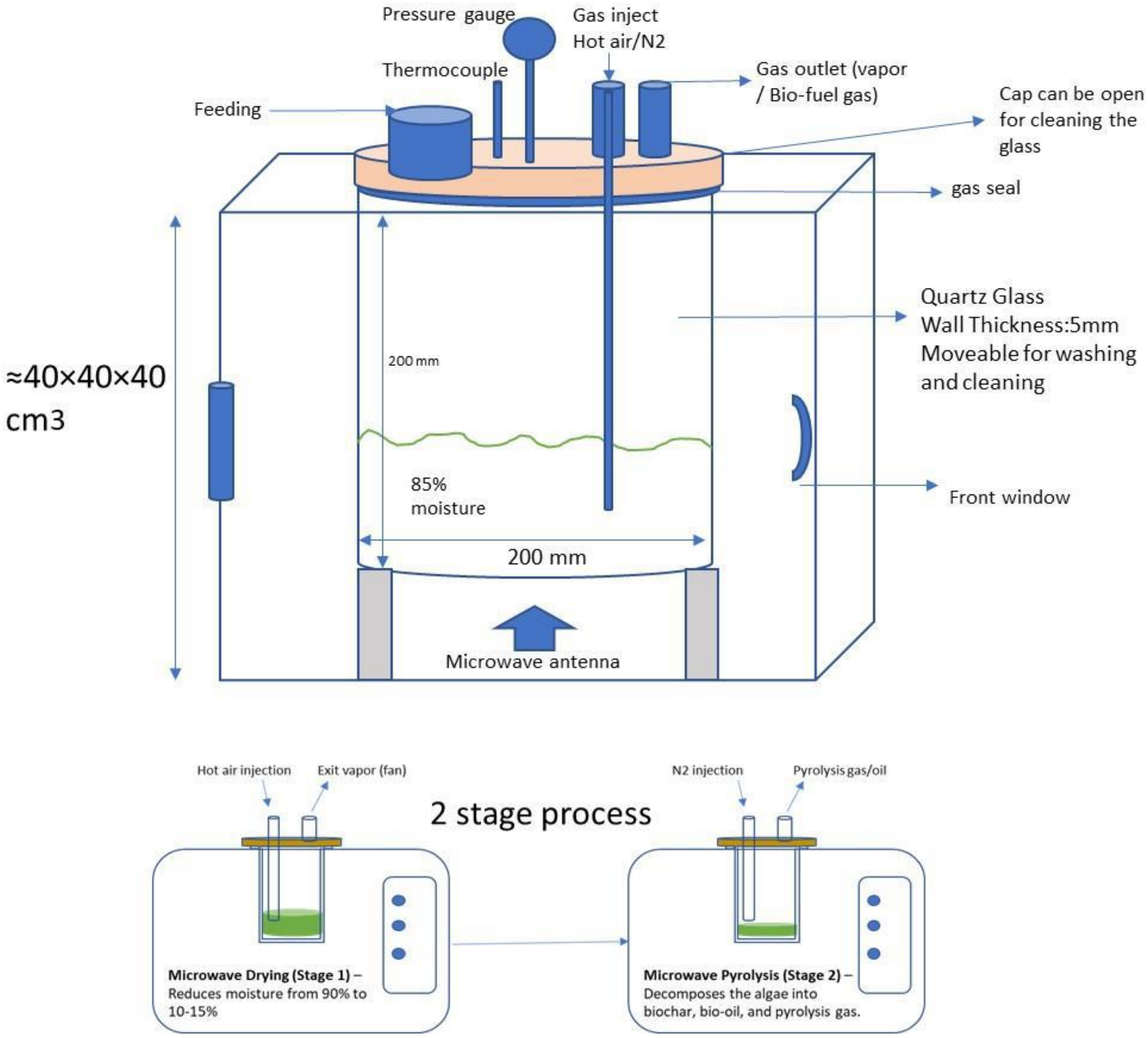

Figure 2 - Preliminary design concept of a microwave-assisted pyrolysis reactor operating in two stages: an initial drying mode followed by nitrogen (N_2) injection and pyrolysis processing (from Deliverable 3.1)

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. Where possible, efforts will be made to reuse it along with the feedstock to enable the microwave heating process, and research will be conducted to investigate its use as a soil amendment, as a precursor to activated carbon and its use in coprocessing of cement. However, the physicochemical properties of the biochar will determine its suitability for these applications.

The lab-scale experimental tests will be conducted in batch mode. However, the integrated-demonstrator plant, which will be installed at US facilities, will operate continuously. The current study is based on simulation data for the integrated demonstrator plant. 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.

5.1.4 Functional unit

For the functional unit, the bioliquid fraction, which after undergoing further purification steps, results in the advanced biofuel, is considered the product of interest. The functional unit is 1 kg of biofuel produced that can be combusted for use in a transport vessel. All subsequent analyses are relative to the functional unit of 1 kg of biofuel. Biochar and a gas fraction are produced as valuable by-products. Hence, the results are also presented from the perspective of these by-products of corresponding amount of electricity produced from a solid-oxide fuel cell by utilising the pyro-gas and biochar produced.

5.1.5 System boundaries

Based on insights from all meetings with partners, it was decided to proceed with the cradle-to-gate system boundary, focusing on the components, transport and operation life cycle stages of the FLEXBY process. In addition to the operational phase, the assessment includes the raw material extraction and manufacturing stages related to the required machinery, as well as the consumption of key operational inputs such as water and electricity and additional raw material (e.g. for developing the catalysts). This allows the study to capture both the embodied impacts of the equipment and the direct resource and energy use during operation.

The deliverable builds on D7.1, which focused on the operation stage, allowing for a detailed assessment of energy requirements and impact hotspots during operation while also enabling a comparison between conventional and MW pyrolysis systems. The operation stage has the most extensive primary and simulation data at the moment, which allows us to better understand process efficiencies, emissions, and resource consumption of FLEXBY's operational phase performance. The operational stage, particularly pyrolysis, reforming, and hydrodeoxygenation, is recognised as energy-intensive, especially when dealing with chemically heterogeneous and high-moisture biomasses (Chamkalani et al., 2020; Yu et al., 2022).

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 data on the post-processing stages already at the preliminary stage of the LCA.

Decommissioning and end-of-life stages of the machinery are not included in the current assessment. The exclusion is mainly due to the low technology readiness level (TRL) of the integrated FLEXBY demonstrator, for which reliable data on dismantling, waste treatment, recycling, and disposal are not yet available. These aspects are planned to be addressed in future LCA iterations as the technology matures and more representative end-of-life data become available.

5.1.6 Data requirements and data collection

Data for the preliminary LCC was gathered through regular technical exchanges and coordination calls with project partners, during which process conditions, operational strategies, and system configurations were jointly reviewed. The tailored Excel templates developed and distributed by **GD** for Deliverable 7.1 (see Annex 1 of Deliverable 7.1) were used to ensure consistent and structured data collection across partners. These templates, organised by process stage, included dedicated sections for inputs, outputs, energy use, and material flows, and were also designed for the LCC to capture machinery-related information such as equipment specifications, capital costs, and replacement schedules.

In this assessment, data collection focused not only on operational expenditures (OPEX) but also on the capital investment (CAPEX) associated with the integrated demonstrator. Accordingly, the LCC incorporates preliminary cost data from **PMI**'s Deliverable D2.3, including equipment sizing and baseline cost estimates from the energy balance and process modelling work. This information was complemented with targeted inputs from key partners: **FRIMA** provided detailed data on microwave reactor components and replacement parts; **US** contributed information regarding upgrading reactors and catalyst requirements; **A4F** supplied cultivation-related data relevant to microalgae feedstock costs; and **IDE** supported assumptions regarding biochar handling and potential valorisation.

Where primary data was still unavailable (particularly for components not yet built or tested) gaps were filled using expert estimates, simulation outputs, or values derived from literature to ensure completeness and consistency ahead of the final LCC and S-LCA.

5.1.7 Data quality control

Data quality was not assessed for this task but will be included in future studies.

5.1.8 Assumptions

Given the early stage of development of the FLEXBY process, the preliminary LCC and S-LCA rely on a combination of primary data, partner-provided estimates, process simulations, and literature values. Whenever direct cost data or detailed operational information were not available, assumptions were formulated based on analogous technologies and expert judgment from involved partners. All assumptions are documented in detail within the process-specific inventory tables of the LCI section (5.2.1.7).

A simplified operational lifetime of 20 years is assumed for the integrated demonstrator, serving as the basis for annualising capital expenditures. To capture the behaviour of components with shorter service lives, the studies also include replacement parts and consumables, based on partner inputs and preliminary durability estimates (e.g., microwave components from **FRIMA**, piping from **US**). Decommissioning costs are not included at this stage but will be included in upcoming LCA studies.

This approach ensures methodological alignment with the early-stage LCA and provides a coherent foundation for cost modelling. At this stage, FLEXBY technologies are broadly positioned at TRL 3-4, with microalgae cultivation efforts advancing the state of the art by developing and testing intensified operational procedures for wastewater-based cultivation, assessing biomass suitability for biofuel production, and improving system understanding to enhance control, replicability, and productivity.

5.1.9 Multifunctionality

According to the ISO 14040-44, allocation in Life Cycle Assessment (LCA) involves the distribution or allocation of input or output flows from a process or product system among multiple products or functions, when a process generates more than one product or service. A methodological approach is required to choose a proportion to allocate burdens. The choice of allocation, whether based on physical properties (e.g., mass or energy content), economic aspects, or system expansion, can significantly influence the results and interpretation of the LCA. The FLEXBY project is still in the process design and lab experiments stage, and after process optimisation, more by-products may be identified within the process and valorised within the system. Currently, the following cases of multifunctionality exist within the project:

1. The microalgae growth phase serves the dual purpose of treating the wastewater as well as producing microalgae that can be valorised for fuel production. This implies that, in addition to producing the microalgae feedstock, there is a wastewater input as avoided waste, treated wastewater that could be a by-product, once its quality is tested and a final use can be defined. The wastewater treatment is currently not the main focus of the project, and only nitrogen and phosphorus measurements are tracked; therefore, the wastewater treatment was modelled as a partial wastewater treatment, using the process 'Treatment of wastewater, unpolluted' from ecoinvent 3.10. The input wastewater was handled using system expansion, with the process of 'market for wastewater treatment being the avoided waste treatment process'.

   A scenario analysis was conducted to compare a scenario where wastewater is released back to the treatment facility and another where partial wastewater treatment by microalgae is considered and thereby reducing the impacts of further wastewater treatment required before releasing the water to the environment.

2. The pyrolysis process produces biofuels, pyro-gas and biochar. The exact applications of the outputs of the process are unclear at this preliminary stage, and therefore system expansion was not performed; instead, the allocation by physical property was performed, using ‘mass’ based allocation.

3. Ammonia, which can be valorised and reused. The valorised ammonia was handled with system expansion.

4. Processing of the bioliquid fraction to produce a liquid biofuel for heavy transport, as well as electricity from the gaseous fraction of this stream: the inventory was partitioned or allocated between the bioliquid fuel fraction and gaseous fraction by mass.

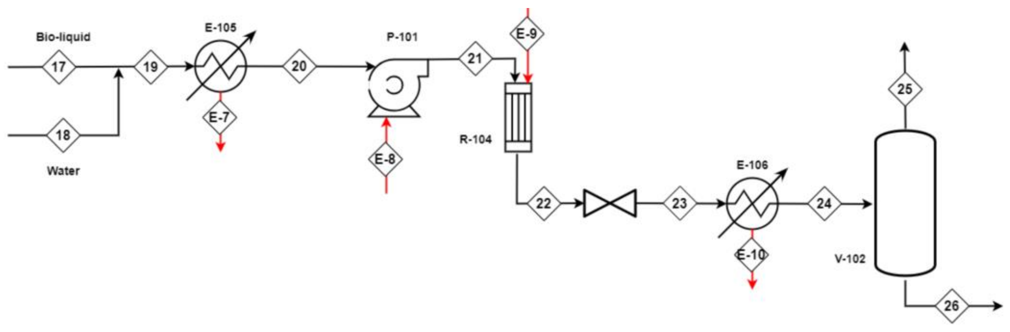

Figure 3 - Process Flow Diagram of bio-liquid refining, with its associated streams, as in Deliverable 2.3

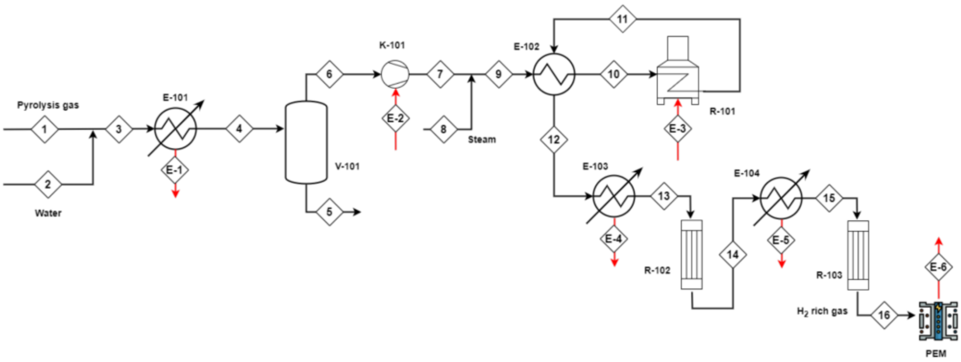

Figure 4 - Process Flow Diagram of pyrolysis gas post-processing, with its associated streams, as in Deliverable 2.3. Note that the latest techonogical development of FLEXBY inlcude a SOFC cell and not a PEM cell

5.1.10 Calculation

The calculations are performed with the open-source software openLCA, v2.5.0, with ecoinvent v3.11 cutoff unit processes as background database for LCC and with SOCA v4 for the S-LCA.

The LCC analysis focuses on monetary costs, assessing capital expenditures, operational expenditures, and replacement costs over the assumed system lifetime.

5.1.11 Interpretation of results

The interpretation of results in this deliverable provides an initial understanding of the economic and social performance of the FLEXBY system at its current development stage, with a structured discussion of the main cost drivers, methodological assumptions, and uncertainties affecting the preliminary LCC, as well as an overview of the social hotspots and stakeholder-related risks emerging from the S-LCA screening. Because the two assessments address different dimensions of sustainability, the interpretation is presented in two dedicated sections (one for LCC and one for S-LCA) each outlining the key insights, limitations, and implications for the next steps toward the final integrated sustainability study at Month 48.

5.1.12 Critical review

Not considered for this study. However, the results are shared and discussed with the FLEXBY consortium.

5.2 Modelling and life cycle inventory

The product system for the preliminary LCC follows the same organisation used in the environmental LCA, reflecting the processes that define the cradle-to-gate stage of the FLEXBY technology. All processes in the foreground system are consistently identified using the naming conventions established during the LCA modelling phase.

The product system begins with the feedstock supply processes. Feedstock 2 (microalgae) includes cultivation and harvesting, while Feedstock 5 (wastewater sludge from dairy treatment plants) is taken directly from wastewater treatment. Both feedstocks undergo drying at **CSIC** facilities prior to pyrolysis. The resulting products (bio-oil, pyro-gas, and biochar) are then routed to their respective upgrading or handling processes.

Consistent with the environmental LCA in D7.1, a feedstock flowrate of 100 kg/h is assumed, in alignment with **PMI**'s process modelling. Operational costs and machinery costs are calculated using data established in D2.3 with this throughput, together with the energy demands, material requirements, and equipment specifications collected from partners. Electricity consumption cost was accounted for with assumptions form the ecoinvent database.

The details of LCI data can be found in section 5.2.1.7

5.2.1.1 Microalgae growth and harvesting

At the current stage, the microalgae cultivation and harvesting stage is carried out in a 1 m^3 and 5 m^2 photosynthetic area capacity raceway in Lisbon, at the wastewater treatment facility, which provides wastewater for treatment and algae growth. The microalgae produced is characterised in the deliverables D2.2 -*Report on microalgae consortium Characterization*- and D2.1 -*Physicochemical sheet for the biomass feedstock*-.

The equipment was modelled initially using the equipment inventory provided by **A4F** for the current FLEXBY demonstrator scale. At this stage of development, costs are based on partner-supplied estimates for all major units, including:

- Raceway pond with paddlewheel agitation, representing the primary cultivation unit.
- Harvesting pump, used to transfer the biomass–water mixture from the raceway to the separation units.

- Settler for primary physical separation, which performs the main harvesting step.
- The microalgae have an uptake of CO_2 during its growth phase, A4F is currently conducting experiments to measure this, however, values for this study were taken from literature.
- At this stage we are still considering the microalgae cultivation (in one scenario) because at this point the algae are cultivated primarily for FLEXBY. However, the aim of the project is to provide the service for urban wastewater treatment and use the waste microalgae resulting from it (SABANA, 2020).

A4F identified the species of microalgae grown in the wastewater as two predominant species of the *Scenedesmus* genus, which has already been studies for biofuel applications because its significant lipid content and growth rate (Deliverable 2.2) a consistent proportion is possibly of the *Desmodesmus* subgenus.

5.2.1.2 Feedstock drying and pyrolysis

Both processes of feedstock drying and pyrolysis rely on machinery supplied by **FRIMA** and will be operated and tested at **CSIC** Facilities.

FRIMA has provided preliminary cost estimates for the complete microwave (MW) pyrolysis unit, including the microwave cavity, control panel and auxiliary components. The material composition of the microwave pyrolysis. These capital costs have been incorporated directly into the LCC model and annualised according to the standard 20-year economic lifetime used throughout the assessment.

In addition to the overall equipment lifetime, **FRIMA** supplied specific durability estimates for the magnetron, the core component that generates microwave energy, at 10.000 hours. Therefore, the LCC includes scheduled replacement costs at the intervals indicated by **FRIMA**. These replacement parts are reflected as operational expenditures over the 20-year period.

Moreover, microwave pyrolysis requires a continuous nitrogen flow to operate. **FRIMA** provided the nitrogen consumption rate, which has been integrated into the model as a recurring operating cost. The nitrogen demand is treated as proportional to the operational hours of the system.

Energy consumption for both drying and pyrolysis is based on the mass and energy balance results shared by **PMI** and the estimation of initial moisture content of the feedstocks provided by CSIC in the D2.1 report. These simulations directly determine electricity-related operating costs, using Spanish electricity price assumptions for consistency with the LCA and other processes in the LCC.

5.2.1.3 Gas fraction processing: Separation from ammonia, WGS, and steam reforming

For the gas fraction processing stage cost estimates were primarily provided by **PMI**, with additional refinement from **US**, especially additional estimations regarding component-specific replacement rates and catalyst requirements. Using Deliverable 4.1- *Report on flexby unique hybrid multifunctional catalysts for all flexible biofuels process at lab-scale* – as a reference, **US** supplied details on the catalysts considered for the WGS and reforming steps, including both a commercial Fe–Cr catalyst and the homemade formulations developed within FLEXBY based on Fe and Fe–Ni supported on ceria–alumina. These inputs, together with raw material needs and indicative lifetimes, were incorporated into the operational expenditure model.

As for the other FLEXBY processes, a 20-year lifetime is assumed for the integrated demonstrator, while individual components follow their own maintenance cycles. Key replacement items include mass-flow controllers, quartz liners**,** WGS reactor stainless-steel tubes**,** electric furnaces/heaters used as heat exchangers. And tubing maintenance. **US** also provided raw material and catalyst information for both WGS and reforming steps, which is incorporated into operational expenditures.

5.2.1.4 Bioliquid processing: H_2-free hydrodeoxygenation

For the bioliquid upgrading stage, data collection followed the same path as the gas fraction processing. Estimate cost inputs were primarily provided by **PMI** and further refined by **US**, who supplied updated estimates for equipment components, replacement frequencies, and catalyst consumption. Again, using Deliverable 4.1 as reference, **US** also specified the catalysts developed for the HDO pathway, including the lab-made activated-carbon-supported formulations based on Ru, Ni and Fe. These catalysts differ from those designed for the gas fraction upgrading route, reflecting the different reaction environments involved.

As with the rest of the system, a 20-year lifetime is assumed for the integrated demonstrator, while individual units follow shorter maintenance or replacement cycles based on partner specifications.

The main recurring cost elements include reactor components, quartz liners, heating elements, and tubing, which follow similar replacement intervals to those used in the gas fraction processing train. Additional costs arise from catalyst usage, for which **US** provided the required raw material quantities and indicative replacement rates.

5.2.1.5 Biochar handling

In the initial FLEXBY system concept, biochar was hypothesised to be reused internally as a catalytic support material. However, ongoing tests performed by **CSIC** indicate that the biochar produced under pyrolysis, particularly when the process is optimised for maximising pyro-gas and bio-oil yields, which is the goal of the FLEXBY system, exhibits a high ash content, which would make the considered physical activation using CO_2 inefficient. This significantly reduces its suitability for in-situ reuse as a catalyst support. As a result, chemical activation is being considered, but further data are needed before this option can be incorporated into the economic model. For this assessment, the system assumes the purchase of commercial activated carbon to fulfil the support role originally intended for activated biochar. Costs associated with this external procurement are included in the operational expenditures of the pyrolysis stage.

In addition to activation-based reuse pathways, another potential in-situ use of biochar is as a microwave precursor, and it is also being considered. Experimental validation would be required, particularly once microwave equipment becomes available at **CSIC**, before this pathway can be assessed from a technical, environmental, or economic perspective.

At the same time, alternative valorisation routes, external to the system, for the non-activated biochar are being evaluated by **IDE** and **CSIC**. Current options under consideration include:

- Use as a soil amendment, depending on compliance with agronomic and regulatory requirements.
- Application as an additive in construction materials, where its physical properties may offer functional benefits.

In both cases, the biochar is not treated as a waste stream in the FLEXBY system. Instead, it is regarded as a co-product with potential value, although no income or avoided-cost credit is modelled at this stage due to insufficient data. These aspects will be further examined and refined in the final LCC once experimental characterisation and market suitability assessments become available.

5.2.1.6 Modelling machinery

The machinery of unit processes considered from cradle to gate was modelled with expert inputs and literature data and datasets adapted from ecoinvent. The overview of machinery used is documented along with associated costs, lifetime and assumed capacity in Table 1. The overall FLEXBY system was assumed to have an operational lifetime of 20 years. (Corollary assumptions: ideal performance, no complete component failures considered, only regular replacements for specific parts with lifetimes shorter than 20 years)

When considering machinery, the information researched or requested included the following:

- Material composition of a product
- Energy required for production of machinery, and the emissions or wastes generated, as the technology evolves, their relationship with product scale and design choices will be investigated
- Energy required to run the machinery
- Any other operating inputs
- Data on maintenance and repair and replacement
- Lifetime of the machinery and its dependence on repair and maintenance or other factors
- For the SOFC cell, 30k euro value was used, based on the GA (pg 138), and the assumption that it operates at 80% energy efficiency (page 15):

5.2.1.7 LCI data

The following tables contain the details of the data used in the LCI.

