S.Chandrasekaran

# BRIDGING TECHNOLOGY AND SOCIETY (BTS)

## Towards context-specific, inclusive, and sustainable design of bio-based value chains for marine biofuels

# Propositions

accompanying the dissertation

## *Bridging Technology and Society (BTS)*
### *Towards context-specific, inclusive, and sustainable design of bio-based value chains for marine biofuels*

By

*Sivaramakrishnan Chandrasekaran*

1. While designing any socio-technical system, sustainability and inclusivity are a necessity, not a choice. *'This proposition pertains to this dissertation.'*

2. Nature is the ideal system, as it has optimised all processes and techniques over billions of years. Therefore, any alternative solution that mimics or resembles the natural order of the system will be the closest optimal sustainable solution. '*This proposition pertains to this dissertation*.'

3. Biomass, due to its well-known familiarity with humans, has the potential to act as the holy grail of sustainable solutions for it has the potential to provide alternatives across sectors, irrespective of nature (energy, food, pharma, petrochemicals), size (small/large scale), and geographical location (global north/south), by providing tailor-made context-dependent impact (economic, environmental, social, and ecological). '*This proposition pertains to this dissertation.*'

4. Alternative technologies that can benefit and be integrated with existing infrastructure are always more beneficial and impactful than novel, disruptive technologies that require new infrastructural development. '*This proposition pertains to this dissertation.'*

5. Colonisation led to unsustainability! Hence, countries should have border-free targets, efforts, and solutions to address the current "global" and "borderless" challenges, which should promote responsible energy and resource dependency, global development, and equal opportunities.

6. Doctoral candidates who are either expats or people with prior relevant non-academic experience are more suited for multi-disciplinary research.

7. The term Sustainable Development is a paradox. Development always comes at a cost (such as resources, efforts, time, opportunity, privilege, or health), and depends on the necessity of human needs, which are always dynamic, going against the meaning of sustainability – "the ability to be maintained at a certain rate or level."

8. To achieve all the promised sustainability targets, social sciences should be combined with applied sciences at the early stages of education for potential holistic, inclusive, and sustainable skill set development in future professionals.

9. Local cuisine, language, wedding tradition, and regional traits (like festivals or habits) are the 4 pillars for understanding and integrating with a foreign culture.

10. Human nature, such as selfishness, greed, protective instincts, and materialistic love, caused climate change. Without individualistic growth and change, humans will be the biggest hurdle to saving humanity or addressing climate change.

*These propositions are regarded as opposable and defendable, and have been approved as such by the promotors Prof. dr. P. Osseweijer and Prof. dr. J.A. Posada Duque.*

# Bridging Technology and Society (BTS)

Towards context-specific, inclusive, and sustainable design of bio-based value chains for marine biofuels

**Sivaramakrishnan CHANDRASEKARAN**

# Bridging Technology and Society (BTS)

## Towards context-specific, inclusive, and sustainable design of bio-based value chains for marine biofuels

**Dissertation**

For the purpose of obtaining the degree of doctor
at Delft University of Technology
by the authority of the Rector Magnificus prof. dr. ir. T.H.J.J. van der Hagen
chair of the Board for Doctorates
to be defended publicly on
Thursday the 13th of November 2025 at 15:00 o' clock

By

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This dissertation has been approved by the promotors.

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Keywords: Conceptual design, biomass, marine biofuels, hydrothermal liquefaction, techno-economic assessment, environmental life cycle assessment

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This thesis is dedicated to Priya and Melle.

For their healthy and prosperous future!

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# GLOSSARY

| | |
|---|---|
| BBVC | Biobased Value Chain |
| CA | Capability Approach |
| CAPEX | Capital Expenses |
| CCUS | Carbon Capture, Utilisation, and Sequestration |
| $CH_4$ | Methane |
| $CO_2$ | Carbon dioxide |
| CSD | Capability Sensitive Design |
| CTA | Continuous Technical Assessment |
| DTL | Direct Thermal Liquefaction |
| e-LCA | Environmental - Life Cycle Assessment |
| EU | European Union |
| EUR | Euro |
| FDA | Food and Drug Administration |
| GHG | Greenhouse gas |
| HFO | Heavy Fuel Oil |
| HHV | Higher Heating Value |
| HTL | Hydrothermal Liquefaction |
| IEA | International Energy Agency |
| IMO | International Maritime Organization |
| IPCC | Intergovernmental Panel on Climate Change |
| ISA | Integrated Sustainability Assessment |
| KPI | Key Performance Indicator |
| LHV | Lower Heating Value |
| MBF | Marine BioFuel |
| MFSP | Minimum Fuel Selling Price |
| MGO | Marie Gas Oil |
| MM | Midstream Modulation |
| NGO | Non-Governmental Organisation |
| $NO_X$ | Nitrogen oxides |
| OPEX | Operating Expenses |
| PNNL | Pacific Northwest National Laboratory |
| RED | Renewable Energy Directive |
| RRI | Responsible Research and Innovation |
| SAF | Sustainable Aviation Fuel |
| SDG | Sustainable Development Goal |
| SIbD | Sustainable and Inclusive by Design |
| S-LCA | Social Life Cycle Assessment |
| $SO_2$ | Sulfur dioxide |