Table 1 - Overview of FLEXBY system CAPEX costs

Component (with energy/material flows for PMI)	Stream in	Cost (€)
Raceway with paddlewheel	Feedstock	8,100
Harvesting pump	Feedstock	240
Settlers	Feedstock	200
microwave pyrolysis (2.45 GHz, 3 kW, able to operate up to 3 bar)	Feedstock	200,000
E-101 - heat exchanger	Gas fraction	9,000
V-101 - flash separator	Gas fraction	1,000
K-101 - compressor	Gas fraction	13,000
E-102 - heat exchanger	Gas fraction	4,000
R-101 - steam reformer	Gas fraction	100,000
E-103 - heat exchanger	Gas fraction	3,000
R-102 - WGS reactor	Gas fraction	1,000
E-104 - heat exchanger	Gas fraction	2,000
R-103 - WGS reactor	Gas fraction	1,000
E-105 - heat exchanger	Bioliquid	8,000
P-101 - compressor pump	Bioliquid	1,000
R-104 - HDO	Bioliquid	US estimate: 35,000 RP0: 65,000
E-106 - heat exchanger	Bioliquid	6,000
V-102 - separator	Bioliquid	1,000
SOFC	1. Gas fraction and 2. gas fraction of bioliquid	30,000
Mass flow controllers	Overall	12,000
Quartz liners	Overall	1,000
Tubing maintainence	Overall	3,000
Cement coprocessing (still adding machinary/process)	Biochar	
Soil amendment (still adding machinary/process)	Biochar	

Table 2 - overview of FLEXBY system OPEX inputs related to machinery energy requirements

Component (with energy/material flows for PMI)	Stream in	microalgae scenario (feedstock 2)	dairy sludge scenario (feedstock 5)	Unit
Raceway with paddlewheel	Feedstock	0.066	-	kWh/kg
Harvesting pump	Feedstock	0.051	-	kWh/kg
Settlers (100/130 L volume)	Feedstock	-	-	kWh/hour
microwave pyrolysis (2.45 GHz, 3 kW, able to operate up to 3 bar)	Feedstock	8	8	kWh/hour
E-101 - heat exchanger	Gas fraction	1.16	1.15	kWh/hour
V-101 - flash separator	Gas fraction			kWh/hour
K-101 - compressor	Gas fraction	0.09	0.06	kWh/hour
E-102 - heat exchanger	Gas fraction			kWh/hour
R-101 - steam reformer	Gas fraction	1.64	2.45	kWh/hour
E-103 - heat exchanger	Gas fraction	0.68	0.76	kWh/hour
R-102 - WGS reactor	Gas fraction			kWh/hour
E-104 - heat exchanger	Gas fraction	0.27	0.31	kWh/hour
R-103 - WGS reactor	Gas fraction			kWh/hour
E-105 - heat exchanger	Bioliquid	4.06	3.92	kWh/hour

P-101 - compressor pump	Bioliquid	0.01	0.01	kWh/hour
R-104 - HDO	Bioliquid	14.04	11.75	kWh/hour
E-106 - heat exchanger	Bioliquid	1.31	1.33	kWh/hour
V-102 - separator	Bioliquid	-	-	kWh/hour
SOFC	Gas fraction	3.66	5.13	kWh/hour
	Gas fraction of bioliquid	22	37.3	kWh/hour

Table 3 - Overview of prices for water and electricity - OPEX

Flow	Ecoinvent 3.11	Unit
Electricity price (solar)	9.77E-02	EURO/kWh
tap water	3.97E-04	EURO/kg

Table 4 - Overview of energy and consumables (aside from catalysts)

Partner	Energy costs	Value	Unit
A4F	electricity to produce 1 kg dry weight of microalgae	238	kJ per kg dry weight
A4F	electricity to harvest 1 kg dry weight of microalgae	8.8	kWh per kg dry weight
CSIC	electricity for drying	0.64	kWh per kg water to be evaporated
CSIC	electricity for pyrolysis	3.7	kWh per kg of pyrolysis feedstock

Table 5 - Overview of costs and characteristics of catalysts

Catalysis precursor	Stream	Quantity precursor	Cost (EUR)/kg		Provided by
Iron (III) nitrate nonahydrate	Bioliquid	8 wt.%	tbd	2g	PMI/US
Nickel (II) nitrate hexahydrate	Bioliquid	8 wt.%	tbd	2g	PMI/US
Ruthenium (III) nitrosyl nitrate	Bioliquid	2 wt.%	6	2g	PMI/US
Acetone	Bioliquid			2g	PMI/US
Activated Carbon DARCO, Sigma Aldirch	Bioliquid		2.52	2g	Business Analitiq
Fe2O3	Gas fraction	15 wt.%		2g	PMI/US
Fe2O3 + NiO	Gas fraction	15 wt.% + 15 wt.%		2g	PMI/US
	Gas fraction			2g	PMI/US
CeO2/Al2O3	Gas fraction			2g	Puralox, Sasol

6 Life Cycle Costing

6.1 Limitations

This preliminary LCC is based on early-stage data, including preliminary equipment costs, simulation outputs, and partner estimates. Some processes, such as biochar activation, are not yet modelled, and decommissioning costs are excluded.

6.2 Life Cycle Inventory and modelling

The creation of life cycle models for the FLEXBY system follows the following steps:

- Data collection for the process machinery, operation and inflows and outflows
- Based on the data collection, creation of life cycle foreground models in the openLCA software.
- Linking of the foreground models to background data contained in the ecoinvent database for the environmental and cost assessment.

6.3 Sensitivity analysis

For this preliminary LCC assessment, the following scenarios have been evaluated: **two different feedstocks**, **2** and **5**, in accordance with Deliverable 2.3 and both scenarios use **microwave pyrolysis**. Although the LCA model has been expanded with new data, we maintain the notation of **2.1** and **5.1**, as in the previous deliverable. Moreover, for feedstock 2 (microalgae)**,** an additional case has been considered in which wastewater treatment is treated as a service, in line with the upscaling objective of FLEXBY (scenario **2.1-SE**). In this case, microalgae are assumed to be produced as part of wastewater treatment rather than solely for the purpose of biofuel production, and the LCC is adjusted accordingly using a **system-expansion** approach. Sensitivity analysis

Table 6 - Sensitivity analysis scenarios

Scenario ID	Feedstock	Conversion method	Notes
2.1	Microalgae (Feedstock 2)	Microwave pyrolysis	Base case for feedstock 2
2.1-SE	Microalgae (Feedstock 2)	Microwave pyrolysis	System expansion: wastewater treatment service considered
5.1	Dairy-based oily sludge (Feedstock 5)	Microwave pyrolysis	Base case for feedstock 5

6.4 Results and interpretation

The results, representing potential LCC hotspots are presented separately for the three main pathways of the FLEXBY system after the pyrolysis occur, hence biofuel (chosen as main reference) pyro-gas and biochar. The results are allocated to the three streams at the pyrolysis process based on the masses of the fractions produced. They are then further allocated based on mass whenever additional multifunctionality occurs as described in section 5.1.9. The results are given per 1 kg of biofuel and the corresponding amounts of the other fractions, as shown in Table 7.

Table 7 -Quantities of the product fractions for which the results are reported (in bold) and intermediate streams.

Final products	S2.1 and S1-SE scaled to 1 kg biofuel	S5.1 scaled to 1 kg biofuel	Unit
Biofuels - cradle to gate (S25)	1	1	kg
Electricity from the biofuel pathway	4.53	12.03	kWh
H2 rich fraction from biofuel pathway (S26)	0.76	1.65	kg
H2 rich gas fraction	0.62	0.42	kg
Electricity from the gas fraction pathway	0.74	1.34	kWh
Biochar	1.15	1.84	kg

6.4.1 Bioliquid pathway

6.4.1.1 Biofuel fraction

The cost structure of biofuel production from the pyrolysis bioliquid fraction is dominated by the **pyrolysis** and **H_2-free hydrodeoxygenation (HDO)**, while **feedstock production** represents a smaller, but still relevant, contribution. Additional upgrading unit operations, including cooling, heat exchangers, compressors, and flash separation, remain marginal contributors, accounting for only very small fractions of the total life cycle cost.

The pyrolysis stage emerges as the largest cost contributor, driven primarily by **energy requirements** (52–61% of the total cost), with the **microwave pyrolysis unit** itself also representing a noticeable share (19–23%). This highlights that pyrolysis is both energy- and capital-intensive within the overall production pathway.

The HDO stage contributes the second-largest cost (19–21%). **Raw material inputs**, particularly those associated with **catalyst** production, form the main cost share, followed by **energy consumption**. Machinery-related costs for the reactor and auxiliary equipment remain negligible, indicating that HDO is largely operational rather than capital-intensive.

For microalgae-based feedstock, cultivation is another notable contributor to total costs. Most costs arise from raw materials, especially the fertilisers used for augmenting the yield, whereas energy used for cultivation and harvesting is comparatively minor.

Table 8 - LCC results for the biofuel production from the bioliquid pathway of the pyrolysis

Process	Total result [EUR] S2.1	Total result [EUR] S2.1-SE	Total result [EUR] S5.1
Stage 3: Pyrolysis | energy requirements - ES	5.54E+00	5.54E+00	5.31E+00
Stage 3: Microwave pyrolysis machinery	2.07E+00	2.07E+00	1.98E+00
Stage 3: Pyrolysis | raw materials	8.67E-02	8.67E-02	8.31E-02
Stage 4.1.3: H2-free hydrodeoxygenation (HDO) (R-104) - Raw Materials	1.39E+00	1.39E+00	1.33E+00

Stage 4.1.3: H2-free hydrodeoxygenation (HDO) (R-104) - Energy requirements	6.26E-01	6.26E-01	5.03E-01
Stage 4.1.3: H2-free hydrodeoxygenation (HDO) (R-104) - Machinery	1.21E-02	1.21E-02	1.16E-02
Stage 4.1.1: Cooling, heat exchanger E-105 (S-20 out) - machinery - ES	1.15E-03	1.15E-03	1.06E-03
Stage 4.1.4: Heat exchanger E-106 - machinery	8.87E-04	8.87E-04	8.15E-04
Stage 4.1.2: Compressor pump P-101 - energy requirements - ES	4.46E-04	4.46E-04	4.28E-04
Stage 4.1.1: Cooling water S18	2.70E-04	2.70E-04	2.30E-04
Stage 4.1.5. Flash separation (V-102) - machinery	2.00E-04	2.00E-04	1.92E-04
Stage 4.1.2: Compressor pump P-101, machinery	1.40E-04	1.40E-04	1.28E-04
Stage 4.1.4: Cooling bioliquid (S22/S23), heat exchanger E-106 - energy requirements - ES	0.00E+00	0.00E+00	0.00E+00
Stage 1: Feedstock Production and transport	8.60E-01	-9.28E-01	0.00E+00
flexby Overall maintainence and replacement	2.98E-02	2.98E-02	2.83E-02
Stage 2: Drying and deodourization of feedstock - ES	0.00E+00	0.00E+00	0.00E+00

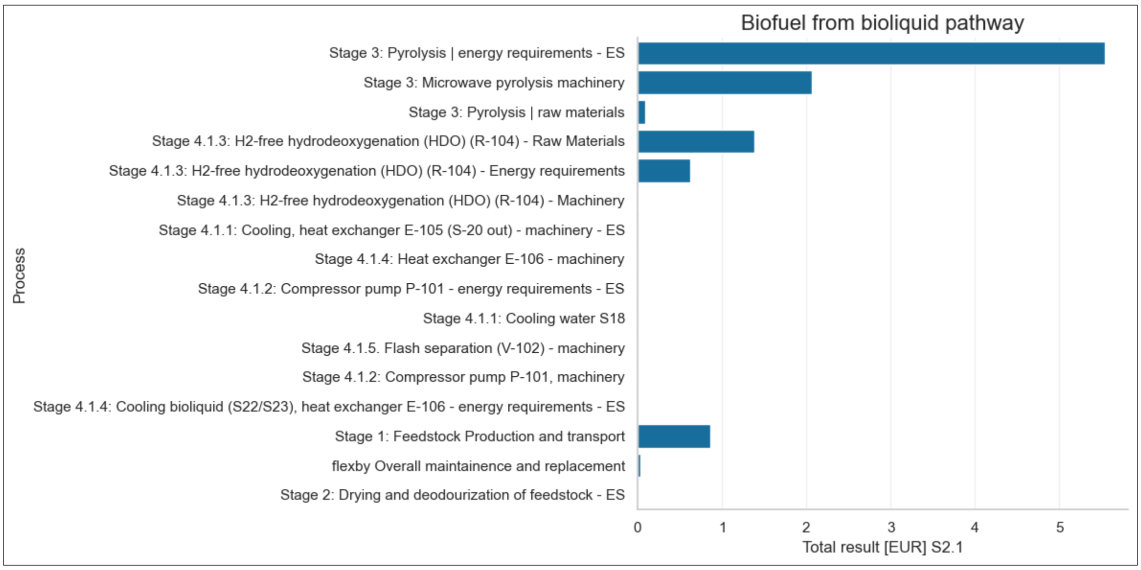

Figure 5 - Detail of scenario 2.1 of biofuel from bioliquid pathway

In the scenario with system-expansion credits for wastewater treatment (**S2.1-SE**), the total LCC is significantly reduced. Pyrolysis and HDO remain the dominant cost contributors, while microalgae cultivation effectively becomes a net cost reduction, as the service provided by wastewater treatment offsets much of the upstream burden. Maintenance and auxiliary unit operations continue to contribute only marginally.

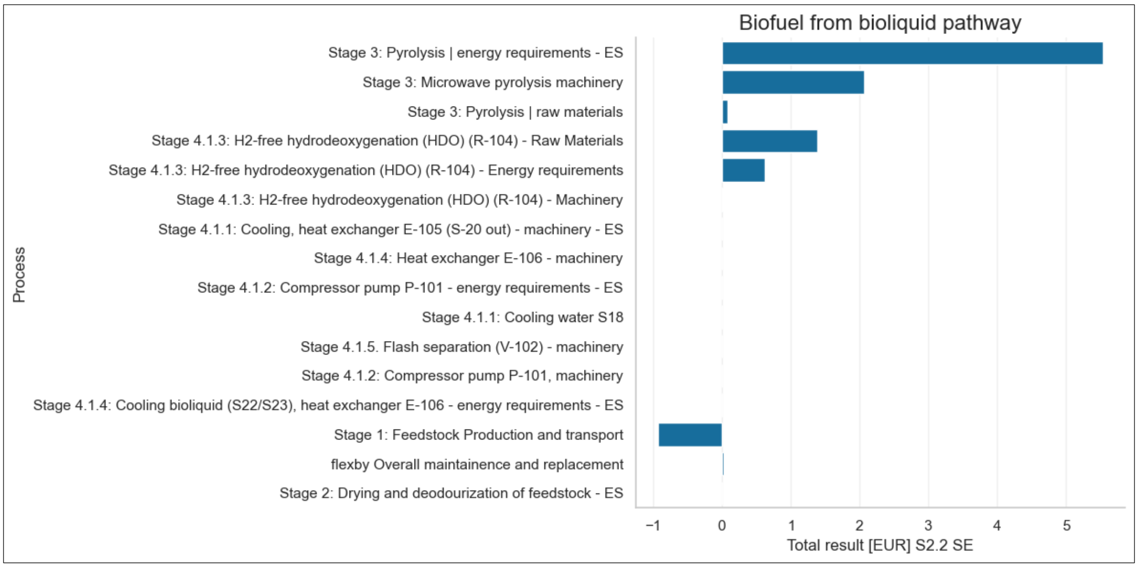

Figure 6 - Detail of scenario 2.1-SE of biofuel from bioliquid pathway

When considering dairy-based oily sludge as feedstock (**S5.1**), the total LCC is approximately 10% lower than conventional microalgae (**S2.1**), entirely due to the absence of feedstock production costs. Pyrolysis and HDO costs remain of similar magnitude, demonstrating that conversion and upgrading costs are largely independent of the feedstock type.

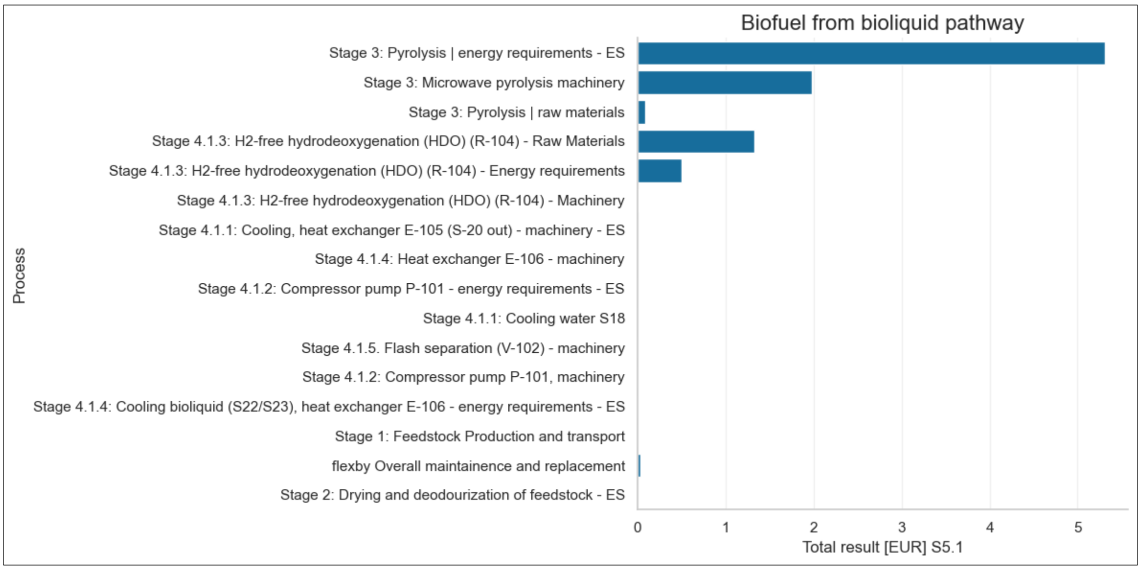

Figure 7 - Detail of scenario 5.1 of biofuel from bioliquid pathway

Scenarios **2.1-SE** and **5.1** behave very similarly. Both scenarios effectively eliminate feedstock cost and as a consequence, the total LCC of the two scenarios is nearly identical, differing by only about 1–2% in favour of scenario **2.1-SE**.

6.4.1.2 Electricity from the gaseous fraction from the bioliquid pathway

The LCC for producing electricity from the gaseous fraction of the bioliquid pathway is again dominated by the conversion process (namely, dominated by the **pyrolysis** and **HDO**), with feedstock production and upgrading auxiliary operations contributing only marginally.

The **pyrolysis stage** is the largest cost contributor across all scenarios. **Energy requirements** are the main driver, followed by the capital costs of the **microwave pyrolysis unit**. Raw material costs associated with pyrolysis are minor.

The **HDO** stage is the second-largest contributor. Here, raw materials (mainly **catalysts**) represent the major cost share, with **energy consumption** being the second most significant component. Machinery costs remain negligible, indicating that HDO is largely operational rather than capital-intensive.

Table 9 - LCC results for the electricity production from the gaseous fraction of the bioliquid pathway of the pyrolysis

Process	Total result [EUR] S2.1	Total result [EUR] S2.1-SE	Total result [EUR] S5.1
Stage 3: Pyrolysis | energy requirements - ES	4.59E+00	4.59E+00	6.67E+00
Stage 3: Microwave pyrolysis machinery	1.71E+00	1.71E+00	2.49E+00
Stage 3: Pyrolysis | raw materials	7.18E-02	7.18E-02	1.05E-01
Stage 4.1.3: H2-free hydrodeoxygenation (HDO) (R-104) - Raw Materials	1.05E+00	1.05E+00	1.67E+00
Stage 4.1.3: H2-free hydrodeoxygenation (HDO) (R-104) - Energy requirements	4.76E-01	4.76E-01	6.32E-01
Stage 4.1.3: H2-free hydrodeoxygenation (HDO) (R-104) - Machinery	9.20E-03	9.20E-03	1.46E-02
Stage 4.1.1: Cooling, heat exchanger E-105 (S-20 out) - machinery - ES	8.77E-04	8.77E-04	1.34E-03
Stage 4.1.4: Heat exchanger E-106 - machinery	6.74E-04	6.74E-04	1.03E-03
Stage 4.1.2: Compressor pump P-101 - energy requirements - ES	3.39E-04	3.39E-04	5.38E-04
Stage 4.1.1: Cooling water S18	2.05E-04	2.05E-04	2.89E-04
Stage 4.1.5. Flash separation (V-102) - machinery	1.52E-04	1.52E-04	2.42E-04
Stage 4.1.2: Compressor pump P-101, machinery	1.06E-04	1.06E-04	1.62E-04

Stage 4.1.4: Cooling bioliquid (S22/S23), heat exchanger E-106 - energy requirements - ES	0.00E+00	0.00E+00	0.00E+00
Stage 1: Feedstock Production and transport	6.90E-01	-7.44E-01	0.00E+00
flexby Overall maintainence and replacement	2.20E-02	2.20E-02	3.56E-02
Stage 2: Drying and deodourization of feedstock - ES	0.00E+00	0.00E+00	0.00E+00
flexby SOFC - gas phase from the biolquid	2.50E-02	2.50E-02	6.37E-02

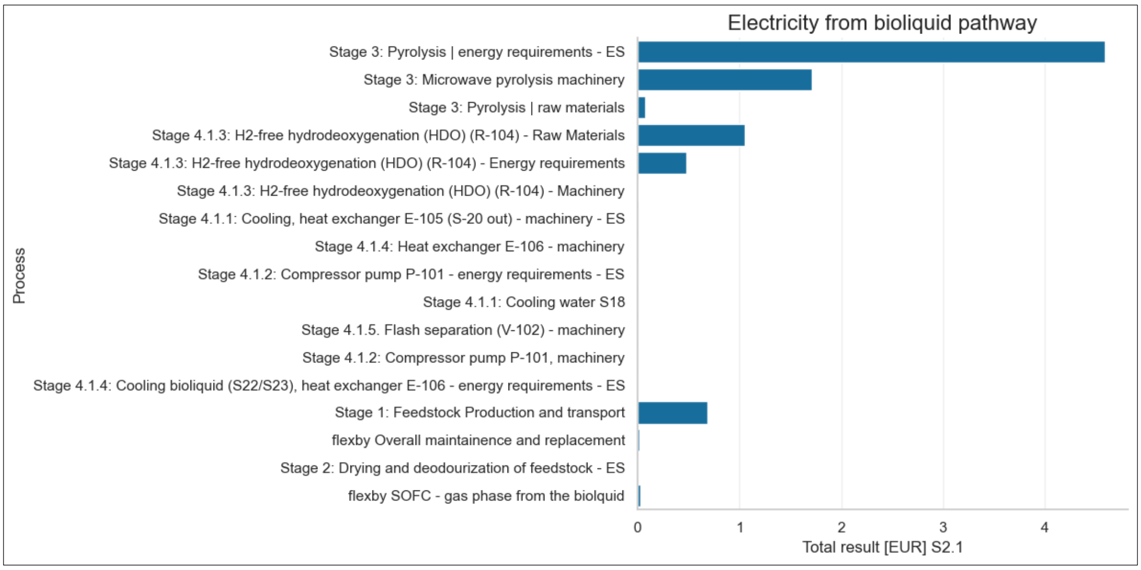

Figure 8 - Detail of scenario 2.1 of electricity from bioliquid pathway

Feedstock production contributes differently depending on the scenario. In the microalgae scenario with system-expansion credit (**S2.1-SE**), feedstock production is effectively a net cost reduction, as the value of wastewater treatment offsets upstream costs. In the dairy sludge scenario (**S5.1**), feedstock production is already zero, since the sludge is a free residual stream. Despite these differences, the remaining costs (mainly from pyrolysis and HDO) are of comparable magnitude, highlighting that the conversion and upgrading stages dominate the LCC regardless of feedstock type.

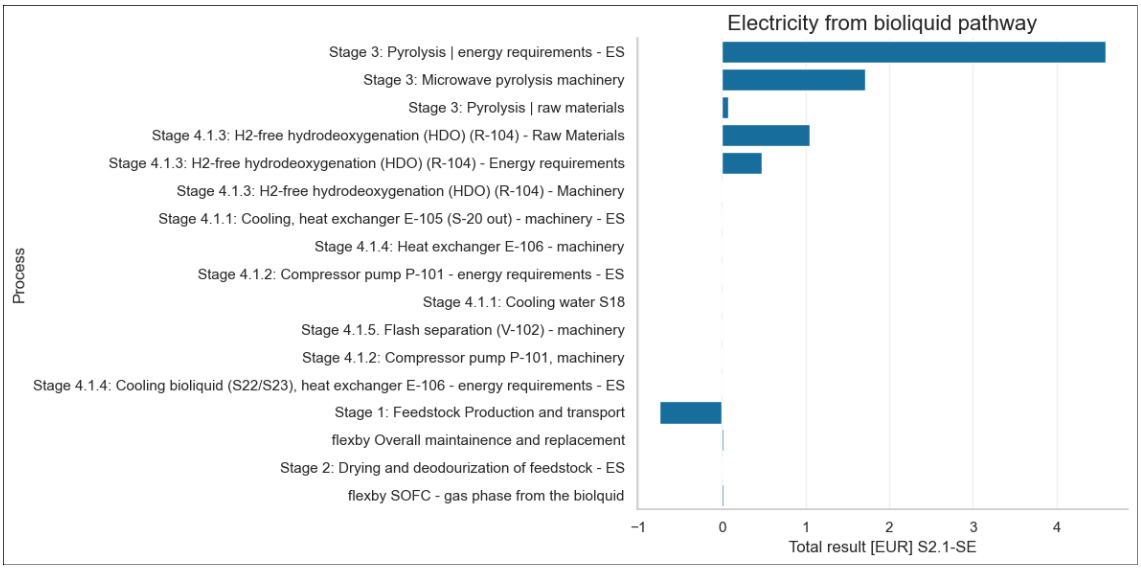

Figure 9 - Detail of scenario 2.1-SE of electricity from bioliquid pathway

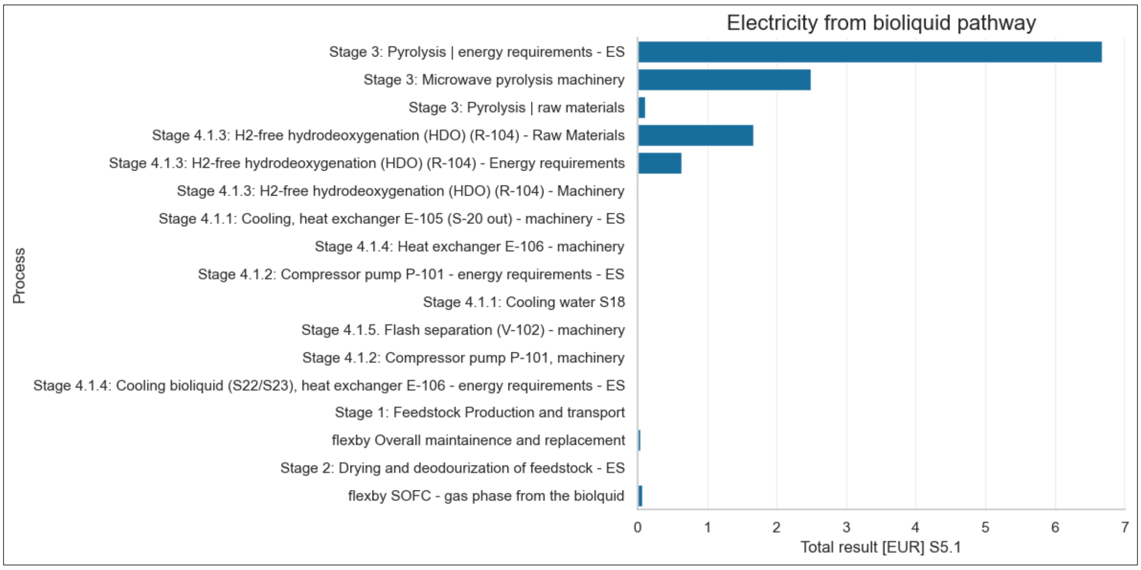

Figure 10 - Detail of scenario 5.1 of electricity from bioliquid pathway

6.4.1.3 Electricity from the gas fraction pathway

The LCC of electricity production from the gaseous fraction of the bioliquid pathway is dominated by the **pyrolysis stage**, with **energy demand** and **microwave pyrolysis machinery** forming the main contributors.

The **upgrading of gas fraction** (including separation, steam reforming, and associated heat exchangers) is the next largest cost contribution. Among these, gas fraction separation and steam reforming represent the bulk of the cost. Cooling and compression operations contribute only minor fractions to the total cost.

The **SOFC** cell for the electricity production itself adds a small but noticeable cost, reflecting the operational requirements to convert the hydrogen-rich gas fraction into electricity. Maintenance and auxiliary equipment costs remain negligible in comparison to pyrolysis and upgrading.

Table 10 - LCC results for the electricity production from the pyro-gas pathway of the pyrolysis

Process	**Total result [EUR] S2.1**	**Total result [EUR] S2.1-SE**	**Total result [EUR] S5.1**
Stage 3: Pyrolysis | energy requirements - ES	3.58E+00	3.58E+00	6.45E+00
Stage 3: Microwave pyrolysis machinery	1.34E+00	1.34E+00	2.41E+00
Stage 3: Pyrolysis | raw materials	5.61E-02	5.61E-02	1.01E-01
Stage 1: Feedstock Production and transport	5.88E-01	-6.35E-01	0.00E+00
Stage 4.3.3. Separation of pyrogas (V-101)	2.24E-01	2.24E-01	1.23E+00
Stage 4.3.6: Steam reforming (R-101)	1.98E-01	1.98E-01	5.02E-01
Stage 4.3.5: heat exchanger E-102, energy requirements - ES	4.34E-02	4.34E-02	1.59E-01
Stage 4.3.12: SOFC electricity production from hydrogen rich pyrogas fraction - ES	3.32E-02	3.32E-02	5.97E-02
Stage 4.3.4: Compression pyrogas. K-101, S7	6.93E-03	6.93E-03	1.13E-02
Stage 4.3.2: Heat exchanger E-101, machinery	3.05E-03	3.05E-03	5.49E-03
Stage 4.3.2. Cooling pyrogas S3, heat exchanger E-101 - ES	2.26E-03	2.26E-03	1.10E-02

Stage 4.3.1: Cooling pyrogas with tap water (S2 - S3) - ES	2.26E-03	2.26E-03	1.10E-02
flexby machinery heat exchanger E-102 (copy)	9.50E-04	9.50E-04	1.64E-03
Stage 4.3.7: cooling reformed gas S11, heat exchanger E-103 - ES	7.14E-04	7.14E-04	1.23E-03
Stage 4.3.9. cooling WGS gas product, heat exchanger E-104 - ES	4.79E-04	4.79E-04	8.26E-04
flexby Overall maintainence and replacement	1.87E-02	1.87E-02	3.37E-02
Stage 2: Drying and deodourization of feedstock - ES	0.00E+00	0.00E+00	0.00E+00

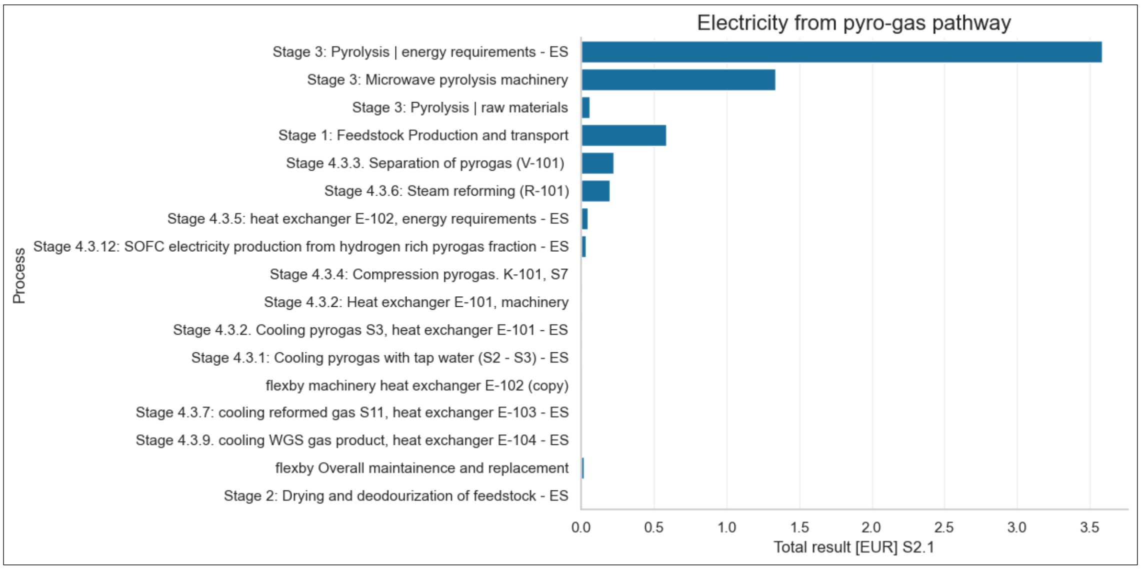

Figure 11 - Detail of scenario 2.1 of electricity from pyro-gas pathway

Across scenarios, feedstock reductions (system-expansion for microalgae in **S2.1-SE** or free dairy-based oily-sludge in **S5.1**) decrease upstream costs, but the remaining LCC is largely driven by pyrolysis and gas upgrading, highlighting these as the economic hotspots for electricity production via the gas fraction pathway as they were via the bioliquid pathway.

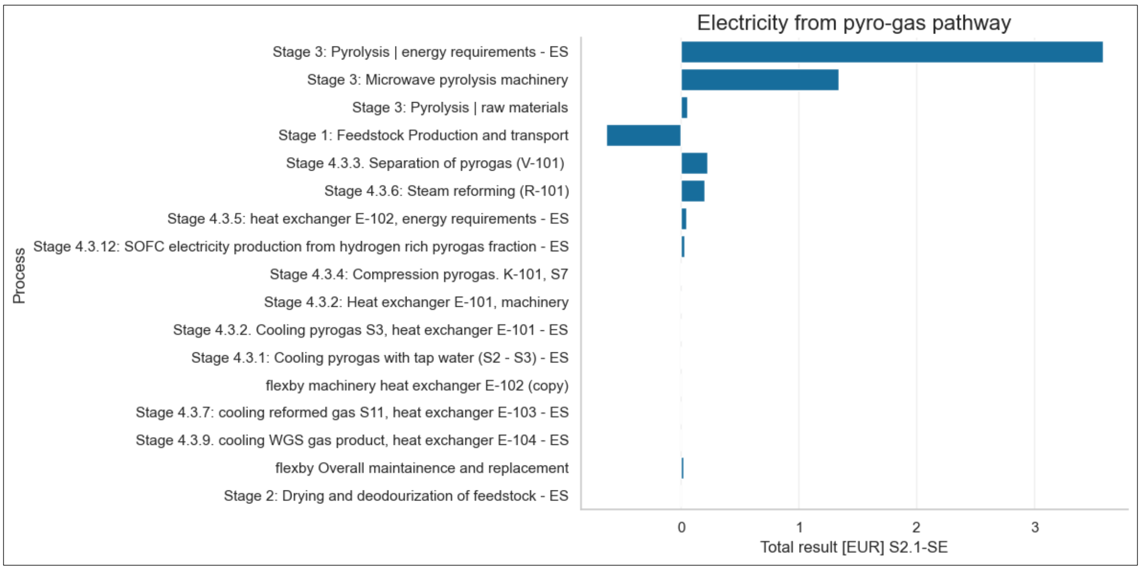

Figure 12 - Detail of scenario 2.1-SE of electricity from pyro-gas pathway

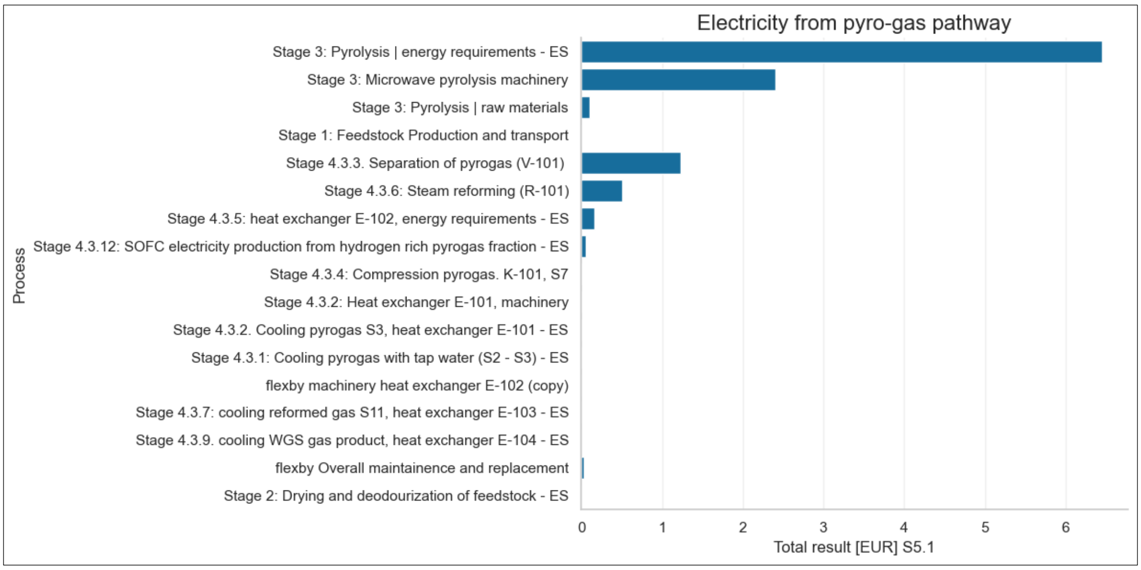

Figure 13 - Detail of scenario 5.1 of electricity from pyro-gas pathway

6.4.2 Biochar pathway

The life LCC for the biochar pathway is again dominated by the **pyrolysis** stage (also because no upgrading is considered yet) which accounts for nearly all operational expenses across scenarios. **Energy requirements** for pyrolysis form the largest single cost share, followed by the capital cost of the **microwave pyrolysis unit**. Raw material inputs for pyrolysis contribute only marginally.

Table 11 - LCC results for the electricity production from the biochar pathway of the pyrolysis

Process	Total result [EUR] S2.1	Total result [EUR] S2.1-SE	Total result [EUR] S5.1
Stage 3: Pyrolysis | energy requirements - ES	3.85E+00	3.85E+00	7.31E+00
Stage 3: Microwave pyrolysis machinery	1.44E+00	1.44E+00	2.73E+00
Stage 3: Pyrolysis | raw materials	6.03E-02	6.03E-02	1.14E-01
Stage 1: Feedstock Production and transport	6.89E-01	-7.43E-01	0.00E+00
flexby Overall maintainence and replacement	2.19E-02	2.19E-02	4.05E-02
Stage 2: Drying and deodourization of feedstock - ES	0.00E+00	0.00E+00	0.00E+00

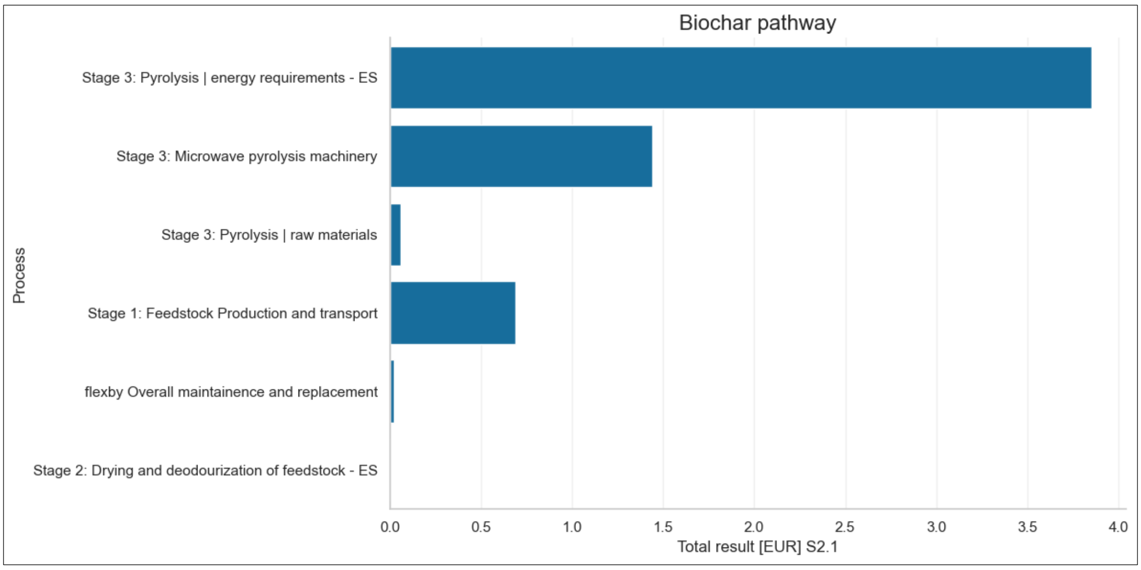

Figure 14 - Detail of scenario 2.1 of biochar pathway

Upstream **feedstock production** remains relevant in the base microalgae scenario (**S2.1**), but in the system-expansion case (**S2.1-SE**) these costs become a net credit due to the integration of wastewater treatment. In the dairy sludge scenario (**S5.1**), feedstock costs are simply eliminated, as the sludge is a free residual stream.

Aside from pyrolysis, all other cost categories (including maintenance) represent negligible contributions (<1%) to the total LCC.

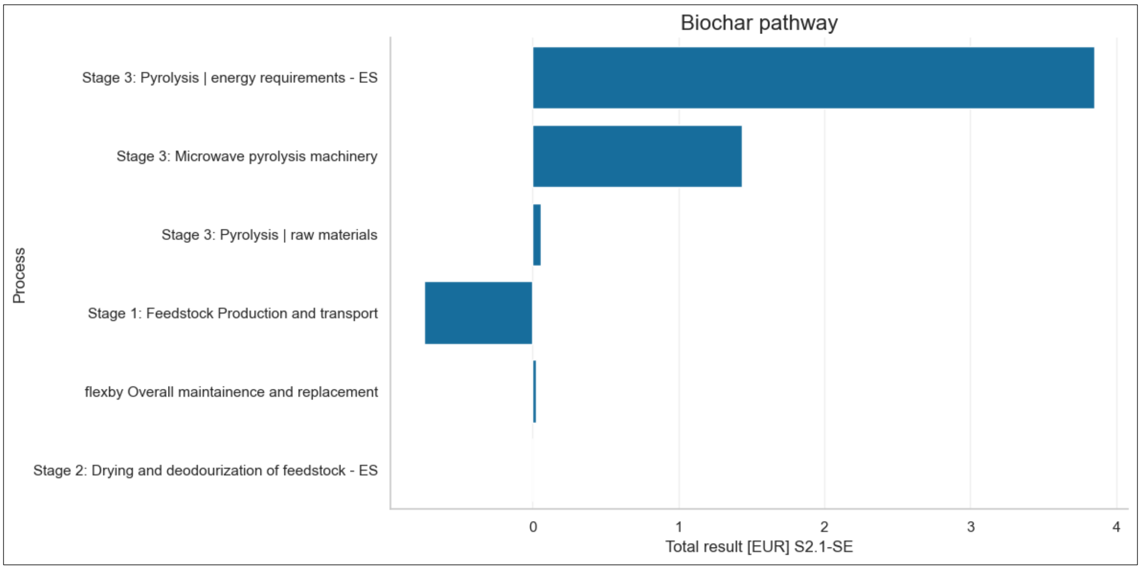

Figure 15 - Detail of scenario 2.1-SE of biochar pathway

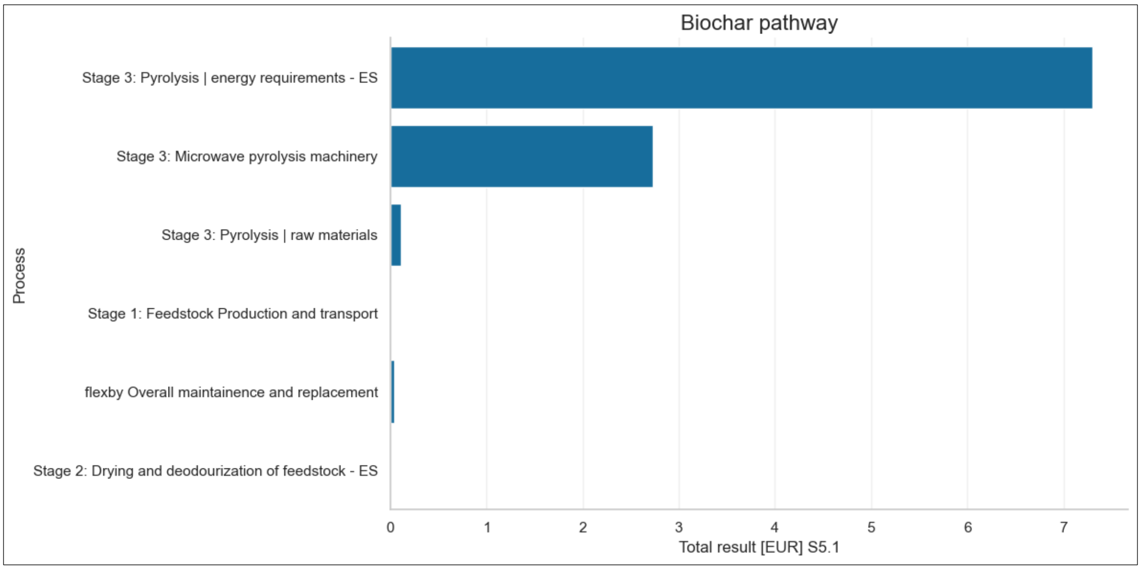

Figure 16 - Detail of scenario 5.1 of biochar pathway

7 Social Life Cycle Assessment

Social Life Cycle Assessment (S-LCA) is a methodological framework for evaluating the social impacts associated with products and services across their entire life cycle, from raw material extraction through energy and material production, use, and end-of-life management (Benoît Norris et al., 2020).

The first formal S-LCA guidelines were published in 2009 by the UNEP/SETAC Life Cycle Initiative (UNEP, 2009), providing an initial structure for defining social indicators, stakeholder groups, and assessment procedures. These guidelines were updated in 2020 (Benoît Norris et al., 2020) to incorporate methodological advances, clarify impact pathways, and strengthen alignment with other life cycle approaches. Building on both editions, the ISO 14075:2024 standard establishes a harmonised set of principles and a high-level framework for conducting S-LCA. It does not prescribe specific methods but provides a foundation intended to support consistency, comparability, and integration with the broader ISO 14040/44 life cycle assessment standards. The Reference scale assessment (type 1 approach in the UNEP 2020 guidelines), which leads to a social performance evaluation, was followed in this study.

7.1 Goal and scope of the Social Life Cycle Assessment

7.2.1. Goal of the study

The intended application of this study is to perform a hotspot analysis of the FLEXBY product system as defined in section 5.1.3 and identify social hotspots based on primary data available for the environmental LCA and LCC combined with generic data from social LCA databases, that can drive further data collection and preventative measures targeting potential social impacts as the project proceeds to higher TRLs.

7.1.1 Functional Unit

S-LCA is a relative approach that is structured around a functional unit. This functional unit quantifies the function of the product system under study. The functional unit was chosen to be the same as in the LCC. The FLEXBY system produces different products: biofuel, electricity from gas fraction, bio-hydrogen and biochar. The biofuel is chosen as the primary product and the remaining were modelled as by-products.

All subsequent analyses are relative to the functional unit of 1 kg of biofuel, as all inputs and outputs in the S-LCI and consequently the S-LCIA are scaled to the functional unit. The results are also represented from the perspective of the by-products.

7.1.2 Multifunctionality

The handling of multifunctionality was the same as established in section 5.1.9. In S-LCA, allocation distributes the social impacts across different products or functions when a process produces multiple outputs, and the partitioning concerns social indicators. The choice of allocation method can influence how social burdens or benefits are attributed within a product system.

7.1.3 Stakeholders

The study is a hotspot analysis of social impacts along the life cycle of the FLEXBY system. Initially all stakeholders as included in the background database of SOCA v4 were considered: society, local community, workers, value chain actors, consumers and children.

7.1.4 Activity variable

In Social LCA, activity variables are used to express the scale or relevance of social impacts associated with a process in a product system. As described by Norris (2006), they represent a measure of process activity or scale that can be linked to output. According to UNEP (2020, p. 63), an activity variable is defined as ‘A measure of process activity or scale which can be related to process output’ thereby allowing social indicators to be quantified in relation to a product's life cycle. The most commonly used activity variable in PSILCA and therefore SOCA, is worker hours, that is, the number of hours worked to produce a specific output in a given process or sector. This measure is well-suited for indicators related to the stakeholder group workers, as it directly reflects the scale of Labour involvement in production.

The calculation follows this basic formula:

$$\textbf{Worker hours} = \frac{\textbf{Unit labour costs}}{\textbf{Mean hourly labour cost (per employee)}}$$

Equation 1

This equation expresses the labour time embedded per unit of output as the ratio of labour compensation per unit of output (**unit labour cost**) to the average hourly cost of labour.

Step 1: Calculating Unit Labour Cost

Unit labour cost is defined as:

$$\text{Unit labour costs} = \frac{\text{Compensation of employees (in USD per country} - \text{specific sector and year)}}{\text{Gross output (in USD per country} - \text{sector and year)}}$$

According to the Eora developers (Lenzen et al., 2015), this variable adheres to the United Nations System of National Accounts (UN SNA) definitions (UN et al., 2009), which define compensation as '*compensation of employees is defined as the total remuneration, in cash or in kind, payable by an enterprise to an employee in return for work done by the latter during the accounting period.'*

7.1.5 System boundaries

The system boundaries follow those established for the LCC in section 5.1.5.