| | |
|---|---|
| SSbD | Safe and Sustainable by Design |
| STS | Socio-Technical Studies |
| TCR | ThermoCatalytic Reforming |
| TEA | Techno-Economic Assessment |
| TRL | Technology Readiness Level |
| UN | United Nations |
| US | United States |
| USD | United States Dollar |
| VSD | Value Sensitive Design |

*"Each of us lives, dependent, and bound by our individual knowledge and our awareness. All that is what we call "reality". However, both knowledge and awareness are equivocal. One's reality might be another's illusion. We all live inside our own fantasies."* **– Itachi Uchiha, from the anime Naruto**

# SUMMARY

Biobased "drop-in" fuels are considered a short-term to mid-term sustainable alternative to the conventional fossil fuels in the shipping sector. Therefore, there is an urgent need for large-scale, global, commercial biofuel value chains to address the market demand. However, persisting challenges over feedstock supply security, social acceptance, and the low commercial-scale deployment of biorefineries indicate the presence of a blind spot in the conventional perspective on developing biobased solutions, and the need to venture beyond the borders of economic feasibility and the environmental footprint of biobased products. Beyond the prevailing technical challenges, the causes underlying these blind spots include non-technical aspects that are often not considered, overlooked or neglected during the conventional conceptual design process, owing to the single-disciplinary (technical) perspective of conventional design and development approach. These non-technical aspects include local contextual knowledge and the stakeholders' perspectives, needs, skillsets, values, capabilities, and capacities. As a part of any biobased value chain, a (global) socio-technical system, the concept of stakeholder participation and inclusion should also play an important role as the sustainability aspect while developing biobased solutions for achieving a just bioeconomy.

This thesis presents and applies an approach to sustainable and inclusive biobased production systems development. Specifically, this dissertation addresses the problem statement: *"How can we design and evaluate the performance of context-specific sustainable and inclusive bio-based value chains, with a special focus on marine biofuel production through hydrothermal liquefaction (HTL)?"*. To answer the main problem statement, the investigation in this thesis is organised around the incorporation of stakeholders' perspectives and contextual knowledge into the conceptual process and value chain design, along with sustainability assessment. The need, motivation, and background of this research are presented in **Chapter 1**. The novelty of this research, the transdisciplinary approach, the biohub concept, and the systemic case study selection methodology are also discussed in **Chapter 1**. Then, by empirical investigation, the incorporation of social aspects (such as values, capabilities, needs, expectations, goals, etc.) into the development of the technical design of biohub, by local stakeholder inclusion and using existing infrastructures, based on olive residues in Spain, is addressed with special focus on the techno-economic feasibility in **Chapter 2**. In **Chapter 2**, the economic feasibility and technical design aspects of biohubs were investigated for a processing residue in a Global North country with existing infrastructures for residue generation and collection. In **Chapter 3**, to expand on the learnings of **Chapter 2**, the economic and environmental performance of field residue-based biohubs in Global South countries is examined. The goal of **Chapter 3** was to develop context-specific and capability-sensitive biohubs based on underutilised or mismanaged field residues

in Spain, Colombia, and Namibia, along with their economic and environmental performance. In **Chapter 4**, based on the design approach implemented in the three case study locations, the (technical, social, and institutional) challenges and opportunities for implementing sustainable and inclusive biohubs in emerging bioeconomies are discussed. **Chapter 5** provides the overall insights of this research while acknowledging its limitations. Finally, **Chapter 6** discusses the potential avenues for future research, along with proposing a novel design framework for sustainable and inclusive biobased value chain design.