7.1.6 Assumptions

Given the early stage of development of the FLEXBY process, the preliminary S-LCA relies on a combination of primary data, partner-provided estimates, process simulations, and literature values. Whenever direct cost data or detailed operational information were not available, assumptions were formulated based on analogous technologies and expert judgment from involved partners. Social data was taken from the SOCA v4 database and at times from the PSILCA v4 database and adapted to the SOCA v4 structure based on the database build approach. All assumptions are documented in detail within the process-specific inventory tables of the LCI section.

A simplified operational lifetime of 20 years is assumed for the integrated demonstrator, serving as the basis for annualising capital expenditures. This approach ensures methodological alignment with the early-stage LCA and provides a coherent foundation for cost modelling. At this stage, FLEXBY technologies are broadly positioned at TRL 2-3-4.

7.1.7 Social Indicators and Social Life Cycle Impact Assessment Method

The study uses the impact assessment method 'Social Impacts weighting method' available in SOCA v4. The impact categories provided in the PSILCA v4.0 database are disaggregated, and each category represents the social indicators provided in the database. Table 13 provides an overview of the social indicators (each indicator is also represented by a standalone impact category), their corresponding stakeholder and subcategory, and they are all measured in medium risk hours with abbreviations representing the indicator, for example 'Evidence of violations of laws and employment regulations' has the abbreviation 'EV' associated with the medium risk hour value. The indicator data were either collected on a country level or sectoral level. Each impact category translated the risk levels of social indicators across the database into medium risk hours with characterisation factors as shown in Table 12. The results for each impact category are a product of the worker hours of the process, the scaling factors based on the quantities used, and cost conversion factors, as well as the characterisation factors of the respective impact category, as shown in the formula below:

$$\begin{aligned} &\text{social indicator impacts (medium risk hours)} \\ &= \sum_{\text{social indicator}}^{w} \text{worker hours} \times \text{scaling factor of processes} \times \text{characterisation factor} \end{aligned}$$

Table 12: Characterisation factors in the PSILCA database

Risk/opportunity level	Characterisation Factor
Very low risk	0.01
Low risk	0.1
Medium risk	1
High risk	10
Very high risk	100
No risk/ opportunity	0
Low opportunity	0.1
Medium opportunity	1
High opportunity	10

Table 13: Impact categories covering the social indicators in PSILCA v4.0

ID	Name	Stakeholder	Subcategory	Unit	Indicator level
I1	Children in employment, female	Workers	Child labour	CE med risk hours	Sector
I2	Children in employment, male	Workers	Child labour	CE med risk hours	Sector
I3	Children in employment, total	Workers	Child labour	CE med risk hours	Sector
I4	Evidence of violations of laws and employment regulations	Workers	Social benefits, legal issues	EV med risk hours	Sector
I5	Freedom of association and collective bargaining	Workers	Freedom of association and collective bargaining	FA med risk hours	Country
I6	Frequency of forced labour	Workers	Forced labour	FL med risk hours	Country
I7	Gender wage gap	Workers	Discrimination	GW med risk hours	Sector
I8	Goods produced by forced labour	Workers	Forced labour	GF med risk hours	Sector
I9	Living wage, per month	Workers	Fair salary	LW med risk hours	Country
I10	Men in the sectoral labour force	Workers	Discrimination	M med risk hours	Sector
I11	Minimum wage, per month	Workers	Fair salary	MW med risk hours	Country
I12	number of strikes	Workers	Freedom of association and collective bargaining	NS med risk hours	Sector
I13	Paid maternity leave	Workers	Social benefits, legal issues	PM med risk hours	Country

I14	Presence of sufficient safety measures	Workers	Health and safety	SS med risk hours	Sector
I15	Rate of fatal accidents at workplace	Workers	Health and safety	FA med risk hours	Sector
I16	Rate of non-fatal accidents at workplace	Workers	Health and safety	NA med risk hours	Sector
I17	Sector average wage, per month	Workers	Fair salary	SA med risk hours	Sector
I18	Trade union density	Workers	Freedom of association and collective bargaining	TU med risk hours	Country
I19	Trafficking in persons	Workers	Forced labour	TP med risk hours	Country
I20	Violations of mandatory health and safety standards	Workers	Health and safety	VS med risk hours	Country
I21	Weekly hours of work per employee female	Workers	Working time	WH med risk hours	Sector
I22	Weekly hours of work per employee male	Workers	Working time	WH med risk hours	Sector
I23	Women in the sectoral labour force	Workers	Discrimination	W med risk hours	Sector
I24	Active involvement of enterprises in corruption and bribery	Value Chain Actors	Corruption	AC med risk hours	Sector
I25	Presence of anti-competitive behaviour or violation of anti-trust and monopoly legislation	Value Chain Actors	Fair competition	AC med risk hours	Sector
I26	Public sector corruption	Value Chain Actors	Corruption	PC med risk hours	Country
I27	Social responsibility along the supply chain	Value Chain Actors	Promoting social responsibility	SS med risk hours	Sector

I28	Access to electricity	Society	Technology development	AE med risk hours	Country
I29	Access to internet	Society	Technology development	AI med risk hours	Country
I30	Animal protection	Society	Ethical treatment of animals	AN med risk hours	Country
I31	Asylum seekers rate	Society	Migration	AS med risk hours	Country
I32	Biodiversity & Habitat	Society	Nature	BH med risk hours	Country
I33	Contribution to economic development	Society	Contribution to economic development	CD med risk hours	Sector
I34	Ecosystem services	Society	Nature	EC med risk hours	Country
I35	Embodied value added total	Society	Contribution to economic development	EV med risk hours	Sector
I36	Emigration rate	Society	Migration	EM med risk hours	Country
I37	Female genital mutilation 15-49	Society	Gender equality and empowerment	FGM med risk hours	Country
I38	Female with account at a financial institution	Society	Gender equality and empowerment	FF med risk hours	Country
I39	Food insecurity	Society	Poverty Alleviation	FI med risk hours	Country
I40	Freedom of the press	Society	Censorship and Oppression	FP med risk hours	Country
I41	Gender inequalities	Society	Gender equality and empowerment	GI med risk hours	Country

I42	Global freedom scores	Society	Access to immaterial resources	GF med risk hours	Country
I43	Global Peace Index	Society	Secure living condition	GP med risk hours	Country
I44	Global Terrorism Index	Society	Secure living conditions	GT med risk hours	Country
I45	Health expenditure, domestic general government	Society	Health and safety	HE med risk hours	Country
I46	Health expenditure, external resources	Society	Health and safety	HE med risk hours	Country
I47	Health expenditure, out-of-pocket	Society	Health and safety	HE med risk hours	Country
I48	Health expenditure, total	Society	Health and safety	HE med risk hours	Country
I49	Household air pollution attributable DALYs, female	Society	Health and safety	HA med risk hours	Country
I50	Household air pollution attributable DALYs, male	Society	Health and safety	HA med risk hours	Country
I51	Illiteracy rate, female	Society	Education and upskilling opportunities	I med risk hours	Country
I52	Illiteracy rate, male	Society	Education and upskilling opportunities	I med risk hours	Country
I53	Illiteracy rate, total	Society	Education and upskilling opportunities	I med risk hours	Country
I54	Immigration rate	Society	Migration	IM med risk hours	Country

I55	Informal employment, female	Society	Contribution to economic development	IE med risk hours	Sector
I56	Informal employment, male	Society	Contribution to economic development	IE med risk hours	Sector
I57	Informal employment, total	Society	Contribution to economic development	IE med risk hours	Sector
I58	International Migrant Stock	Society	Migration	IS med risk hours	Country
I59	International migrant workers in the sector	Society	Migration	IW med risk hours	Sector
I60	Internet freedom scores	Society	Censorship and Oppression	IF med risk hours	Country
I61	Labour productivity	Society	Contribution to economic development	LP med risk hours	Country
I62	Life expectancy at birth	Society	Health and safety	LE med risk hours	Country
I63	Net migration rate	Society	Migration	NM med risk hours	Country
I64	Number of threatened species	Society	Nature	NT med risk hours	Sector
I65	Political stability and absence of violence	Society	Governance	PS med risk hours	Country
I66	Pollution level of the country	Society	Safe and healthy living conditions	PL med risk hours	Country
I67	Population below national poverty line	Society	Poverty alleviation	PP med risk hours	Country
I68	Public expenditure on education	Society	Education and upskilling opportunities	PE med risk hours	Country

I69	R&D expenditures	Society	Technology development	RD med risk hours	Country
I70	Rate of researchers	Society	Technology development	RR med risk hours	Country
I71	Safe access to Drinking water coverage	Society	Poverty Alleviation	DW med risk hours	Country
I72	Sanitation coverage	Society	Poverty Alleviation	SC med risk hours	Country
I73	Social Protection Expenditures	Society	Secure living conditions	SR med risk hours	Country
I74	State of democracy	Society	Governance	SD med risk hours	Country
I75	Unemployment rate in the country	Society	Local employment	UR med risk hours	Country
I76	Youth illiteracy rate, female	Society	Education and upskilling opportunities	YI med risk hours	Country
I77	Youth illiteracy rate, male	Society	Education and upskilling opportunities	YI med risk hours	Country
I78	Youth illiteracy rate, total	Society	Education and upskilling opportunities	YI med risk hours	Country
I79	Youth unemployment	Society	Education and upskilling opportunities	YU med risk hours	Country
I80	Certified environmental management systems	Local Community	Access to material resources	CE med risk hours	Sector
I81	Embodied agricultural area footprint	Local Community	Environmental footprints	EA med risk hours	Sector
I82	Embodied CO2 footprint	Local Community	GHG footprints	EC med risk hours	Sector
I83	Embodied CO2-eq footprint	Local Community	Environmental footprints	EC med risk hours	Sector

I84	Embodied forest area footprint	Local Community	Environmental footprints	EF med risk hours	Sector
I85	Embodied water footprint	Local Community	Environmental footprints	EW med risk hours	Sector
I86	Extraction of biomass (related to area)	Local Community	Access to material resources	EB med risk hours	Country
I87	Extraction of biomass (related to population)	Local Community	Access to material resources	EB med risk hours	Country
I88	Extraction of fossil fuels	Local Community	Access to material resources	EF med risk hours	Country
I89	Extraction of industrial and construction minerals	Local Community	Access to material resources	EI med risk hours	Country
I90	Extraction of ores	Local Community	Access to material resources	EO med risk hours	Country
I91	Homicides	Local Community	Secure living condition	HO med risk hours	Country
I92	Indigenous People Rights Protection Index	Local Community	Respect of indigenous rights	IP med risk hours	Country
I93	Internally displaced people	Local Community	Secure living condition	ID med risk hours	Country
I94	Level of industrial water use (related to renewable water resources)	Local Community	Access to material resources	IW med risk hours	Country
I95	Level of industrial water use (related to total withdrawal)	Local Community	Access to material resources	IW med risk hours	Country
I96	Presence of indigenous population	Local Community	Respect of indigenous rights	PI med risk hours	Country
I97	Waste management	Local Community	Access to material resources	WM med risk hours	Country
I98	Data protection and privacy	Consumer	Consumer protection	DP med risk hours	Country
I99	Online Consumer Protection Legislation	Consumer	Consumer protection	OC med risk hours	Country

I100	Child marriage, female	Children	Children welfare	CM med risk hours	Country
I101	Child marriage, male	Children	Children welfare	CM med risk hours	Country
I102	Female genital mutilation 0-14	Children	Children welfare	FGM med risk hours	Country
I103	Mean years of schooling, female	Children	Education	S med risk hours	Country
I104	Mean years of schooling, male	Children	Education	S med risk hours	Country
I105	Mean years of schooling, total	Children	Education	S med risk hours	Country
I106	Under-five mortality rate	Children	Health and Safety	UM med risk hours	Country

7.1.8 Process-specific life cycle inventory

The product system for the S-LCA follows the same quantitative process-based model approach used in the environmental LCA and LCC, reflecting the processes that define the cradle-gate stages of the FLEXBY technology and including all the flows normalised to the functional unit. All processes in the foreground system are consistently identified using the naming conventions established during the LCA modelling phase. The additional data for the social LCA study concerns the activity variables (worker hours) and the social flows or indicators associated with the processes.

The SOCA v4 database was used as a background database for this case study. The SOCA v4 database used includes the ecoinvent 3.12 database with cut-off unit processes with social data added on from PSILCA 4.0. The SOCA database is built on ecoinvent's process-based database structure. Whereas the PSILCA database is an input-output LCA database. Process-based LCA databases are structured by scientifically analysing the physical process and building the datasets bottom up (i.e. mass/material balance, scientific characteristics, etc.). Input-output databases use historical data of economic transactions to trace along a given supply chain. The process-based databases have more specific datasets, but less complete coverage, whereas input-output databases have lesser specificity but higher global coverage.

The PSILCA database has cost data from the year 2015, and applies the USD 2015, the SOCA v4.0 database has cost values updated to EUR2025 with economic conversion factors. Modelling was performed by performing necessary conversions when working with data from PSILCA.

The social data was added to the most intensive foreground unit processes and a literature review was conducted to identify social issues that occur and are to be included in the S-LCA study. Data collection conducted for the eLCA and LCC was applied to the S-LCA models as well. Missing data was taken from secondary sources such as the PSILCA and SOCA databases. The following sections detail the social indicator data added to the FLEXBY unit processes.

7.1.8.1 Stage 1: Feedstock production

Feedstock 2

The equipment was modelled initially using the equipment inventory provided by **A4F** for the current FLEXBY demonstrator scale. At this stage of development, costs are based on partner-supplied estimates for all major units and taken from the LCC. The worker hours were estimated using data from PSILCA v4 and scaling them to the process specific data. The background datasets used are specified in Table 14.

Table 14: PSILCA processes corresponding to Cultivation and harvesting of feedstock

Process/equipment	PSILCA process	Worker hour/USD
Raceway pond with paddlewheel	Machinery and equipment n.e.c.	3.81E-02
Harvesting pump	Machinery and equipment n.e.c.	3.81E-02
Settler for harvesting	Machinery and equipment n.e.c.	3.81E-02
Municipal Wastewater	Sewage and refuse disposal, sanitation and similar activities - PT	3.37E-02
Electricity	Electrical energy, gas, steam and hot water	1.57E-02
Salts	Chemicals, chemical products and man-made fibres	3.37E-02
Cultivation process	Sewage and refuse disposal, sanitation and similar activities – PT	3.37E-02
Harvesting process	Products of agriculture, hunting and related services	3.37E-02

At this stage the model considers scenarios for the microalgae cultivation without wastewater treatment as well as with partial wastewater treatment and not complete treatment, because at this point the algae are cultivated for FLEXBY and the water quality is only assessed for N, P and C content. However, the project also aims to test the provision of the service for urban wastewater treatment and use the microalgae resulting from it, considered as a waste residue in the classification of biofuels feedstocks.

A4F identified the species of microalgae grown in the wastewater as two predominant species of the *Scenedesmus* genus, which has already been studies for biofuel applications because its significant lipid content and growth rate (Deliverable 2.2) a consistent proportion is possibly of the *Desmodesmus* subgenus.

Feedstock 5

Feedstock 5, dairy sludge, was treated as a burden free input.

7.1.8.2 Stage 2: Feedstock drying and deodorisation and Stage 3: Pyrolysis

Both processes of feedstock drying and pyrolysis rely on machinery supplied by **FRIMA** and will be operated and tested at **CSIC**.

FRIMA has provided preliminary cost estimates for the complete microwave (MW) pyrolysis unit, including the microwave cavity, control panel and auxiliary components. The material composition of the microwave pyrolysis. These capital costs have been incorporated directly into the model and annualised according to the standard 20-year economic lifetime used throughout the assessment. The replacement has been modelled with the social data from the process

In addition, to the overall equipment lifetime, **FRIMA** supplied specific durability estimates for the magnetron, the core component that generates microwave energy has a lifetime of 10,000 hours. Therefore, the study includes scheduled replacement costs at the intervals indicated by **FRIMA**. These replacement parts are reflected as operational expenditures over the 20-year period.

Moreover, microwave pyrolysis requires a continuous nitrogen flow to operate. **FRIMA** provided the nitrogen consumption rate, which has been integrated into the model as a recurring operating cost. The nitrogen demand is treated as proportional to the operational hours of the system.

Energy consumption for both drying and pyrolysis is based on the mass and energy balance results shared by **PMI**. These simulations directly determine electricity-related operating costs, using Spanish electricity price assumptions for consistency with the LCA and other processes in the LCC.

Table 15: PSILCA processes corresponding to Cultivation and harvesting of feedstock

Process/equipment	PSILCA process	Worker hour/kg
Microwave Pyrolysis machinery - DE	Machinery and equipment n.e.c.	3.58E-02
Replacement parts	Machinery and equipment n.e.c.	3.58E-02

7.1.8.3 Gas fraction and Bioliquid processing

For the gas fraction processing stage cost estimates were primarily provided by **PMI**, with additional refinement from **US**, especially additional estimations regarding component-specific replacement rates and catalyst requirements. Using Deliverable 4.1 as a reference, **US** supplied details on the catalysts considered for the WGS and reforming steps, including both a commercial Fe-Cr catalyst and the homemade formulations developed within FLEXBY based on Fe and Fe–Ni supported on ceria–alumina. These inputs, together with raw material and indicative lifetimes, were incorporated into the operational expenditure model.

For the bioliquid upgrading stage, data collection followed the same path as the gas fraction processing. Estimate cost inputs were primarily provided by **PMI** and further refined by **US**, who supplied updated estimates for equipment components, replacement frequencies, and catalyst consumption. Again, using Deliverable 4.1 as reference, **US** also specified the catalysts developed for the HDO pathway, including the homemade activated-carbon-supported formulations based on Ru, Ni and Fe. These catalysts differ from those designed for the gas fraction upgrading route, reflecting the different reaction environments involved.

As for the other FLEXBY processes, a 20-year lifetime is assumed for the integrated demonstrator, while individual components follow their own maintenance cycles. Key replacement items include mass-flow controllers, quartz liners**,** WGS reactor stainless-steel tubes**, and** electric furnaces/heaters used as heat exchangers. And tubing maintenance. **US** also provided raw material and catalyst information for both WGS and reforming steps, which is incorporated into operational expenditures.

The integrated demonstrator carrying out both processing stages is in the same location, at present, Seville in Spain. The social indicators were added for the overall processing steps, with social indicator data taken from the manufacturing of chemicals and chemical products in Spain.

Table 16: PSILCA processes corresponding to processing pyrolysis fractions

Process/equipment	**PSILCA process**	**Worker hour/USD**
Gas fraction processing	Manufacture of chemicals and chemical products - ES	4.55E-03
Bioliquid processing	Manufacture of chemicals and chemical products - ES	1.43E-02

7.1.8.4 Biochar handling

The biochar fraction processing and applications are as described in 5.2.1.5. The results are mainly influenced by the stages leading upto pyrolysis.

7.2 Results and interpretation

The results are presented separately for the three pathways after the pyrolysis step of the FLEXBY system, biofuel (chosen as main reference) produced from the bioliquid processing along with electricity, whose results are reported separately, pyro-gas and biochar. The multifunctionality in the product system is handled as described in section 6.1. The results are given per 1 kg of biofuel and the corresponding amounts of the other fractions scaled accordingly, as shown in Table 7.

The impacts reported here are based on the preliminary LCA data and consider the upstream supply chain for machinery, equipment, and energy inputs, which introduces several social risk hotspots. These risks reflect conditions associated with conventional industrial manufacturing, metals extraction, and energy production. As such, the results can be interpreted as guidance on topics that can be proactively assessed and addressed in the project.

The first set of results are displayed as radar charts. The charts display results obtained in medium risk hours for the 106 impact categories, each corresponding to the indicator by the same name, were normalised using Microsoft Excel and adapted for the radar chart (inspired by Gavrilan, V., 2024). The results used in the charts are presented in the appendix. A second perspective is presented by showing a breakdown of the baseline scenario S2.1 and highlighting the contribution of individual stages to the hotspots. The results reveal hotspots associated with the six stakeholder groups of Workers, Value Chain Actors, Local community, Children and Society

7.2.1 Bioliquid pathway

The radar charts in Figure 17: Hotspot analysis of S2.1, S2.1-SE and S5.1 for the production of biofuels with the FLEXBY system and Figure 18 shows the hotspots in medium risk hours of the product systems across all the social indicators (both country and sector based), and Figure 19 shows the contributions of individual stages to the sector indicators. Within the *workers stakeholder* category, the most prominent potential sector-level hotspots are associated with *health and safety*, notably the rate of fatal accidents at the workplace (I15) and the *rate of non-fatal accidents at the workplace* (I16). These indicators show elevated medium risk hours across industrial processing stages such as pyrolysis and HDO-related energy use, pyrolysis machinery (a larger contribution due to the higher cost) and machinery replacement activities. In addition, the indicator *evidence* of *violations of laws and employment regulations* (I4), under the subcategory *social benefits and legal issues*, represents a significant hotspot, indicating structural compliance risks in the industrial sectors supplying equipment, energy, and materials to the FLEXBY system. These sector-level impacts are consistent with upstream manufacturing and heavy-industry activities, including metal processing, machinery fabrication, and chemical production.

Indicators linked to the *fair salary* subcategory also contribute notably to the sector-level social risk profile. In particular, *sector average wage per month* (I17) and *living wage per month* (I9) indicate risks related to income adequacy within the sectors involved in biofuel processing and infrastructure supply. Furthermore, employment structure indicators such as *informal employment* (I55-I57) and international *migrant workers in the sector*

(I59) point to labour arrangements that are typically associated with reduced job security and social protection, reinforcing the relevance of employment quality as a social issue in the FLEXBY supply chain.

Gender-related impacts form a distinct hotspot cluster under the *discrimination* subcategory. Elevated medium risk hours for the *gender wage gap* (I7) and *women in the sectoral labour force* (I23) reflect gender inequalities within industrial and energy-related sectors; these are the typical industry values from ILOSTAT. These indicators are interpreted as value-chain-level risks rather than direct project-level impacts, indicating that gender-related social risks are embedded in upstream sectoral contexts rather than generated by FLEXBY operations themselves.

At the *society stakeholder* level, several country-level indicators provide important contextual information for interpreting the sectoral hotspots. Elevated medium risk hours for *biodiversity and habitat* (I32), *ecosystem services* (I34), and the number of *threatened species* (I64) indicate that the supply chain has some ecological sensitivity. Additional contextual indicators, including *unemployment rate in the country* (I75), *population below the national poverty line* (I67), and *governance-related indicators such as freedom of the press* (I40) and *political stability and absence of violence* (I65), describe the national conditions in Spain (pyrolysis and bioliquid processing, as well as machinery involved the processing), Portugal (feedstock growth), Germany and Japan (sourcing of pyrolysis machinery).

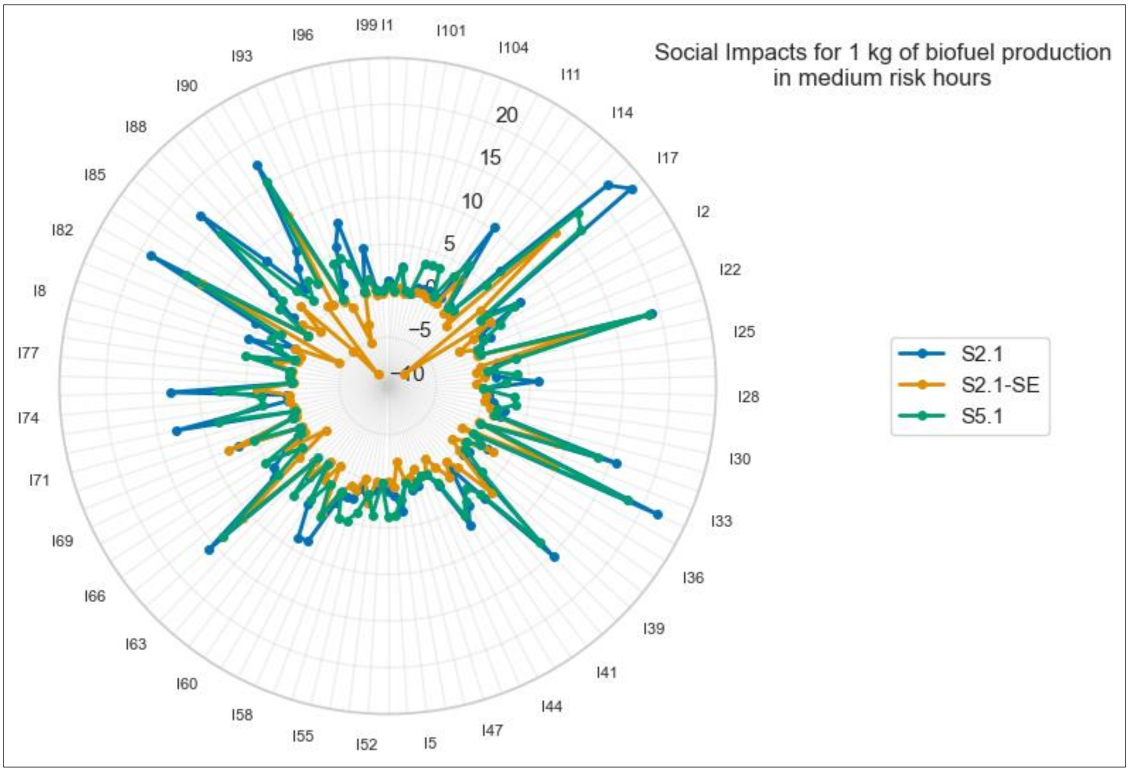

Figure 17: Hotspot analysis of S2.1, S2.1-SE and S5.1 for the production of biofuels with the FLEXBY system

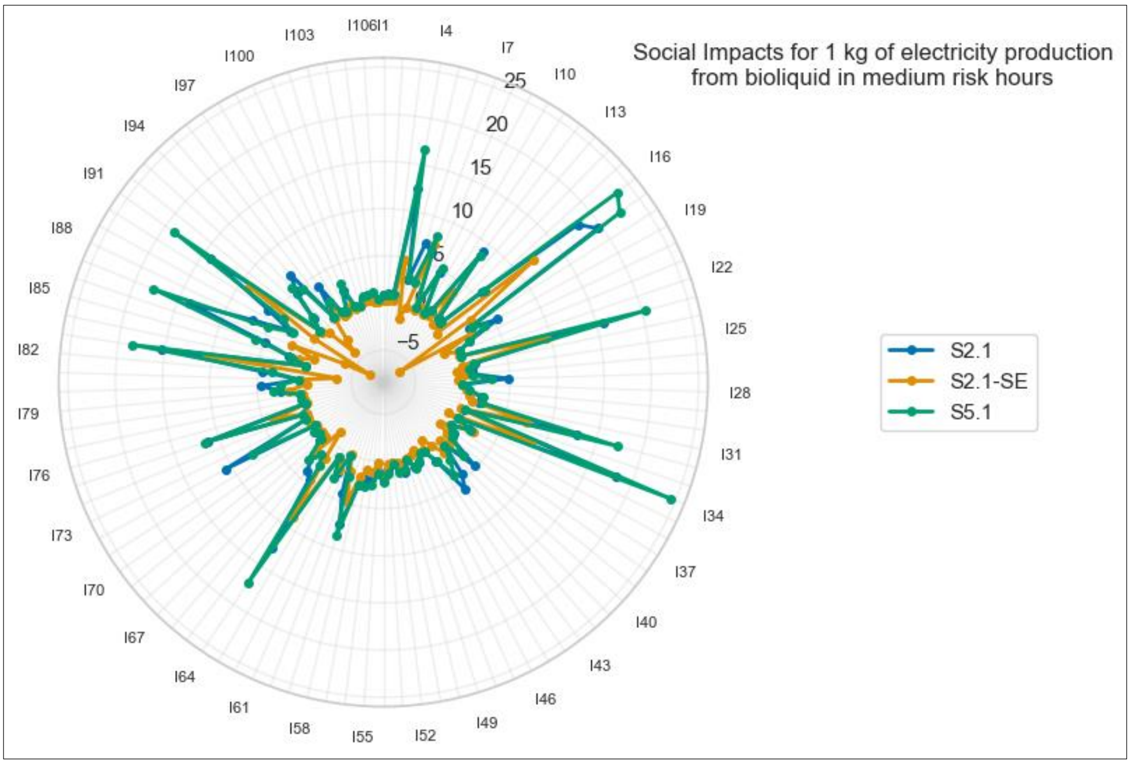

Figure 18: Hotspot analysis of S2.1, S2.1-SE and S5.1 for the production of electricity from the gaseous fraction of the bioliquid from the FLEXBY system

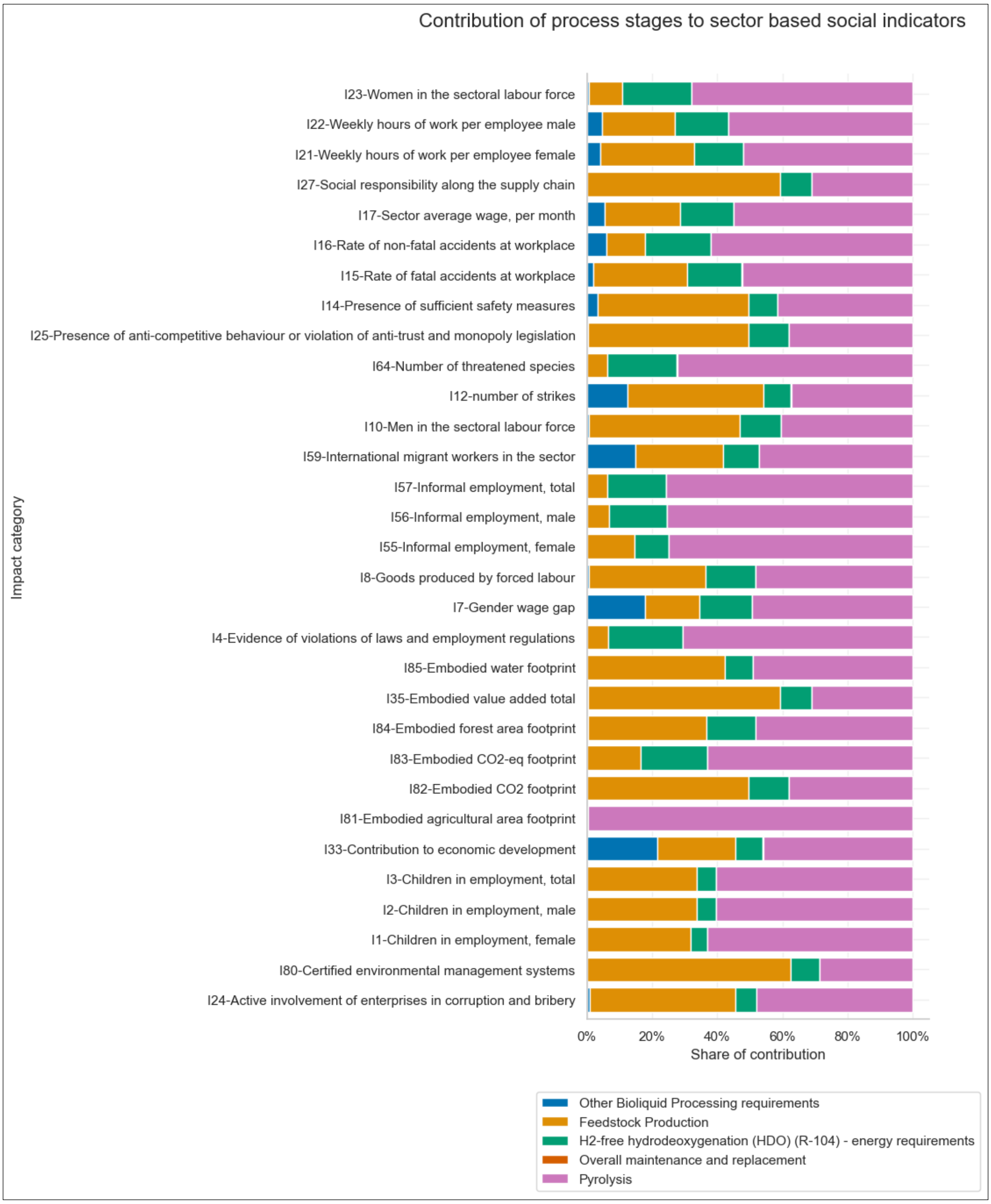

Figure 19 - Relative contributions of process stages to the sector social indicators for the production of biofuel

7.2.2 Gas fraction and biochar pathways

The radar charts in Figure 20 and Figure 21 show the hotspots for the biochar and electricity production from gas fraction. For the biochar and gas fraction fractions, the results represent partitioned medium risk hours after addressing multifunctionality, consequently, Stage 1 (Feedstock production and transport) and Stage 3 (Pyrolysis) retain very similar relative hotspot structures for both co-products because they are largely driven by the same shared upstream inputs related to the feedstock and pyrolysis (energy, equipment, and industrial supply chains). In the radar-chart representation (data in Appendix 13 and Appendix 14), the higher potential sector-level hotspots are associated with the *workers and value chain actors* stakeholders, especially *labour rights and regulatory compliance* (I4 Evidence of violations of laws and employment regulations*), occupational health and safety* (I15–I16 fatal and non-fatal accidents), *wage and employment conditions* (I17 Sector average wage, I55–I57 informal employment, I59 migrant workers in the sector), and *gender-related labour structure* (I7 gender wage gap, I23 women in the sectoral labour force). The *society* indicators provide the geographic context in which these sector risks occur (Spain for conversion and processing, Portugal for feedstock sourcing), with higher *medium risk hours in ecosystem- and resource-related* indicators (e.g., I32 Biodiversity & Habitat, I34 Ecosystem services, I64 threatened species) reflecting the broader socio-environmental conditions of FLEXBY.

For the gas fraction, as shown in Figure 21, Stage 4.3 Gas fraction processing, includes steam reforming and water gas shift (WGS) processes, which introduce a different set of upstream values (notably energy, catalysts and process equipment associated with reforming and WGS units). The negative medium risk hours are due to the assumptions of avoided impacts from the valorisation of ammonia.

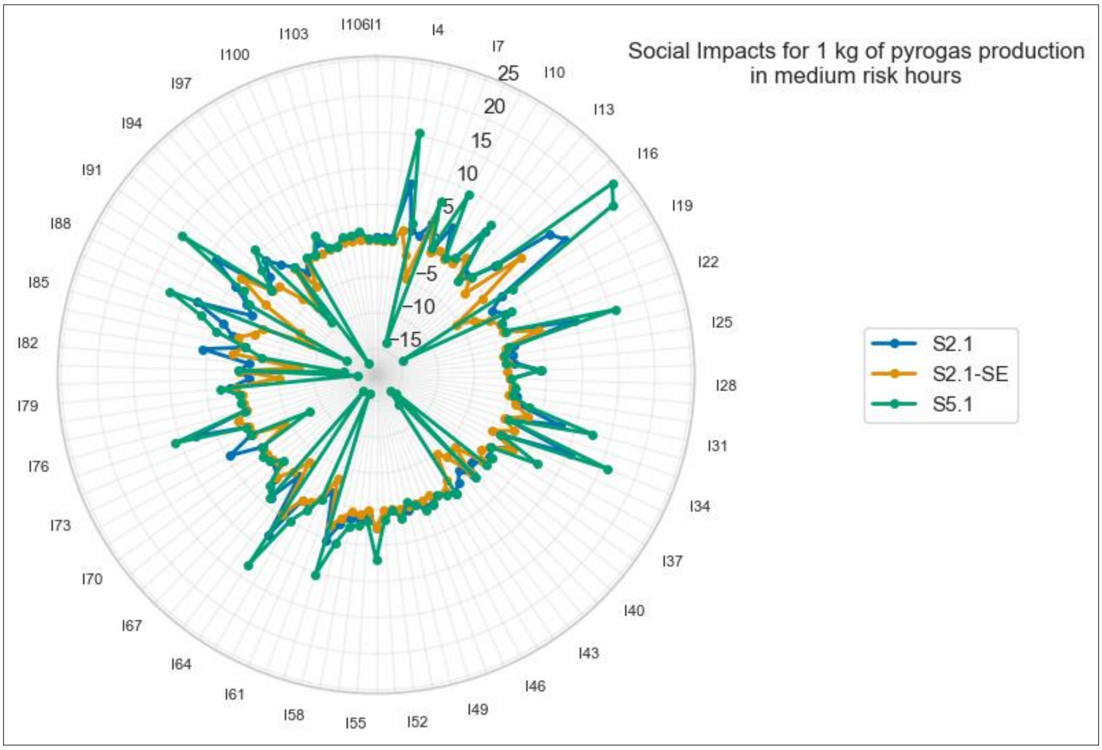

Figure 20: Hotspot analysis of S2.1, S2.1-SE and S5.1 for the production of electricity from the gas fraction pathway of the FLEXBY system

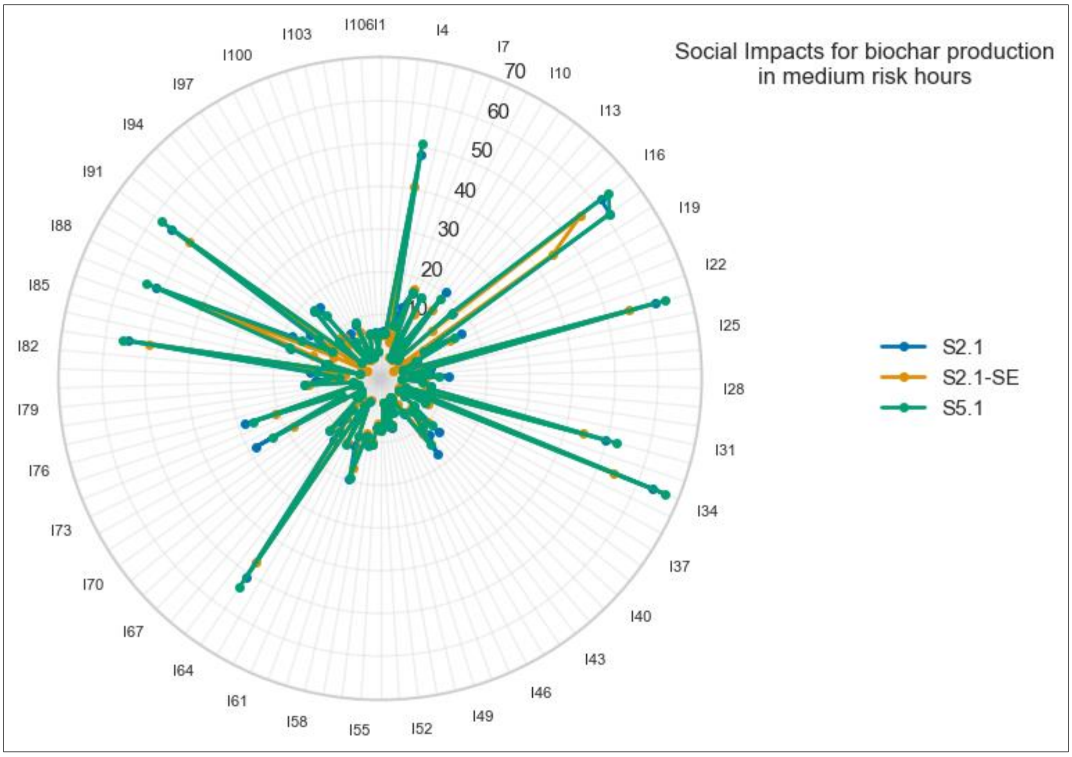

Figure 21: Hotspot analysis of S2.1, S2.1-SE and S5.1 of biochar in the FLEXBY system

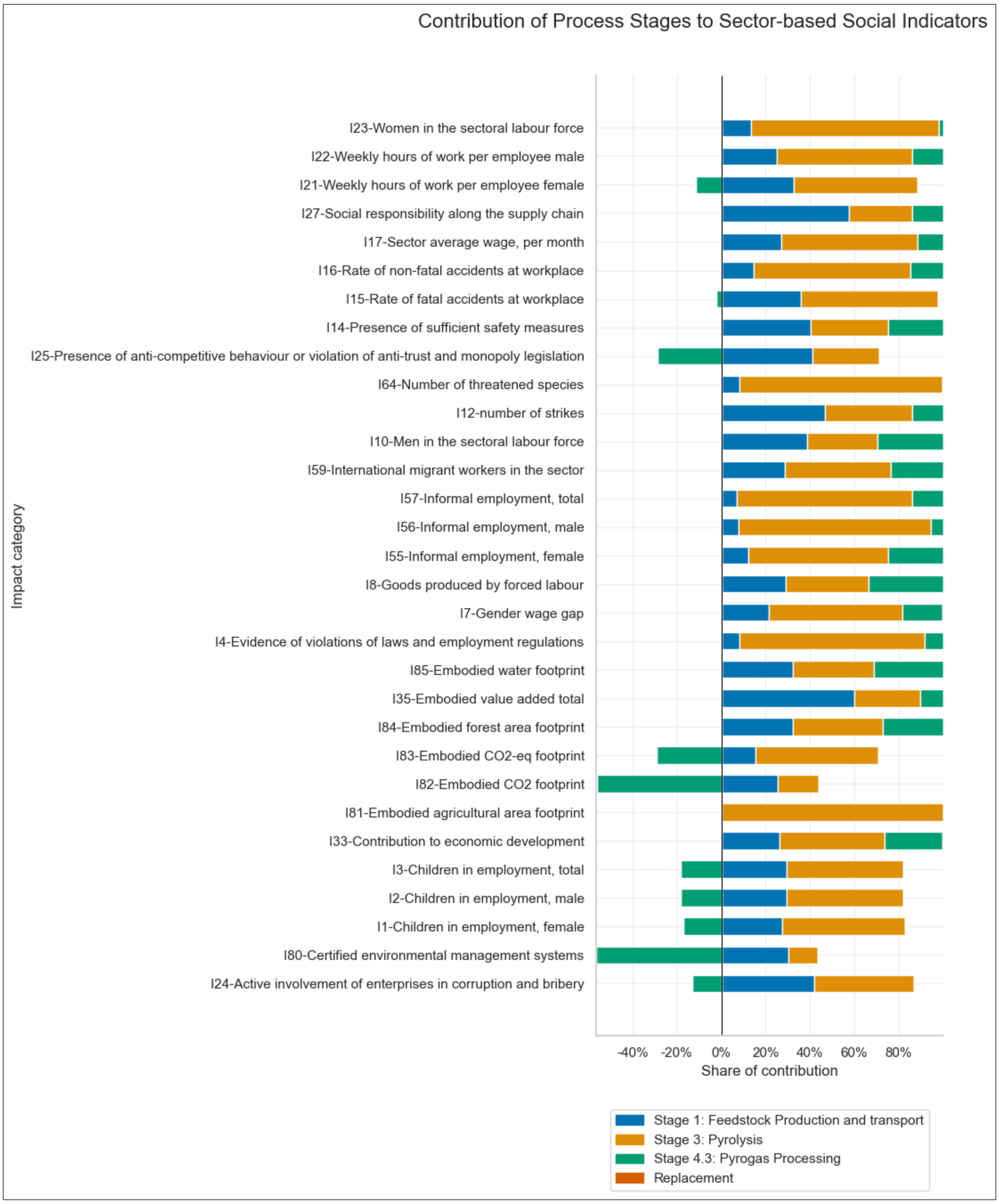

Figure 22: Relative contributions of process stages to the sector social indicators for the production of electricity from gas fraction

Across all three FLEXBY pathways, the Contribution to *economic development* (I33) indicates the value creation along the system’s life cycle. This contribution is linked to activities such as manufacturing and maintaining processing machinery, producing and handling feedstocks, and operating and servicing pyrolysis and upgrading units, which together support employment, skills development, and technical learning in industrial and energy-related sectors.

7.3 Integration of Social Surveys within the Social LCA Framework

In addition to the database-driven social LCA conducted in this case, a structured social survey was initially designed to capture perception-based, qualitative, and stakeholder-specific social impacts of the FLEXBY system, found in the file - Supplementary information '***Supplementary information – FLEXBY Social sustainability survey'***.

The survey complements the quantitative medium-risk-hour results by providing contextual insights from technology expert perspectives, particularly relevant at the current early TRL of FLEXBY. The survey is aimed at exploration of expected positive and negative social effects, perceived risks, social acceptance, learning and upskilling potential, and views on just transition, innovation, and governance. This is particularly important for emerging technologies where large-scale operational data is limited, and future deployment pathways are still evolving.

The use of Likert-scale questions enables semi-quantitative comparison across life-cycle stages and stakeholder groups, while open-ended questions support the identification of social opportunities, concerns, and mitigation pathways not captured by predefined indicators. The survey is not used to replace the social LCA results, but rather to triangulate findings, validate hotspot interpretations, and inform future data collection priorities, including primary data gathering and stakeholder interviews as the FLEXBY system progresses toward higher TRL scale operations.

8 From the preliminary LCC and S-LCA to the final integrated sustainability study

As the FLEXBY system develops and more experimental results are obtained, the final sustainability assessment will be significantly refined. By the project's end, testing of the fully designed microwave pyrolysis unit with real feedstocks will provide empirical energy demands and laboratory analyses will also clarify the properties of bio-oil, gas fraction, and biochar, enabling more accurate evaluation of valorisation pathways, potential revenues, and overall system economics.

The final study will also integrate an ex-ante perspective, accounting for technological learning, market evolution, and system scaling to assess long-term economic potential. Real operational data will allow more precise modelling of maintenance, component replacement, and system reliability, while co-location with wastewater treatment will be better quantified, capturing net economic and environmental benefits.

The early social LCA study relies on the LCA models developed for the environmental LCA and life cycle costing studies, with additional social data being integrated from the process-based background database of SOCA 4.0. The results indicate the medium-risk hours based on social data collected across different years from the respective global sectors, future studies will also use the input-output database of PSILCA. As the FLEXBY system moves from conceptual design to pilot operation, greater emphasis can be placed on foreground social data, including working conditions, safety management practices, and organisational structures directly associated with system operation. The study will evolve from this preliminary, sector-based screening toward a more refined assessment that progressively incorporates technology-specific, site-specific, and process-specific social information, for which an initial survey that will be circulated can be found in the supplementary information File 1. Gender based social targets will be set and measures to reach targets will be implemented throughout the project development to address the gender equality issues that arise in similar sectors.

This study shows inherited upstream social risks and further studies will illustrate the influence that project design and governance can have on them, thereby strengthening the robustness and decision relevance of the final integrated sustainability assessment in line with UNEP/SETAC social LCA guidance.

9 Conclusions

At the current TRL of the FLEXBY system, absolute cost figures are not intended to be interpreted as indicators of economic feasibility or site-specific social impacts; however, the preliminary socio-economic assessment provides an early identification of hotspots and structural cost drivers that can guide further system optimisation. Similarly, the social LCA results should be interpreted as a screening-level identification of potential social risk hotspots to focus on, rather than as definitive indicators of social performance

Across all scenarios, energy demand (particularly during pyrolysis) dominates the life cycle costs, followed by catalyst-related raw material expenses in the upgrading steps. The dominant social hotspots are associated with worker health and safety, labour rights compliance, wage conditions, and gender-related labour structures in manufacturing, energy, and equipment supply sectors. These findings are consistent with the industrial nature of microwave pyrolysis, upgrading, and auxiliary processing.

These findings (especially related to the energy consumption during the pyrolysis step) are aligned with expectations from the state-of-the-art literature, where thermo-chemical conversion of wet, heterogeneous biomass is known to be energy-intensive. Nevertheless, it is important to note that, in the planned FLEXBY configuration, this energy demand will be entirely supplied by photovoltaic sources, significantly mitigating the environmental burden of the energy consumption. Moreover, the FLEXBY configuration benefits from critical advantages, one of these as demonstrated in Deliverable 7.1, microwave-assisted pyrolysis displays lower energy consumption than both conventional and flash pyrolysis, and it uses only photovoltaic energy. Eventually, further reductions in energy demand are expected through the optimisation process foreseen in WP5, which will aim to identify the best operating conditions by balancing energy input and process efficiency; however, this activity has not yet started and therefore is not reflected in the current results.