**Chapter 1** of this dissertation presents the motivation, needs, and background of this research. The contribution of the shipping sector to global climate change and the potential for "Drop-in" marine biofuels as an alternative fuel as a short- to mid-term solution is discussed. From a commercial perspective, for a large-scale market demand such as marine biofuels, the sustainability benefits of drop-in biofuels and the recent maturity levels of different thermochemical technologies for drop-in biofuel production are discussed. From a systems perspective, the opportunities and challenges of developing biobased value chains indicate biomass mobilisation and social acceptance to be the major hurdles, especially at large scales, for the global deployment of the bioeconomy. From a social perspective, the conceptual design process of biorefineries is identified to be one of the key means of inclusion of stakeholders, especially the biomass producers. This thesis introduces the concept of biohub as a win-win collaboration between biomass suppliers and biofuel consumers while ensuring benefits at the biomass production, to overcome the previously mentioned challenges. Therefore, a transdisciplinary approach is implemented to validate the concepts proposed in the literature for early-stage inclusion of stakeholders' perspectives for achieving context-specific biohub designs. A novel, holistic, and systemic methodology is presented to selected case studies for empirical investigation. The mismanaged and underutilised residues from the olive sector in Spain, the coffee sector in Colombia, and the encroacher bush sector in Namibia are investigated in this thesis.

In **Chapter 2**, an approach to establish the design space of biohubs with the incorporation of stakeholders' capabilities is presented. The concepts of Value-Sensitive Design (VSD) and Capability Approach (CA) serve as an initial basis for this approach, which is further validated through a case study on marine biofuel production based on olive residues in the Andalusian region of Spain. In a multi-disciplinary team, the Design Propositions (DPs) are derived by participatory techniques and a multi-stakeholder workshop, which considers stakeholders' perspectives and local contextual knowledge, from technical and non-technical aspects. Different conceptual biohub alternatives were designed to accommodate the different choices of design variables made by local stakeholders to achieve a context-specific, sustainable, and capability-sensitive design.

Process models were developed in Aspen Plus for obtaining mass and energy balances for 21 different biohub scenarios based on the design specifications. Finally, the economic feasibility of the designed biohubs was investigated through a techno-economic evaluation. Overall, it was concluded that HTL biofuel systems based on olive residues for marine biofuel production in the Mediterranean region can be an economically viable and environmentally friendly alternative pathway for handling the polluting residue streams for a sustainable future.

A similar approach to **Chapter 2** was followed in **Chapter 3**, however, **Chapter 3** builds upon the insights (such as coprocessing of HTL biocrudes and performing fractionation, use of biochar to satisfy internal process heat) obtained from **Chapter 2** to investigate the biohub design for the valorisation of field residues. The scope was expanded to analyse the potential of biohubs development in three countries with different archetypes for commercialisation. The three case studies considered olive tree pruning in Spain, coffee pulp in Colombia, and encroacher bush in Namibia. The design space was set, and design propositions were obtained using participatory techniques and multi-stakeholder workshops. The sustainability performance of the design alternatives was assessed by performing a techno-economic evaluation and an environmental life cycle assessment. The importance of the influence of context on the biohub designs is highlighted through choices of the design variables, such as scale and location of the biorefinery, feedstock selection, and preprocessing techniques based on the prevailing technical skills of the biomass producers.

**Chapter 4** reflects on the transdisciplinary approach performed across all three case studies to identify the opportunities, bottlenecks, and challenges for biohubs development in emerging bioeconomies, especially from a designer's perspective. The empirical stage of the Value Sensitive Design was taken as the focus of investigation. The design propositions were analysed. Biohub characteristics in terms of design space were compared to elucidate general (such as the possibility to use all types of available residues, a technology with minimum water consumption, choice of biorefinery ownership, etc.) and context-specific characteristics (such as biorefinery products, feedstock preprocessing location, etc.). Based on the Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis of the existing sectors, the enablers (such as maximum value addition near the biomass producing region, marketable anchor product, capacity building, etc.) for commercial implementation at the context site are identified. Furthermore, the context-specific purposes (such as strengthening the existing sector for sustainability, contributing to the local sustainable development goals, improving energy and material security, etc.) for developing biohubs which address the needs of local stakeholders in the three different archetypes of the emerging bioeconomy are discussed, along with their potential conflicts and trade-offs (such as global sustainability vs local sustainability, efficiency vs inclusivity of the biohubs, economies of scale vs economies of scope, etc.). Finally, it is concluded with a recommendation for a transdisciplinary framework for early-stage consideration of non-technical and technical aspects using the concepts of engineering and social sciences for the development and assessment of a circular, inclusive, sustainable, and holistic system that promotes local development by addressing global issues. The framework should incorporate both qualitative and quantitative indicators for truly evaluating the overall performance of the developed systems and for effective representation of the context for decision makers.