The assessment highlighted the advantage of wastewater treatment as an additional service of FLEXBY when using the microalgae feedstock. When microalgae are produced as a by-product of wastewater treatment rather than as a dedicated feedstock, the system benefits from substantial cost offsets. This reflects both the state of the art in microalgae-based biorefineries and the project’s long-term vision: coupling biomass production to an existing service that already requires nutrient removal and CO_2 uptake. Under such integrated system, feedstock costs approach zero or become net credits.

Furthermore, the project is exploring multiple valorisation routes for all process fractions, which is essential for the economics of emerging biorefinery concepts. The main products (biofuel, electricity from gas fraction, both from the bioliquid and gas fraction itself) are being valorised within the current system boundaries, demonstrating circularity within the system, which will be a focus in upcoming LCAs. Other products also show promising value potential. Specifically:

- Biochar is still under investigation by the consortium, but several realistic valorisation pathways already exist: chemical activation (since physical activation has been advised against by **CSIC** due to the physical property of the biochar), or direct application as a soil amendment or in the construction sector. These pathways could provide economic and environmental co-benefits, reduce disposal costs and improve overall system circularity.
- Ammonia recovery from the process offers another valorisation opportunity. If captured and valorised as a usable product, it will contribute to reducing operational costs and social impacts from the production of ammonia, while reducing emissions associated with nitrogen losses to the atmosphere.

Overall, the study highlights the project's strategic choices to valorise outputs but have potential to reduce costs, however these will be thoroughly assessed and further developing the project with measures to check potential social hotspots can help sustainably scale the process system to higher TRLs.

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11 Appendix 1 – Results of the social hotspots weighting method applied on S2.1, S2.1-SE and S5.1 for the production of biofuels

	Name			S2.1	S2.1-SE	S5.1
I17	Sector average wage, per month	Workers	Fair salary	2.34E+01	2.66E+00	1.64E+01
I16	Rate of non-fatal accidents at workplace	Workers	Health and safety	2.17E+01	1.41E+01	1.74E+01
I23	Women in the sectoral labour force	Workers	Discrimination	1.92E+01	1.15E+01	1.87E+01
I4	Evidence of violations of laws and employment regulations	Workers	Social benefits, legal issues	1.53E+01	5.69E+00	1.32E+01
I12	number of strikes	Workers	Freedom of association and collective bargaining	1.03E+01	3.62E+00	5.41E+00
I6	Frequency of forced labour	Workers	Forced labour	8.65E+00	-3.00E-01	1.98E+00
I7	Gender wage gap	Workers	Discrimination	7.04E+00	8.18E+00	5.25E+00
I15	Rate of fatal accidents at workplace	Workers	Health and safety	6.99E+00	-1.13E+00	4.84E+00
I19	Trafficking in persons	Workers	Forced labour	6.62E+00	2.70E+00	5.91E+00
I9	Living wage, per month	Workers	Fair salary	5.72E+00	4.80E-01	3.97E+00
I5	Freedom of association and collective bargaining	Workers	Freedom of association and collective bargaining	3.24E+00	-1.97E+00	2.04E+00
I18	Trade union density	Workers	Freedom of association and collective bargaining	2.84E+00	-8.06E+00	1.93E+00

I20	Violations of mandatory health and safety standards	Workers	Health and safety	1.98E+00	-1.71E+00	1.19E+00
I2	Children in employment, male	Workers	Child labour	1.20E+00	3.20E-01	3.60E+00
I3	Children in employment, total	Workers	Child labour	1.20E+00	3.20E-01	3.60E+00
I1	Children in employment, female	Workers	Child labour	1.07E+00	3.20E-01	6.80E-01
I11	Minimum wage, per month	Workers	Fair salary	8.40E-01	1.40E-01	3.50E+00
I13	Paid maternity leave	Workers	Social benefits, legal issues	7.60E-01	-4.60E-01	3.30E-01
I14	Presence of sufficient safety measures	Workers	Health and safety	3.90E-01	-5.00E-02	4.80E-01
I21	Weekly hours of work per employee female	Workers	Working time	3.10E-01	7.00E-02	2.30E-01
I8	Goods produced by forced labour	Workers	Forced labour	2.90E-01	-1.50E-01	1.70E-01
I22	Weekly hours of work per employee male	Workers	Working time	2.80E-01	2.00E-02	2.20E-01
I10	Men in the sectoral labour force	Workers	Discrimination	2.20E-01	-4.00E-02	1.10E-01
I27	Social responsibility along the supply chain	Value Chain Actors	Promoting social responsibility	5.88E+00	-8.10E-01	2.50E+00
I24	Active involvement of enterprises in corruption and bribery	Value Chain Actors	Corruption	1.77E+00	-4.00E-02	3.77E+00
I26	Public sector corruption	Value Chain Actors	Corruption	1.39E+00	2.70E-01	3.67E+00

I25	Presence of anti-competitive behaviour or violation of anti-trust and monopoly legislation	Value Chain Actors	Fair competition	1.27E+00	-6.60E-01	5.90E-01
I34	Ecosystem services	Society	Nature	2.18E+01	9.58E+00	1.82E+01
I64	Number of threatened species	Society	Nature	1.58E+01	1.08E+01	1.37E+01
I32	Biodiversity & Habitat	Society	Nature	1.57E+01	8.88E+00	1.36E+01
I75	Unemployment rate in the country	Society	Local employment	1.32E+01	3.89E+00	7.80E+00
I72	Sanitation coverage	Society	Poverty Alleviation	1.30E+01	1.70E-01	8.27E+00
I59	International migrant workers in the sector	Society	Migration	8.48E+00	5.22E+00	5.62E+00
I43	Global Peace Index	Society	Secure living condition	7.10E+00	-1.10E-01	5.88E+00
I40	Freedom of the press	Society	Censorship and Oppression	5.71E+00	1.24E+00	5.06E+00
I65	Political stability and absence of violence	Society	Governance	5.49E+00	1.96E+00	4.88E+00
I42	Global freedom scores	Society	Access to immaterial resources	5.28E+00	1.62E+00	4.70E+00
I60	Internet freedom scores	Society	Censorship and Oppression	5.03E+00	1.99E+00	4.60E+00
I66	Pollution level of the country	Society	Safe and healthy living conditions	4.83E+00	-2.04E+00	1.18E+00
I58	International Migrant Stock	Society	Migration	3.42E+00	2.27E+00	2.08E+00
I79	Youth unemployment	Society	Education and upskilling opportunities	3.06E+00	1.99E+00	5.45E+00
I62	Life expectancy at birth	Society	Health and safety	2.78E+00	2.39E+00	5.29E+00
I67	Population below national poverty line	Society	Poverty alleviation	2.71E+00	2.37E+00	5.29E+00

I30	Animal protection	Society	Ethical treatment of animals	2.54E+00	9.80E-01	1.84E+00
I57	Informal employment, total	Society	Contribution to economic development	2.43E+00	1.15E+00	4.97E+00
I54	Immigration rate	Society	Migration	2.39E+00	2.44E+00	1.63E+00
I56	Informal employment, male	Society	Contribution to economic development	2.36E+00	1.50E+00	4.90E+00
I36	Emigration rate	Society	Migration	2.34E+00	3.09E+00	1.61E+00
I31	Asylum seekers rate	Society	Migration	2.34E+00	1.45E+00	1.61E+00
I44	Global Terrorism Index	Society	Secure living conditions	1.89E+00	-1.46E+00	1.42E+00
I50	Household air pollution attributable DALYs, male	Society	Health and safety	1.64E+00	6.40E-01	3.76E+00
I48	Health expenditure, total	Society	Health and safety	1.25E+00	-2.00E-01	9.20E-01
I55	Informal employment, female	Society	Contribution to economic development	1.16E+00	0.00E+00	3.79E+00
I63	Net migration rate	Society	Migration	1.14E+00	1.07E+00	5.80E-01
I51	Illiteracy rate, female	Society	Education and upskilling opportunities	1.09E+00	1.00E-01	3.77E+00
I47	Health expenditure, out-of-pocket	Society	Health and safety	1.05E+00	-8.80E-01	4.50E-01
I53	Illiteracy rate, total	Society	Education and upskilling opportunities	9.80E-01	1.20E-01	3.71E+00
I38	Female with account at a financial institution	Society	Gender equality and empowerment	9.40E-01	-1.25E+00	4.40E-01

I41	Gender inequalities	Society	Gender equality and empowerment	9.20E-01	1.00E-01	3.56E+00
I68	Public expenditure on education	Society	Education and upskilling opportunities	8.70E-01	-4.00E-02	4.50E-01
I35	Embodied value added total	Society	Contribution to economic development	8.10E-01	-1.06E+00	3.10E-01
I74	State of democracy	Society	Governance	7.60E-01	4.00E-01	3.45E+00
I39	Food insecurity	Society	Poverty Alleviation	7.00E-01	1.30E-01	3.48E+00
I29	Access to internet	Society	Technology development	6.50E-01	4.10E-01	3.43E+00
I70	Rate of researchers	Society	Technology development	6.40E-01	6.00E-02	4.90E-01
I73	Social Protection Expenditures	Society	Secure living conditions	5.90E-01	4.50E-01	3.39E+00
I33	Contribution to economic development	Society	Contribution to economic development	5.80E-01	2.60E-01	4.30E-01
I77	Youth illiteracy rate, male	Society	Education and upskilling opportunities	4.60E-01	2.20E-01	3.70E-01
I78	Youth illiteracy rate, total	Society	Education and upskilling opportunities	4.60E-01	2.20E-01	3.60E-01
I69	R&D expenditures	Society	Technology development	3.30E-01	1.00E-02	2.20E-01
I52	Illiteracy rate, male	Society	Education and upskilling opportunities	2.80E-01	1.30E-01	2.40E-01
I45	Health expenditure, domestic general government	Society	Health and safety	2.30E-01	-6.00E-02	1.30E-01
I71	Safe access to Drinking water coverage	Society	Poverty Alleviation	1.80E-01	-3.00E-02	8.00E-02

I49	Household air pollution attributable DALYs, female	Society	Health and safety	1.70E-01	2.00E-02	4.00E-01
I61	Labour productivity	Society	Contribution to economic development	1.70E-01	-2.00E-02	4.10E-01
I37	Female genital mutilation 15-49	Society	Gender equality and empowerment	1.60E-01	-4.00E-02	9.00E-02
I76	Youth illiteracy rate, female	Society	Education and upskilling opportunities	1.40E-01	-4.00E-02	9.00E-02
I46	Health expenditure, external resources	Society	Health and safety	5.00E-02	0.00E+00	4.00E-02
I28	Access to electricity	Society	Technology development	3.00E-02	2.00E-02	6.00E-02

12 Appendix 2 – Results of the social hotspots weighting method applied on S2.1, S2.1-SE and S5.1 for the production of electricity from the gaseous fraction of bioliquids

	Name	Stakeholder	Subcategory	S2.1	S2.1-SE	S5.1
I1	Children in employment, female	Workers	Child labour	9.20E-01	3.10E-01	8.70E-01
I2	Children in employment, male	Workers	Child labour	1.02E+00	3.10E-01	9.40E-01
I3	Children in employment, total	Workers	Child labour	1.02E+00	3.10E-01	9.40E-01
I4	Evidence of violations of laws and employment regulations	Workers	Social benefits, legal issues	1.24E+01	4.72E+00	1.66E+01
I5	Freedom of association and collective bargaining	Workers	Freedom of association and collective bargaining	2.76E+00	-1.42E+00	2.91E+00
I6	Frequency of forced labour	Workers	Forced labour	7.07E+00	-1.10E-01	2.74E+00
I7	Gender wage gap	Workers	Discrimination	6.21E+00	7.12E+00	8.11E+00
I8	Goods produced by forced labour	Workers	Forced labour	2.40E-01	-1.10E-01	2.30E-01
I9	Living wage, per month	Workers	Fair salary	4.73E+00	5.20E-01	5.22E+00
I10	Men in the sectoral labour force	Workers	Discrimination	1.80E-01	-2.00E-02	1.50E-01
I11	Minimum wage, per month	Workers	Fair salary	7.30E-01	1.60E-01	8.00E-01
I12	number of strikes	Workers	Freedom of association and collective bargaining	8.95E+00	3.57E+00	8.54E+00

I13	Paid maternity leave	Workers	Social benefits, legal issues	6.30E-01	-3.60E-01	4.40E-01
I14	Presence of sufficient safety measures	Workers	Health and safety	3.40E-01	-2.00E-02	2.90E-01
I15	Rate of fatal accidents at workplace	Workers	Health and safety	5.78E+00	-7.30E-01	6.08E+00
I16	Rate of non-fatal accidents at workplace	Workers	Health and safety	1.81E+01	1.21E+01	2.35E+01
I17	Sector average wage, per month	Workers	Fair salary	1.96E+01	2.93E+00	2.24E+01
I18	Trade union density	Workers	Freedom of association and collective bargaining	2.39E+00	-6.36E+00	2.68E+00
I19	Trafficking in persons	Workers	Forced labour	5.42E+00	2.28E+00	3.93E+00
I20	Violations of mandatory health and safety standards	Workers	Health and safety	1.68E+00	-1.28E+00	1.71E+00
I21	Weekly hours of work per employee female	Workers	Working time	2.60E-01	6.00E-02	2.80E-01
I22	Weekly hours of work per employee male	Workers	Working time	2.40E-01	4.00E-02	2.80E-01
I23	Women in the sectoral labour force	Workers	Discrimination	1.57E+01	9.56E+00	2.04E+01
I24	Active involvement of enterprises in corruption and bribery	Value Chain Actors	Corruption	1.57E+00	1.30E-01	1.40E+00
I25	Presence of anti-competitive behaviour or violation of anti-trust and monopoly legislation	Value Chain Actors	Fair competition	1.03E+00	-5.10E-01	7.70E-01
I26	Public sector corruption	Value Chain Actors	Corruption	1.17E+00	2.80E-01	1.03E+00

I27	Social responsibility along the supply chain	Value Chain Actors	Promoting social responsibility	4.83E+00	-5.30E-01	3.01E+00
I28	Access to electricity	Society	Technology development	3.00E-02	2.00E-02	4.00E-02
I29	Access to internet	Society	Technology development	5.80E-01	3.90E-01	7.30E-01
I30	Animal protection	Society	Ethical treatment of animals	2.08E+00	8.20E-01	2.36E+00
I31	Asylum seekers rate	Society	Migration	1.97E+00	1.26E+00	2.19E+00
I32	Biodiversity & Habitat	Society	Nature	1.28E+01	7.37E+00	1.73E+01
I33	Contribution to economic development	Society	Contribution to economic development	5.30E-01	2.70E-01	6.60E-01
I34	Ecosystem services	Society	Nature	1.82E+01	8.38E+00	2.44E+01
I35	Embodied value added total	Society	Contribution to economic development	6.60E-01	-8.40E-01	4.10E-01
I36	Emigration rate	Society	Migration	1.97E+00	2.57E+00	2.19E+00
I37	Female genital mutilation 15-49	Society	Gender equality and empowerment	1.30E-01	-3.00E-02	1.20E-01
I38	Female with account at a financial institution	Society	Gender equality and empowerment	7.80E-01	-9.70E-01	6.00E-01
I39	Food insecurity	Society	Poverty Alleviation	7.00E-01	2.30E-01	9.80E-01
I40	Freedom of the press	Society	Censorship and Oppression	4.77E+00	1.18E+00	3.07E+00
I41	Gender inequalities	Society	Gender equality and empowerment	8.00E-01	1.50E-01	9.00E-01
I42	Global freedom scores	Society	Access to immaterial resources	4.34E+00	1.40E+00	2.41E+00

I43	Global Peace Index	Society	Secure living condition	5.85E+00	6.00E-02	3.98E+00
I44	Global Terrorism Index	Society	Secure living conditions	1.65E+00	-1.04E+00	1.73E+00
I45	Health expenditure, domestic general government	Society	Health and safety	1.90E-01	-4.00E-02	1.90E-01
I46	Health expenditure, external resources	Society	Health and safety	4.00E-02	0.00E+00	5.00E-02
I47	Health expenditure, out-of-pocket	Society	Health and safety	9.40E-01	-6.00E-01	8.00E-01
I48	Health expenditure, total	Society	Health and safety	1.10E+00	-6.00E-02	1.37E+00
I49	Household air pollution attributable DALYs, female	Society	Health and safety	1.50E-01	3.00E-02	1.60E-01
I50	Household air pollution attributable DALYs, male	Society	Health and safety	1.39E+00	5.90E-01	1.18E+00
I51	Illiteracy rate, female	Society	Education and upskilling opportunities	1.01E+00	2.20E-01	1.35E+00
I52	Illiteracy rate, male	Society	Education and upskilling opportunities	2.40E-01	1.20E-01	3.20E-01
I53	Illiteracy rate, total	Society	Education and upskilling opportunities	9.20E-01	2.30E-01	1.27E+00
I54	Immigration rate	Society	Migration	2.01E+00	2.05E+00	2.22E+00
I55	Informal employment, female	Society	Contribution to economic development	1.08E+00	1.40E-01	1.38E+00
I56	Informal employment, male	Society	Contribution to economic development	1.97E+00	1.28E+00	2.59E+00

I57	Informal employment, total	Society	Contribution to economic development	2.10E+00	1.08E+00	2.86E+00
I58	International Migrant Stock	Society	Migration	2.85E+00	1.93E+00	2.80E+00
I59	International migrant workers in the sector	Society	Migration	7.41E+00	4.79E+00	8.61E+00
I60	Internet freedom scores	Society	Censorship and Oppression	4.13E+00	1.69E+00	2.27E+00
I61	Labour productivity	Society	Contribution to economic development	1.50E-01	0.00E+00	1.80E-01
I62	Life expectancy at birth	Society	Health and safety	2.31E+00	2.00E+00	3.07E+00
I63	Net migration rate	Society	Migration	9.30E-01	8.80E-01	7.60E-01
I64	Number of threatened species	Society	Nature	1.28E+01	8.82E+00	1.72E+01
I65	Political stability and absence of violence	Society	Governance	4.51E+00	1.68E+00	2.65E+00
I66	Pollution level of the country	Society	Safe and healthy living conditions	3.99E+00	-1.53E+00	1.73E+00
I67	Population below national poverty line	Society	Poverty alleviation	2.25E+00	1.98E+00	3.06E+00
I68	Public expenditure on education	Society	Education and upskilling opportunities	7.10E-01	-2.00E-02	6.00E-01
I69	R&D expenditures	Society	Technology development	2.70E-01	1.00E-02	2.80E-01
I70	Rate of researchers	Society	Technology development	5.30E-01	7.00E-02	6.50E-01
I71	Safe access to Drinking water coverage	Society	Poverty Alleviation	1.40E-01	-2.00E-02	1.00E-01
I72	Sanitation coverage	Society	Poverty Alleviation	1.07E+01	4.70E-01	7.40E+00

I73	Social Protection Expenditures	Society	Secure living conditions	5.30E-01	4.20E-01	6.80E-01
I74	State of democracy	Society	Governance	6.70E-01	3.80E-01	7.40E-01
I75	Unemployment rate in the country	Society	Local employment	1.12E+01	3.82E+00	1.16E+01
I76	Youth illiteracy rate, female	Society	Education and upskilling opportunities	1.30E-01	-2.00E-02	1.30E-01
I77	Youth illiteracy rate, male	Society	Education and upskilling opportunities	3.90E-01	1.90E-01	4.90E-01
I78	Youth illiteracy rate, total	Society	Education and upskilling opportunities	3.80E-01	1.90E-01	4.80E-01
I79	Youth unemployment	Society	Education and upskilling opportunities	2.53E+00	1.68E+00	3.27E+00
I80	Certified environmental management systems	Local Community	Access to material resources	4.57E+00	-2.50E-01	2.56E+00
I81	Embodied agricultural area footprint	Local Community	Environmental footprints	4.50E-01	4.50E-01	5.90E-01
I82	Embodied CO2 footprint	Local Community	GHG footprints	4.56E+00	-3.46E+00	3.49E+00
I83	Embodied CO2-eq footprint	Local Community	Environmental footprints	1.53E+01	1.04E+01	1.84E+01
I84	Embodied forest area footprint	Local Community	Environmental footprints	0.00E+00	0.00E+00	0.00E+00
I85	Embodied water footprint	Local Community	Environmental footprints	1.93E+00	9.50E-01	1.62E+00
I86	Extraction of biomass (related to area)	Local Community	Access to material resources	4.86E+00	-5.90E-01	5.88E+00
I87	Extraction of biomass (related to population)	Local Community	Access to material resources	1.38E+01	2.16E+00	1.79E+01
I88	Extraction of fossil fuels	Local Community	Access to material resources	6.88E+00	-3.86E+00	5.12E+00

I89	Extraction of industrial and construction minerals	Local Community	Access to material resources	2.87E+00	-6.84E+00	2.61E+00
I90	Extraction of ores	Local Community	Access to material resources	6.00E+00	3.10E-01	4.17E+00
I91	Homicides	Local Community	Secure living condition	1.42E+01	9.00E+00	1.89E+01
I92	Indigenous People Rights Protection Index	Local Community	Respect of indigenous rights	2.80E-01	-2.00E-02	2.90E-01
I93	Internally displaced people	Local Community	Secure living condition	1.56E+00	-6.50E-01	1.73E+00
I94	Level of industrial water use (related to renewable water resources)	Local Community	Access to material resources	4.79E+00	-4.03E+00	5.46E+00
I95	Level of industrial water use (related to total withdrawal)	Local Community	Access to material resources	6.63E+00	-2.52E+00	4.69E+00
I96	Presence of indigenous population	Local Community	Respect of indigenous rights	2.80E-01	8.00E-02	3.10E-01
I97	Waste management	Local Community	Access to material resources	3.88E+00	1.21E+00	1.85E+00
I98	Data protection and privacy	Consumer	Consumer protection	2.70E-01	-2.80E-01	2.10E-01
I99	Online Consumer Protection Legislation	Consumer	Consumer protection	1.00E-01	-1.80E-01	9.00E-02
I100	Child marriage, female	Children	Children welfare	2.16E+00	3.40E-01	2.95E+00
I101	Child marriage, male	Children	Children welfare	1.60E-01	-7.00E-02	2.10E-01
I102	Female genital mutilation 0-14	Children	Children welfare	7.00E-02	0.00E+00	8.00E-02
I103	Mean years of schooling, female	Children	Education	7.40E-01	3.40E-01	9.30E-01
I104	Mean years of schooling, male	Children	Education	7.40E-01	3.40E-01	9.30E-01
I105	Mean years of schooling, total	Children	Education	8.60E-01	2.30E-01	1.15E+00

I106	Under-five mortality rate	Children	Health and Safety	3.20E-01	1.40E-01	4.10E-01

13 Appendix 3 – Results of the social hotspots weighting method applied on S2.1, S2.1-SE and S5.1 for the production of electricity from gas fraction

	Name	Stakeholder	Subcategory	S2.1	S2.1-SE	S5.1
I1	Children in employment, female	Workers	Child labour	5.50E-01	4.00E-02	2.50E-01
I2	Children in employment, male	Workers	Child labour	6.00E-01	0.00E+00	2.10E-01
I3	Children in employment, total	Workers	Child labour	6.00E-01	0.00E+00	2.10E-01
I4	Evidence of violations of laws and employment regulations	Workers	Social benefits, legal issues	8.32E+00	1.76E+00	1.55E+01
I5	Freedom of association and collective bargaining	Workers	Freedom of association and collective bargaining	2.06E+00	-1.50E+00	3.00E+00
I6	Frequency of forced labour	Workers	Forced labour	1.59E+00	-4.53E+00	-1.40E+01
I7	Gender wage gap	Workers	Discrimination	3.72E+00	4.50E+00	7.07E+00
I8	Goods produced by forced labour	Workers	Forced labour	2.40E-01	-6.00E-02	5.10E-01
I9	Living wage, per month	Workers	Fair salary	4.30E+00	7.20E-01	9.43E+00
I10	Men in the sectoral labour force	Workers	Discrimination	1.80E-01	0.00E+00	3.30E-01
I11	Minimum wage, per month	Workers	Fair salary	6.00E-01	1.10E-01	9.10E-01

I12	number of strikes	Workers	Freedom of association and collective bargaining	6.33E+00	1.75E+00	7.52E+00
I13	Paid maternity leave	Workers	Social benefits, legal issues	5.00E-02	-7.90E-01	-1.33E+00
I14	Presence of sufficient safety measures	Workers	Health and safety	3.10E-01	1.00E-02	4.50E-01
I15	Rate of fatal accidents at workplace	Workers	Health and safety	3.67E+00	-1.88E+00	4.05E+00
I16	Rate of non-fatal accidents at workplace	Workers	Health and safety	1.23E+01	7.11E+00	2.35E+01
I17	Sector average wage, per month	Workers	Fair salary	1.36E+01	-5.40E-01	2.18E+01
I18	Trade union density	Workers	Freedom of association and collective bargaining	1.96E+00	-5.50E+00	3.81E+00
I19	Trafficking in persons	Workers	Forced labour	-3.70E-01	-3.06E+00	-1.45E+01
I20	Violations of mandatory health and safety standards	Workers	Health and safety	1.26E+00	-1.27E+00	2.05E+00
I21	Weekly hours of work per employee female	Workers	Working time	1.40E-01	-2.00E-02	1.10E-01
I22	Weekly hours of work per employee male	Workers	Working time	1.70E-01	-1.00E-02	2.50E-01
I23	Women in the sectoral labour force	Workers	Discrimination	9.95E+00	4.68E+00	1.58E+01
I24	Active involvement of enterprises in corruption and bribery	Value Chain Actors	Corruption	9.50E-01	-2.80E-01	5.00E-02

I25	Presence of anti-competitive behaviour or violation of anti-trust and monopoly legislation	Value Chain Actors	Fair competition	4.40E-01	-8.80E-01	-5.70E-01
I26	Public sector corruption	Value Chain Actors	Corruption	5.10E-01	-2.50E-01	-6.50E-01
I27	Social responsibility along the supply chain	Value Chain Actors	Promoting social responsibility	4.14E+00	-4.40E-01	4.29E+00
I28	Access to electricity	Society	Technology development	2.00E-02	1.00E-02	3.00E-02
I29	Access to internet	Society	Technology development	4.80E-01	3.10E-01	7.80E-01
I30	Animal protection	Society	Ethical treatment of animals	1.01E+00	-6.00E-02	4.40E-01
I31	Asylum seekers rate	Society	Migration	1.67E+00	1.07E+00	3.07E+00
I32	Biodiversity & Habitat	Society	Nature	7.81E+00	3.14E+00	1.25E+01
I33	Contribution to economic development	Society	Contribution to economic development	3.70E-01	1.40E-01	7.40E-01
I34	Ecosystem services	Society	Nature	1.04E+01	2.04E+00	1.60E+01
I35	Embodied value added total	Society	Contribution to economic development	5.40E-01	-7.30E-01	5.30E-01
I36	Emigration rate	Society	Migration	2.48E+00	2.99E+00	6.90E+00
I37	Female genital mutilation 15-49	Society	Gender equality and empowerment	1.00E-01	-3.00E-02	1.20E-01
I38	Female with account at a financial institution	Society	Gender equality and empowerment	7.20E-01	-7.70E-01	1.07E+00
I39	Food insecurity	Society	Poverty Alleviation	6.30E-01	2.30E-01	1.14E+00
I40	Freedom of the press	Society	Censorship and Oppression	-6.40E-01	-3.70E+00	-1.48E+01

I41	Gender inequalities	Society	Gender equality and empowerment	6.70E-01	1.10E-01	1.07E+00
I42	Global freedom scores	Society	Access to immaterial resources	-1.05E+00	-3.55E+00	-1.57E+01
I43	Global Peace Index	Society	Secure living condition	1.90E-01	-4.75E+00	-1.34E+01
I44	Global Terrorism Index	Society	Secure living conditions	1.15E+00	-1.14E+00	1.34E+00
I45	Health expenditure, domestic general government	Society	Health and safety	2.60E-01	6.00E-02	6.70E-01
I46	Health expenditure, external resources	Society	Health and safety	3.00E-02	0.00E+00	5.00E-02
I47	Health expenditure, out-of-pocket	Society	Health and safety	8.50E-01	-4.60E-01	1.12E+00
I48	Health expenditure, total	Society	Health and safety	8.50E-01	-1.40E-01	1.40E+00
I49	Household air pollution attributable DALYs, female	Society	Health and safety	1.40E-01	3.00E-02	2.10E-01
I50	Household air pollution attributable DALYs, male	Society	Health and safety	6.90E-01	1.00E-02	-4.90E-01
I51	Illiteracy rate, female	Society	Education and upskilling opportunities	8.70E-01	1.90E-01	1.55E+00
I52	Illiteracy rate, male	Society	Education and upskilling opportunities	1.70E-01	7.00E-02	3.10E-01
I53	Illiteracy rate, total	Society	Education and upskilling opportunities	7.80E-01	1.90E-01	1.42E+00
I54	Immigration rate	Society	Migration	2.51E+00	2.55E+00	6.95E+00

I55	Informal employment, female	Society	Contribution to economic development	9.40E-01	1.40E-01	1.69E+00
I56	Informal employment, male	Society	Contribution to economic development	1.37E+00	7.80E-01	2.31E+00
I57	Informal employment, total	Society	Contribution to economic development	1.53E+00	6.60E-01	2.75E+00
I58	International Migrant Stock	Society	Migration	2.61E+00	1.82E+00	5.32E+00
I59	International migrant workers in the sector	Society	Migration	5.43E+00	3.20E+00	1.04E+01
I60	Internet freedom scores	Society	Censorship and Oppression	-1.23E+00	-3.31E+00	-1.59E+01
I61	Labour productivity	Society	Contribution to economic development	1.20E-01	-1.00E-02	2.10E-01
I62	Life expectancy at birth	Society	Health and safety	1.50E+00	1.24E+00	2.42E+00
I63	Net migration rate	Society	Migration	1.55E+00	1.50E+00	4.88E+00
I64	Number of threatened species	Society	Nature	8.01E+00	4.60E+00	1.32E+01
I65	Political stability and absence of violence	Society	Governance	-9.90E-01	-3.40E+00	-1.57E+01
I66	Pollution level of the country	Society	Safe and healthy living conditions	3.78E+00	-9.20E-01	3.90E+00
I67	Population below national poverty line	Society	Poverty alleviation	1.49E+00	1.26E+00	2.61E+00
I68	Public expenditure on education	Society	Education and upskilling opportunities	1.10E-01	-5.10E-01	-1.07E+00

I69	R&D expenditures	Society	Technology development	2.10E-01	-1.00E-02	3.20E-01
I70	Rate of researchers	Society	Technology development	4.10E-01	1.00E-02	7.50E-01
I71	Safe access to Drinking water coverage	Society	Poverty Alleviation	9.00E-02	-5.00E-02	0.00E+00
I72	Sanitation coverage	Society	Poverty Alleviation	4.57E+00	-4.18E+00	-8.02E+00
I73	Social Protection Expenditures	Society	Secure living conditions	4.40E-01	3.40E-01	7.30E-01
I74	State of democracy	Society	Governance	5.60E-01	3.10E-01	8.30E-01
I75	Unemployment rate in the country	Society	Local employment	7.86E+00	1.54E+00	1.08E+01
I76	Youth illiteracy rate, female	Society	Education and upskilling opportunities	1.20E-01	0.00E+00	2.00E-01
I77	Youth illiteracy rate, male	Society	Education and upskilling opportunities	2.80E-01	1.10E-01	4.60E-01
I78	Youth illiteracy rate, total	Society	Education and upskilling opportunities	2.80E-01	1.20E-01	4.80E-01
I79	Youth unemployment	Society	Education and upskilling opportunities	1.75E+00	1.02E+00	2.99E+00
I80	Certified environmental management systems	Local Community	Access to material resources	-1.03E+00	-5.14E+00	-1.59E+01
I81	Embodied agricultural area footprint	Local Community	Environmental footprints	3.50E-01	3.50E-01	5.70E-01
I82	Embodied CO2 footprint	Local Community	GHG footprints	-9.00E-01	-7.74E+00	-1.42E+01
I83	Embodied CO2-eq footprint	Local Community	Environmental footprints	5.70E+00	1.48E+00	-2.57E+00
I84	Embodied forest area footprint	Local Community	Environmental footprints	0.00E+00	0.00E+00	0.00E+00

I85	Embodied water footprint	Local Community	Environmental footprints	2.06E+00	1.22E+00	4.42E+00
I86	Extraction of biomass (related to area)	Local Community	Access to material resources	3.82E+00	-8.20E-01	6.97E+00
I87	Extraction of biomass (related to population)	Local Community	Access to material resources	8.26E+00	-1.69E+00	1.22E+01
I88	Extraction of fossil fuels	Local Community	Access to material resources	4.90E-01	-8.66E+00	-1.40E+01
I89	Extraction of industrial and construction minerals	Local Community	Access to material resources	1.83E+00	-6.45E+00	1.57E+00
I90	Extraction of ores	Local Community	Access to material resources	4.42E+00	-4.30E-01	3.18E+00
I91	Homicides	Local Community	Secure living condition	8.79E+00	4.37E+00	1.45E+01
I92	Indigenous People Rights Protection Index	Local Community	Respect of indigenous rights	1.40E-01	-1.10E-01	4.00E-02
I93	Internally displaced people	Local Community	Secure living condition	1.43E+00	-4.60E-01	2.85E+00
I94	Level of industrial water use (related to renewable water resources)	Local Community	Access to material resources	3.51E+00	-4.01E+00	5.61E+00
I95	Level of industrial water use (related to total withdrawal)	Local Community	Access to material resources	1.53E+00	-6.27E+00	-9.06E+00
I96	Presence of indigenous population	Local Community	Respect of indigenous rights	1.50E-01	-2.00E-02	1.10E-01
I97	Waste management	Local Community	Access to material resources	-1.49E+00	-3.77E+00	-1.66E+01
I98	Data protection and privacy	Consumer	Consumer protection	2.40E-01	-2.30E-01	3.50E-01
I99	Online Consumer Protection Legislation	Consumer	Consumer protection	8.00E-02	-1.50E-01	1.30E-01
I100	Child marriage, female	Children	Children welfare	1.38E+00	-1.70E-01	2.42E+00

I101	Child marriage, male	Children	Children welfare	1.10E-01	-9.00E-02	2.00E-01
I102	Female genital mutilation 0-14	Children	Children welfare	5.00E-02	-1.00E-02	7.00E-02
I103	Mean years of schooling, female	Children	Education	6.00E-01	2.60E-01	1.07E+00
I104	Mean years of schooling, male	Children	Education	6.00E-01	2.60E-01	1.07E+00
I105	Mean years of schooling, total	Children	Education	7.50E-01	2.10E-01	1.35E+00
I106	Under-five mortality rate	Children	Health and Safety	2.40E-01	9.00E-02	4.10E-01

14 Appendix 4 – Results of the social hotspots weighting method applied on S2.1, S2.1-SE and S5.1 for the production of biochar

	Name	Stakeholder	Subcategory	S2.1	S2.1-SE	S5.1
I1	Children in employment, female	Workers	Child labour	5.91E+00	5.30E+00	5.47E+00
I2	Children in employment, male	Workers	Child labour	6.16E+00	5.45E+00	5.69E+00
I3	Children in employment, total	Workers	Child labour	6.16E+00	5.45E+00	5.69E+00
I4	Evidence of violations of laws and employment regulations	Workers	Social benefits, legal issues	4.82E+01	4.05E+01	5.10E+01
I5	Freedom of association and collective bargaining	Workers	Freedom of association and collective bargaining	8.18E+00	4.01E+00	7.91E+00
I6	Frequency of forced labour	Workers	Forced labour	1.23E+01	5.18E+00	7.65E+00
I7	Gender wage gap	Workers	Discrimination	1.64E+01	1.73E+01	1.66E+01
I8	Goods produced by forced labour	Workers	Forced labour	6.98E-01	3.49E-01	6.61E-01
I9	Living wage, per month	Workers	Fair salary	1.62E+01	1.20E+01	1.62E+01
I10	Men in the sectoral labour force	Workers	Discrimination	4.74E-01	2.68E-01	4.22E-01
I11	Minimum wage, per month	Workers	Fair salary	5.58E+00	5.01E+00	5.28E+00

I12	number of strikes	Workers	Freedom of association and collective bargaining	2.06E+01	1.53E+01	1.84E+01
I13	Paid maternity leave	Workers	Social benefits, legal issues	1.58E+00	5.93E-01	1.34E+00
I14	Presence of sufficient safety measures	Workers	Health and safety	1.13E+00	7.81E-01	1.00E+00
I15	Rate of fatal accidents at workplace	Workers	Health and safety	1.80E+01	1.15E+01	1.76E+01
I16	Rate of non-fatal accidents at workplace	Workers	Health and safety	6.15E+01	5.54E+01	6.38E+01
I17	Sector average wage, per month	Workers	Fair salary	6.12E+01	4.46E+01	6.11E+01
I18	Trade union density	Workers	Freedom of association and collective bargaining	7.19E+00	-1.54E+00	7.11E+00
I19	Trafficking in persons	Workers	Forced labour	1.68E+01	1.37E+01	1.46E+01
I20	Violations of mandatory health and safety standards	Workers	Health and safety	4.50E+00	1.54E+00	4.25E+00
I21	Weekly hours of work per employee female	Workers	Working time	8.10E-01	6.14E-01	7.88E-01
I22	Weekly hours of work per employee male	Workers	Working time	7.64E-01	5.62E-01	7.63E-01
I23	Women in the sectoral labour force	Workers	Discrimination	6.16E+01	5.54E+01	6.40E+01
I24	Active involvement of enterprises in corruption and bribery	Value Chain Actors	Corruption	7.03E+00	5.59E+00	6.29E+00
I25	Presence of anti-competitive behaviour or violation of anti-trust and monopoly legislation	Value Chain Actors	Fair competition	2.63E+00	1.09E+00	2.29E+00

I26	Public sector corruption	Value Chain Actors	Corruption	6.47E+00	5.58E+00	5.92E+00
I27	Social responsibility along the supply chain	Value Chain Actors	Promoting social responsibility	1.11E+01	5.75E+00	8.89E+00
I28	Access to electricity	Society	Technology development	1.34E-01	1.27E-01	1.35E-01
I29	Access to internet	Society	Technology development	5.22E+00	5.03E+00	4.99E+00
I30	Animal protection	Society	Ethical treatment of animals	7.04E+00	5.78E+00	7.09E+00
I31	Asylum seekers rate	Society	Migration	7.03E+00	6.32E+00	7.02E+00
I32	Biodiversity & Habitat	Society	Nature	4.96E+01	4.41E+01	5.24E+01
I33	Contribution to economic development	Society	Contribution to economic development	1.34E+00	1.08E+00	1.31E+00
I34	Ecosystem services	Society	Nature	6.37E+01	5.39E+01	6.69E+01
I35	Embodied value added total	Society	Contribution to economic development	1.48E+00	-1.28E-02	1.18E+00
I36	Emigration rate	Society	Migration	7.03E+00	7.63E+00	7.02E+00
I37	Female genital mutilation 15-49	Society	Gender equality and empowerment	3.66E-01	2.12E-01	3.40E-01
I38	Female with account at a financial institution	Society	Gender equality and empowerment	2.06E+00	3.09E-01	1.81E+00
I39	Food insecurity	Society	Poverty Alleviation	5.41E+00	4.95E+00	5.19E+00
I40	Freedom of the press	Society	Censorship and Oppression	1.38E+01	1.02E+01	1.13E+01
I41	Gender inequalities	Society	Gender equality and empowerment	5.82E+00	5.16E+00	5.52E+00
I42	Global freedom scores	Society	Access to immaterial resources	1.24E+01	9.52E+00	9.96E+00

I43	Global Peace Index	Society	Secure living condition	1.71E+01	1.13E+01	1.45E+01
I44	Global Terrorism Index	Society	Secure living conditions	4.93E+00	2.25E+00	4.67E+00
I45	Health expenditure, domestic general government	Society	Health and safety	5.39E-01	3.08E-01	5.07E-01
I46	Health expenditure, external resources	Society	Health and safety	1.26E-01	8.90E-02	1.27E-01
I47	Health expenditure, out-of-pocket	Society	Health and safety	2.06E+00	5.16E-01	1.72E+00
I48	Health expenditure, total	Society	Health and safety	3.50E+00	2.34E+00	3.54E+00
I49	Household air pollution attributable DALYs, female	Society	Health and safety	7.52E-01	6.27E-01	7.04E-01
I50	Household air pollution attributable DALYs, male	Society	Health and safety	6.94E+00	6.14E+00	6.30E+00
I51	Illiteracy rate, female	Society	Education and upskilling opportunities	6.50E+00	5.71E+00	6.30E+00
I52	Illiteracy rate, male	Society	Education and upskilling opportunities	8.72E-01	7.54E-01	9.16E-01
I53	Illiteracy rate, total	Society	Education and upskilling opportunities	6.26E+00	5.57E+00	6.08E+00
I54	Immigration rate	Society	Migration	7.14E+00	7.18E+00	7.11E+00
I55	Informal employment, female	Society	Contribution to economic development	6.64E+00	5.70E+00	6.40E+00
I56	Informal employment, male	Society	Contribution to economic development	1.06E+01	9.93E+00	1.07E+01

I57	Informal employment, total	Society	Contribution to economic development	1.09E+01	9.84E+00	1.10E+01
I58	International Migrant Stock	Society	Migration	9.18E+00	8.26E+00	8.84E+00
I59	International migrant workers in the sector	Society	Migration	1.97E+01	1.71E+01	1.92E+01
I60	Internet freedom scores	Society	Censorship and Oppression	1.20E+01	9.53E+00	9.57E+00
I61	Labour productivity	Society	Contribution to economic development	7.94E-01	6.40E-01	7.66E-01
I62	Life expectancy at birth	Society	Health and safety	1.20E+01	1.17E+01	1.22E+01
I63	Net migration rate	Society	Migration	2.50E+00	2.44E+00	2.25E+00
I64	Number of threatened species	Society	Nature	5.10E+01	4.70E+01	5.40E+01
I65	Political stability and absence of violence	Society	Governance	1.31E+01	1.02E+01	1.06E+01
I66	Pollution level of the country	Society	Safe and healthy living conditions	7.11E+00	1.61E+00	4.58E+00
I67	Population below national poverty line	Society	Poverty alleviation	1.20E+01	1.17E+01	1.22E+01
I68	Public expenditure on education	Society	Education and upskilling opportunities	1.91E+00	1.18E+00	1.72E+00
I69	R&D expenditures	Society	Technology development	8.60E-01	6.06E-01	8.43E-01
I70	Rate of researchers	Society	Technology development	1.85E+00	1.39E+00	1.90E+00
I71	Safe access to Drinking water coverage	Society	Poverty Alleviation	3.44E-01	1.79E-01	2.86E-01
I72	Sanitation coverage	Society	Poverty Alleviation	2.83E+01	1.81E+01	2.38E+01

I73	Social Protection Expenditures	Society	Secure living conditions	5.08E+00	4.96E+00	4.85E+00
I74	State of democracy	Society	Governance	5.39E+00	5.10E+00	5.10E+00
I75	Unemployment rate in the country	Society	Local employment	2.83E+01	2.09E+01	2.65E+01
I76	Youth illiteracy rate, female	Society	Education and upskilling opportunities	3.45E-01	1.98E-01	3.23E-01
I77	Youth illiteracy rate, male	Society	Education and upskilling opportunities	1.37E+00	1.18E+00	1.41E+00
I78	Youth illiteracy rate, total	Society	Education and upskilling opportunities	1.36E+00	1.17E+00	1.40E+00
I79	Youth unemployment	Society	Education and upskilling opportunities	1.27E+01	1.18E+01	1.28E+01
I80	Certified environmental management systems	Local Community	Access to material resources	1.01E+01	5.33E+00	7.83E+00
I81	Embodied agricultural area footprint	Local Community	Environmental footprints	4.85E+00	4.84E+00	4.62E+00
I82	Embodied CO2 footprint	Local Community	GHG footprints	1.14E+01	3.42E+00	9.93E+00
I83	Embodied CO2-eq footprint	Local Community	Environmental footprints	5.45E+01	4.95E+01	5.59E+01
I84	Embodied forest area footprint	Local Community	Environmental footprints	5.90E-04	1.20E-04	5.57E-04
I85	Embodied water footprint	Local Community	Environmental footprints	8.38E+00	7.40E+00	7.59E+00
I86	Extraction of biomass (related to area)	Local Community	Access to material resources	1.73E+01	1.18E+01	1.76E+01
I87	Extraction of biomass (related to population)	Local Community	Access to material resources	5.15E+01	3.99E+01	5.39E+01
I88	Extraction of fossil fuels	Local Community	Access to material resources	1.78E+01	7.03E+00	1.55E+01

I89	Extraction of industrial and construction minerals	Local Community	Access to material resources	8.34E+00	-1.35E+00	7.81E+00
I90	Extraction of ores	Local Community	Access to material resources	1.44E+01	8.72E+00	1.21E+01
I91	Homicides	Local Community	Secure living condition	5.50E+01	4.99E+01	5.81E+01
I92	Indigenous People Rights Protection Index	Local Community	Respect of indigenous rights	8.84E-01	5.83E-01	8.58E-01
I93	Internally displaced people	Local Community	Secure living condition	8.18E+00	5.97E+00	7.84E+00
I94	Level of industrial water use (related to renewable water resources)	Local Community	Access to material resources	1.71E+01	8.32E+00	1.72E+01
I95	Level of industrial water use (related to total withdrawal)	Local Community	Access to material resources	1.69E+01	7.74E+00	1.45E+01
I96	Presence of indigenous population	Local Community	Respect of indigenous rights	8.58E-01	6.52E-01	8.43E-01
I97	Waste management	Local Community	Access to material resources	7.70E+00	5.03E+00	5.48E+00
I98	Data protection and privacy	Consumer	Consumer protection	7.12E-01	1.64E-01	6.36E-01
I99	Online Consumer Protection Legislation	Consumer	Consumer protection	2.86E-01	9.91E-03	2.69E-01
I100	Child marriage, female	Children	Children welfare	8.80E+00	6.99E+00	9.30E+00
I101	Child marriage, male	Children	Children welfare	6.08E-01	3.75E-01	6.40E-01
I102	Female genital mutilation 0-14	Children	Children welfare	2.27E-01	1.55E-01	2.22E-01
I103	Mean years of schooling, female	Children	Education	5.79E+00	5.40E+00	5.58E+00
I104	Mean years of schooling, male	Children	Education	5.79E+00	5.40E+00	5.58E+00
I105	Mean years of schooling, total	Children	Education	5.93E+00	5.31E+00	5.71E+00

I106	Under-five mortality rate	Children	Health and Safety	1.46E+00	1.28E+00	1.47E+00

15 Appendix 5 – Results of the relative contributions of process stages to the social hotspots in S2.1

	Impact category (results in med risk hours)	Other Bioliquid Processing requirements	Feedstock Production	HDO (R-104) - energy requirements	Overall replacement	Pyrolysis	Indicator scope
I1	Children in employment, female	5.20E-04	3.41E-01	5.58E-02	8.51E-07	6.78E-01	Sector level
I2	Children in employment, male	6.20E-04	4.04E-01	7.03E-02	8.51E-07	7.23E-01	Sector level
I3	Children in employment, total	6.20E-04	4.04E-01	7.03E-02	8.51E-07	7.23E-01	Sector level
I4	Evidence of violations of laws and employment regulations	6.18E-03	9.73E-01	3.53E+00	8.51E-05	1.08E+01	Sector level
I5	Freedom of association and collective bargaining	6.54E-03	1.03E+00	5.37E-01	8.51E-07	1.67E+00	Country level
I6	Frequency of forced labour	1.07E-02	6.53E+00	4.99E-01	8.51E-07	1.61E+00	Country level
I7	Gender wage gap	1.26E+00	1.17E+00	1.14E+00	8.51E-03	3.47E+00	Sector level
I8	Goods produced by forced labour	1.68E-03	1.03E-01	4.43E-02	8.51E-06	1.39E-01	Sector level
I9	Living wage, per month	1.29E-01	1.44E+00	7.40E-01	8.50E-04	3.42E+00	Country level
I10	Men in the sectoral labour force	1.49E-03	1.02E-01	2.82E-02	8.51E-06	8.91E-02	Sector level
I11	Minimum wage, per month	4.20E-04	1.58E-01	4.50E-02	8.51E-07	6.36E-01	Country level
I12	number of strikes	1.27E+00	4.33E+00	8.72E-01	8.51E-03	3.85E+00	Sector level
I13	Paid maternity leave	1.32E-02	4.16E-01	5.36E-02	8.51E-05	2.81E-01	Country level

I14	Presence of sufficient safety measures	1.26E-02	1.82E-01	3.44E-02	8.51E-06	1.64E-01	Sector level
I15	Rate of fatal accidents at workplace	1.36E-01	2.02E+00	1.17E+00	8.50E-04	3.66E+00	Sector level
I16	Rate of non-fatal accidents at workplace	1.27E+00	2.61E+00	4.36E+00	8.51E-03	1.34E+01	Sector level
I17	Sector average wage, per month	1.27E+00	5.42E+00	3.82E+00	8.51E-03	1.29E+01	Sector level
I18	Trade union density	1.31E-01	7.28E-01	4.82E-01	8.50E-04	1.50E+00	Country level
I19	Trafficking in persons	6.60E-03	3.32E+00	6.82E-01	8.51E-06	2.61E+00	Country level
I20	Violations of mandatory health and safety standards	1.29E-01	6.81E-01	2.80E-01	8.50E-04	8.93E-01	Country level
I21	Weekly hours of work per employee female	1.28E-02	8.93E-02	4.72E-02	8.51E-05	1.61E-01	Sector level
I22	Weekly hours of work per employee male	1.28E-02	6.15E-02	4.55E-02	8.51E-05	1.56E-01	Sector level
I23	Women in the sectoral labour force	1.34E-01	1.92E+00	4.07E+00	8.50E-04	1.30E+01	Sector level
I24	Active involvement of enterprises in corruption and bribery	1.41E-02	7.92E-01	1.11E-01	0.00E+00	8.50E-01	Sector level
I25	Presence of anti-competitive behaviour or violation of anti-trust and monopoly legislation	2.98E-03	6.28E-01	1.55E-01	8.51E-06	4.83E-01	Sector level
I26	Public sector corruption	2.05E-03	5.22E-01	8.87E-02	8.51E-06	7.73E-01	Country level
I27	Social responsibility along the supply chain	7.02E-03	3.48E+00	5.66E-01	8.51E-07	1.83E+00	Sector level
I28	Access to electricity	1.40E-04	3.56E-03	6.04E-03	8.51E-07	2.37E-02	Country level

I29	Access to internet	2.90E-04	4.71E-02	2.52E-02	8.51E-07	5.74E-01	Country level
I30	Animal protection	1.43E-02	5.45E-01	4.85E-01	8.51E-05	1.50E+00	Country level
I31	Asylum seekers rate	1.27E-01	6.22E-01	1.10E-01	8.50E-04	1.48E+00	Country level
I32	Biodiversity & Habitat	6.64E-03	1.01E+00	3.63E+00	8.51E-07	1.11E+01	Country level
I33	Contribution to economic development	1.26E-01	1.40E-01	4.85E-02	8.50E-04	2.68E-01	Sector level
I34	Ecosystem services	1.27E+00	1.90E+00	4.58E+00	8.51E-03	1.41E+01	Country level
I35	Embodied value added total	2.62E-03	4.76E-01	7.82E-02	8.51E-05	2.49E-01	Sector level
I36	Emigration rate	1.27E-01	6.27E-01	1.10E-01	8.50E-04	1.48E+00	Country level
I37	Female genital mutilation 15-49	1.40E-03	6.15E-02	2.22E-02	8.51E-06	7.14E-02	Country level
I38	Female with account at a financial institution	2.31E-03	4.72E-01	8.51E-02	8.51E-06	3.82E-01	Country level
I39	Food insecurity	3.80E-04	4.58E-02	3.92E-02	0.00E+00	6.18E-01	Country level
I40	Freedom of the press	6.97E-03	3.33E+00	4.54E-01	8.51E-06	1.92E+00	Country level
I41	Gender inequalities	4.90E-04	1.74E-01	6.18E-02	8.51E-07	6.87E-01	Country level
I42	Global freedom scores	5.06E-03	3.29E+00	3.58E-01	8.51E-07	1.62E+00	Country level
I43	Global Peace Index	8.84E-03	3.84E+00	6.69E-01	8.51E-07	2.59E+00	Country level
I44	Global Terrorism Index	6.12E-03	6.62E-01	2.83E-01	8.51E-06	9.39E-01	Country level
I45	Health expenditure, domestic general government	1.48E-03	8.44E-02	3.42E-02	8.51E-06	1.07E-01	Country level
I46	Health expenditure, external resources	1.29E-03	9.57E-03	7.93E-03	8.51E-06	2.62E-02	Country level
I47	Health expenditure, out-of-pocket	2.62E-03	5.64E-01	1.15E-01	8.51E-06	3.63E-01	Country level

I48	Health expenditure, total	1.09E-03	2.63E-01	2.43E-01	8.51E-07	7.47E-01	Country level
I49	Household air pollution attributable DALYs, female	2.60E-04	5.37E-02	1.64E-02	8.51E-07	1.01E-01	Country level
I50	Household air pollution attributable DALYs, male	1.34E-03	6.74E-01	1.13E-01	8.51E-07	8.51E-01	Country level
I51	Illiteracy rate, female	1.83E-03	1.16E-01	1.16E-01	8.51E-06	8.53E-01	Country level
I52	Illiteracy rate, male	1.42E-03	2.41E-02	6.26E-02	8.51E-06	1.93E-01	Country level
I53	Illiteracy rate, total	1.77E-03	7.25E-02	1.01E-01	8.51E-06	8.05E-01	Country level
I54	Immigration rate	1.27E-01	6.48E-01	1.17E-01	8.50E-04	1.50E+00	Country level
I55	Informal employment, female	1.08E-03	1.68E-01	1.22E-01	8.51E-07	8.74E-01	Sector level
I56	Informal employment, male	1.06E-03	1.59E-01	4.20E-01	8.51E-07	1.78E+00	Sector level
I57	Informal employment, total	1.41E-03	1.52E-01	4.38E-01	8.51E-07	1.84E+00	Sector level
I58	International Migrant Stock	1.28E-01	1.20E+00	2.34E-01	8.50E-04	1.86E+00	Country level
I59	International migrant workers in the sector	1.27E+00	2.28E+00	9.30E-01	8.51E-03	4.00E+00	Sector level
I60	Internet freedom scores	4.83E-03	3.15E+00	3.32E-01	8.51E-07	1.54E+00	Country level
I61	Labour productivity	2.70E-04	3.35E-02	2.07E-02	8.51E-07	1.14E-01	Country level
I62	Life expectancy at birth	7.90E-04	1.57E-01	5.24E-01	8.51E-07	2.10E+00	Country level
I63	Net migration rate	2.66E-03	5.13E-01	1.49E-01	8.51E-06	4.74E-01	Country level
I64	Number of threatened species	2.68E-02	9.62E-01	3.37E+00	8.51E-03	1.14E+01	Sector level
I65	Political stability and absence of violence	1.73E-02	3.31E+00	4.04E-01	8.51E-05	1.76E+00	Country level

I66	Pollution level of the country	8.69E-03	3.56E+00	2.96E-01	8.51E-06	9.67E-01	Country level
I67	Population below national poverty line	2.12E-03	8.88E-02	5.25E-01	8.51E-06	2.10E+00	Country level
I68	Public expenditure on education	1.34E-02	3.79E-01	1.14E-01	8.51E-05	3.63E-01	Country level
I69	R&D expenditures	4.00E-04	9.47E-02	5.52E-02	8.51E-07	1.78E-01	Country level
I70	Rate of researchers	1.92E-03	1.11E-01	1.30E-01	8.51E-06	4.00E-01	Country level
I71	Safe access to Drinking water coverage	3.60E-04	9.66E-02	1.87E-02	8.51E-07	5.99E-02	Country level
I72	Sanitation coverage	2.87E-02	7.10E+00	1.29E+00	8.51E-05	4.54E+00	Country level
I73	Social Protection Expenditures	2.30E-04	2.83E-02	1.57E-02	8.51E-07	5.45E-01	Country level
I74	State of democracy	3.60E-04	1.32E-01	3.26E-02	8.51E-07	5.98E-01	Country level
I75	Unemployment rate in the country	1.27E+00	4.51E+00	1.80E+00	8.51E-03	5.56E+00	Country level
I76	Youth illiteracy rate, female	3.00E-04	5.55E-02	2.14E-02	8.51E-07	6.77E-02	Country level
I77	Youth illiteracy rate, male	1.52E-03	6.84E-02	9.70E-02	8.51E-06	2.98E-01	Country level
I78	Youth illiteracy rate, total	3.80E-04	6.51E-02	9.62E-02	8.51E-07	2.96E-01	Country level
I79	Youth unemployment	2.42E-03	2.60E-01	5.67E-01	8.51E-06	2.23E+00	Country level
I80	Certified environmental management systems	5.48E-03	3.50E+00	4.96E-01	8.51E-07	1.61E+00	Sector level
I81	Embodied agricultural area footprint	1.30E-04	1.40E-03	5.60E-04	0.00E+00	4.98E-01	Sector level
I82	Embodied CO2 footprint	3.51E-03	2.73E+00	6.81E-01	8.51E-06	2.10E+00	Sector level
I83	Embodied CO2-eq footprint	8.02E-03	3.06E+00	3.87E+00	8.51E-06	1.18E+01	Sector level
I84	Embodied forest area footprint	9.45E-07	9.05E-05	3.73E-05	0.00E+00	1.20E-04	Sector level
I85	Embodied water footprint	1.92E-03	9.65E-01	1.99E-01	8.51E-07	1.12E+00	Sector level

I86	Extraction of biomass (related to area)	1.29E-01	1.10E+00	8.42E-01	8.50E-04	3.72E+00	Country level
I87	Extraction of biomass (related to population)	1.33E-01	1.71E+00	3.73E+00	8.50E-04	1.14E+01	Country level
I88	Extraction of fossil fuels	7.77E-03	4.16E+00	1.02E+00	8.51E-06	3.27E+00	Country level
I89	Extraction of industrial and construction minerals	1.59E-02	1.34E+00	4.93E-01	8.51E-05	1.65E+00	Country level
I90	Extraction of ores	2.04E-02	3.93E+00	8.17E-01	8.51E-05	2.55E+00	Country level
I91	Homicides	9.60E-03	1.21E+00	3.99E+00	8.51E-07	1.22E+01	Country level
I92	Indigenous People Rights Protection Index	1.49E-03	1.06E-01	5.80E-02	8.51E-06	1.81E-01	Country level
I93	Internally displaced people	4.24E-03	4.27E-01	2.17E-01	0.00E+00	1.18E+00	Country level
I94	Level of industrial water use (related to renewable water resources)	1.29E-01	1.30E+00	7.81E-01	8.50E-04	3.59E+00	Country level
I95	Level of industrial water use (related to total withdrawal)	1.32E-01	4.29E+00	6.11E-01	8.50E-04	3.05E+00	Country level
I96	Presence of indigenous population	1.29E-02	9.20E-02	5.79E-02	8.51E-05	1.78E-01	Country level
I97	Waste management	4.62E-03	3.25E+00	3.68E-01	8.51E-07	1.16E+00	Country level
I98	Data protection and privacy	3.80E-04	1.51E-01	4.35E-02	8.51E-07	1.34E-01	Country level
I99	Online Consumer Protection Legislation	2.50E-04	4.29E-02	1.72E-02	8.51E-07	5.64E-02	Country level
I100	Child marriage, female	8.30E-04	1.17E-01	6.12E-01	8.51E-07	1.92E+00	Country level
I101	Child marriage, male	2.50E-04	1.54E-02	4.42E-02	8.51E-07	1.35E-01	Country level

I102	Female genital mutilation 0-14	1.34E-03	2.45E-02	1.43E-02	8.51E-06	4.64E-02	Country level
I103	Mean years of schooling, female	1.89E-03	6.70E-02	6.62E-02	8.51E-06	7.01E-01	Country level
I104	Mean years of schooling, male	1.89E-03	6.70E-02	6.62E-02	8.51E-06	7.01E-01	Country level
I105	Mean years of schooling, total	1.89E-03	9.52E-02	7.44E-02	8.51E-06	7.27E-01	Country level
I106	Under-five mortality rate	3.20E-04	4.93E-02	6.97E-02	8.51E-07	2.63E-01	Country level

16 Appendix 6 – Results of the relative contributions of process stages to the social hotspots in S2.1

	Impact category	Stage 1: Feedstock Production	Stage 3: Pyrolysis	Stage 4.3: Gas fraction Processing	Replacement	Indicator scope
I1	Children in employment, female	4.20E-01	8.42E-01	-2.64E-01	9.61E-07	Sector level
I2	Children in employment, male	4.97E-01	8.95E-01	-3.09E-01	9.61E-07	Sector level
I3	Children in employment, total	4.97E-01	8.95E-01	-3.09E-01	9.61E-07	Sector level
I4	Evidence of violations of laws and employment regulations	1.20E+00	1.26E+01	1.23E+00	9.61E-05	Sector level
I5	Freedom of association and collective bargaining	1.27E+00	1.95E+00	4.93E-01	9.61E-07	Country level
I6	Frequency of forced labour	8.04E+00	1.88E+00	-7.05E+00	9.61E-07	Country level
I7	Gender wage gap	1.44E+00	4.05E+00	1.22E+00	9.61E-03	Sector level
I8	Goods produced by forced labour	1.27E-01	1.62E-01	1.47E-01	9.61E-06	Sector level
I9	Living wage, per month	1.77E+00	3.98E+00	2.00E+00	9.60E-04	Country level
I10	Men in the sectoral labour force	1.26E-01	1.04E-01	9.58E-02	9.61E-06	Sector level
I11	Minimum wage, per month	1.95E-01	7.93E-01	8.53E-02	9.61E-07	Country level
I12	number of strikes	5.33E+00	4.49E+00	1.58E+00	9.61E-03	Sector level
I13	Paid maternity leave	5.12E-01	3.28E-01	-7.48E-01	9.61E-05	Country level

I14	Presence of sufficient safety measures	2.25E-01	1.96E-01	1.38E-01	9.61E-06	Sector level
I15	Rate of fatal accidents at workplace	2.49E+00	4.28E+00	-1.51E-01	9.60E-04	Sector level
I16	Rate of non-fatal accidents at workplace	3.22E+00	1.57E+01	3.23E+00	9.61E-03	Sector level
I17	Sector average wage, per month	6.68E+00	1.50E+01	2.87E+00	9.61E-03	Sector level
I18	Trade union density	8.97E-01	1.74E+00	8.90E-01	9.60E-04	Country level
I19	Trafficking in persons	4.08E+00	3.10E+00	-7.86E+00	9.61E-06	Country level
I20	Violations of mandatory health and safety standards	8.39E-01	1.04E+00	3.80E-01	9.60E-04	Country level
I21	Weekly hours of work per employee female	1.10E-01	1.88E-01	-3.87E-02	9.61E-05	Sector level
I22	Weekly hours of work per employee male	7.58E-02	1.82E-01	4.25E-02	9.61E-05	Sector level
I23	Women in the sectoral labour force	2.37E+00	1.52E+01	3.11E-01	9.60E-04	Sector level
I24	Active involvement of enterprises in corruption and bribery	9.75E-01	1.04E+00	-3.05E-01	1.62E-14	Sector level
I25	Presence of anti-competitive behaviour or violation of anti-trust and monopoly legislation	7.73E-01	5.63E-01	-5.41E-01	9.61E-06	Sector level
I26	Public sector corruption	6.44E-01	9.53E-01	-6.77E-01	9.61E-06	Country level
I27	Social responsibility along the supply chain	4.29E+00	2.14E+00	1.03E+00	9.61E-07	Sector level
I28	Access to electricity	4.39E-03	2.82E-02	3.11E-03	9.61E-07	Country level
I29	Access to internet	5.80E-02	7.22E-01	7.59E-02	9.61E-07	Country level
I30	Animal protection	6.72E-01	1.75E+00	-5.94E-01	9.61E-05	Country level
I31	Asylum seekers rate	7.67E-01	1.72E+00	5.24E-01	9.60E-04	Country level
I32	Biodiversity & Habitat	1.24E+00	1.29E+01	-7.91E-02	9.61E-07	Country level
I33	Contribution to economic development	1.72E-01	3.13E-01	1.74E-01	9.60E-04	Sector level
I34	Ecosystem services	2.34E+00	1.64E+01	5.45E-03	9.61E-03	Country level
I35	Embodied value added total	5.87E-01	2.91E-01	1.01E-01	9.61E-05	Sector level
I36	Emigration rate	7.72E-01	1.72E+00	1.97E+00	9.60E-04	Country level
I37	Female genital mutilation 15-49	7.58E-02	8.33E-02	2.78E-02	9.61E-06	Country level
I38	Female with account at a financial institution	5.82E-01	4.45E-01	2.74E-01	9.61E-06	Country level

I39	Food insecurity	5.65E-02	7.73E-01	3.00E-01	1.60E-14	Country level
I40	Freedom of the press	4.11E+00	2.29E+00	-7.55E+00	9.61E-06	Country level
I41	Gender inequalities	2.14E-01	8.53E-01	1.46E-01	9.61E-07	Country level
I42	Global freedom scores	4.05E+00	1.95E+00	-7.89E+00	9.61E-07	Country level
I43	Global Peace Index	4.73E+00	3.07E+00	-7.45E+00	9.61E-07	Country level
I44	Global Terrorism Index	8.16E-01	1.10E+00	1.55E-01	9.61E-06	Country level
I45	Health expenditure, domestic general government	1.04E-01	1.24E-01	2.31E-01	9.61E-06	Country level
I46	Health expenditure, external resources	1.18E-02	3.06E-02	9.62E-03	9.61E-06	Country level
I47	Health expenditure, out-of-pocket	6.95E-01	4.24E-01	4.16E-01	9.61E-06	Country level
I48	Health expenditure, total	3.24E-01	8.72E-01	3.41E-01	9.61E-07	Country level
I49	Household air pollution attributable DALYs, female	6.62E-02	1.23E-01	5.86E-02	9.61E-07	Country level
I50	Household air pollution attributable DALYs, male	8.31E-01	1.04E+00	-6.36E-01	9.61E-07	Country level
I51	Illiteracy rate, female	1.43E-01	1.05E+00	3.70E-01	9.61E-06	Country level
I52	Illiteracy rate, male	2.98E-02	2.25E-01	4.74E-02	9.61E-06	Country level
I53	Illiteracy rate, total	8.93E-02	9.91E-01	3.28E-01	9.61E-06	Country level
I54	Immigration rate	7.98E-01	1.75E+00	1.98E+00	9.60E-04	Country level
I55	Informal employment, female	2.07E-01	1.07E+00	4.18E-01	9.61E-07	Sector level
I56	Informal employment, male	1.96E-01	2.13E+00	1.37E-01	9.61E-07	Sector level
I57	Informal employment, total	1.87E-01	2.19E+00	3.80E-01	9.61E-07	Sector level
I58	International Migrant Stock	1.48E+00	2.17E+00	1.05E+00	9.60E-04	Country level
I59	International migrant workers in the sector	2.81E+00	4.67E+00	2.30E+00	9.61E-03	Sector level
I60	Internet freedom scores	3.88E+00	1.85E+00	-7.95E+00	9.61E-07	Country level
I61	Labour productivity	4.13E-02	1.38E-01	4.43E-02	9.61E-07	Country level
I62	Life expectancy at birth	1.94E-01	2.50E+00	1.83E-02	9.61E-07	Country level
I63	Net migration rate	6.33E-01	5.53E-01	1.61E+00	9.61E-06	Country level
I64	Number of threatened species	1.19E+00	1.33E+01	-6.52E-02	9.61E-03	Sector level
I65	Political stability and absence of violence	4.08E+00	2.10E+00	-7.96E+00	9.61E-05	Country level

I66	Pollution level of the country	4.38E+00	1.13E+00	1.29E+00	9.61E-06	Country level
I67	Population below national poverty line	1.09E-01	2.50E+00	8.23E-02	9.61E-06	Country level
I68	Public expenditure on education	4.67E-01	4.24E-01	-6.86E-01	9.61E-05	Country level
I69	R&D expenditures	1.17E-01	2.07E-01	5.05E-02	9.61E-07	Country level
I70	Rate of researchers	1.37E-01	4.67E-01	1.42E-01	9.61E-06	Country level
I71	Safe access to Drinking water coverage	1.19E-01	6.99E-02	-2.35E-02	9.61E-07	Country level
I72	Sanitation coverage	8.74E+00	5.35E+00	-5.86E+00	9.61E-05	Country level
I73	Social Protection Expenditures	3.49E-02	6.88E-01	6.52E-02	9.61E-07	Country level
I74	State of democracy	1.63E-01	7.50E-01	8.85E-02	9.61E-07	Country level
I75	Unemployment rate in the country	5.56E+00	6.48E+00	2.12E+00	9.61E-03	Country level
I76	Youth illiteracy rate, female	6.84E-02	7.90E-02	7.41E-02	9.61E-07	Country level
I77	Youth illiteracy rate, male	8.42E-02	3.48E-01	7.07E-02	9.61E-06	Country level
I78	Youth illiteracy rate, total	8.02E-02	3.45E-01	7.78E-02	9.61E-07	Country level
I79	Youth unemployment	3.20E-01	2.65E+00	1.83E-01	9.61E-06	Country level
I80	Certified environmental management systems	4.32E+00	1.88E+00	-8.05E+00	9.61E-07	Sector level
I81	Embodied agricultural area footprint	1.72E-03	6.33E-01	4.20E-04	-1.11E-16	Sector level
I82	Embodied CO2 footprint	3.37E+00	2.45E+00	-7.44E+00	9.61E-06	Sector level
I83	Embodied CO2-eq footprint	3.77E+00	1.38E+01	-7.28E+00	9.61E-06	Sector level
I84	Embodied forest area footprint	1.10E-04	1.40E-04	9.31E-05	1.04E-17	Sector level
I85	Embodied water footprint	1.19E+00	1.36E+00	1.15E+00	9.61E-07	Sector level
I86	Extraction of biomass (related to area)	1.36E+00	4.33E+00	1.19E+00	9.60E-04	Country level
I87	Extraction of biomass (related to population)	2.11E+00	1.33E+01	-5.10E-01	9.60E-04	Country level
I88	Extraction of fossil fuels	5.13E+00	3.82E+00	-8.06E+00	9.61E-06	Country level
I89	Extraction of industrial and construction minerals	1.66E+00	1.92E+00	-2.92E-01	9.61E-05	Country level
I90	Extraction of ores	4.85E+00	2.98E+00	1.38E-01	9.61E-05	Country level
I91	Homicides	1.49E+00	1.43E+01	9.14E-02	9.61E-07	Country level
I92	Indigenous People Rights Protection Index	1.31E-01	2.11E-01	-8.18E-02	9.61E-06	Country level

I93	Internally displaced people	5.26E-01	1.42E+00	6.20E-01	8.24E-14	Country level
I94	Level of industrial water use (related to renewable water resources)	1.60E+00	4.19E+00	5.25E-01	9.60E-04	Country level
I95	Level of industrial water use (related to total withdrawal)	5.29E+00	3.55E+00	-6.08E+00	9.60E-04	Country level
I96	Presence of indigenous population	1.13E-01	2.07E-01	-4.39E-02	9.61E-05	Country level
I97	Waste management	4.01E+00	1.35E+00	-8.05E+00	9.61E-07	Country level
I98	Data protection and privacy	1.86E-01	1.57E-01	8.57E-02	9.61E-07	Country level
I99	Online Consumer Protection Legislation	5.29E-02	6.59E-02	3.07E-02	9.61E-07	Country level
I100	Child marriage, female	1.44E-01	2.24E+00	1.01E-01	9.61E-07	Country level
I101	Child marriage, male	1.89E-02	1.58E-01	1.85E-02	9.61E-07	Country level
I102	Female genital mutilation 0-14	3.02E-02	5.41E-02	9.34E-03	9.61E-06	Country level
I103	Mean years of schooling, female	8.26E-02	8.70E-01	1.25E-01	9.61E-06	Country level
I104	Mean years of schooling, male	8.26E-02	8.70E-01	1.25E-01	9.61E-06	Country level
I105	Mean years of schooling, total	1.17E-01	9.00E-01	3.26E-01	9.61E-06	Country level
I106	Under-five mortality rate	6.08E-02	3.12E-01	6.81E-02	9.61E-07	Country level