**Chapter 5** provides the overall conclusions by presenting the study findings (such as the economic benefit of co-processing, environmental impact of valorising mismanaged or under-utilised biomass, addressing social sustainability by including local stakeholders in co-designing biohubs), and recognising the limitations (such as restriction in case study selection methodology due to the COVID-19 pandemic, use of literature data for process simulations instead of actual experimental data for HTL and upgrading processes).

**Chapter 6** recommends avenues to further strengthen the research and a framework for sustainable and inclusive design practice. It presents an answer to the main problem statement by addressing the three sub-research questions mentioned in **Chapter 1**. Particularly, it is concluded that the early stage consideration of local contextual knowledge and stakeholders' perspectives during the conceptual design of biobased value chains can de-risk the commercialisation pathway by four ways: Firstly, systematic selection of case studies to implement potential marine biofuel biohubs, by providing equal importance to achieving the end product and societal benefits or relevance, while considering the technical (at the level of both product and value chain), social (contextual status-quo), and political sustainability mandates results in identification of potential value chain specific threats and opportunities. Secondly, co-designing biohubs with an understanding of local context and social factors can lead to new feedstock opportunities, benefiting from existing infrastructures and practices, developing a transition pathway with a need for minimal behavioural or systematic changes for the stakeholders involved. Thirdly, context-specific and capability-sensitive biohubs can unlock the mobilisation potential of field residues, which are underutilised or mismanaged, on a large scale while contributing to the development at or near the biomass production site. Finally, with a transdisciplinary and multi-actor approach for co-designing commercial biohubs, the bridge between theory and practice can be addressed, while promoting knowledge exchange and trust building amongst different stakeholders. Further leading to better informed decision-making to address conflicts and tensions for streamlining efforts across farms, regions, sectors, borders, and continents. Based on these findings, a design framework to develop sustainable and inclusive biobased value chains with stakeholder engagement is suggested. The framework combines the aspects of policy (such as the International Maritime Organization (IMO) 2020, Renewable Energy Directive, etc.), commercialisation (such as fuel standards), sustainability (such as economic feasibility, environmental impacts, and social needs), and stakeholder (such as farmers, government, technology providers, etc.) inclusion while developing context-specific biohubs to address global needs. For a more realistic design, the approach involves stakeholder engagement at various stages, from contextual understanding, conceptual design of biobased value chains, to implementation.

Although this study focused on the conceptual stages of design, **Chapter 6** recommends that future work related to techno-economic feasibility and stakeholder inclusion, in terms of opportunities and challenges during the pilot-scale development and commercialisation of technologies, needs to be understood to strengthen the framework for enabling global commercial development of socially just bioeconomies.

# SAMENVATTING

Biobased "drop-in" brandstoffen worden in de scheepvaartsector gezien als een duurzaam alternatief voor conventionele fossiele brandstoffen op de korte tot middellange termijn. Om aan de toenemende marktvraag te voldoen, is er dan ook dringend behoefte aan grootschalige, wereldwijde commerciële waardeketens voor de productie van biobrandstoffen. Desondanks blijven er hardnekkige uitdagingen bestaan op het gebied van leveringszekerheid, maatschappelijke acceptatie en de beperkte commerciële toepassing van bioraffinaderijen. Deze knelpunten wijzen op een blinde vlek in het gangbare perspectief op de ontwikkeling van biobased oplossingen. Er is noodzaak om verder te kijken dan louter economische haalbaarheid en de ecologische voetafdruk van biobased producten. Naast technische obstakels spelen ook niet-technische factoren een cruciale rol—factoren die binnen conventionele, monodisciplinaire (voornamelijk technische) ontwerp- en ontwikkelingsprocessen vaak worden genegeerd, over het hoofd gezien of onderbelicht blijven. Deze niet-technische aspecten omvatten onder andere lokale contextuele kennis, evenals de perspectieven, behoeften, waarden, vaardigheden, kansen en capaciteiten van betrokken stakeholders. Als onlosmakelijk onderdeel van elke biobased waardeketen—op te vatten als een (mondiaal) sociaal-technisch systeem—zou stakeholderparticipatie en -inclusie een fundamentele rol moeten spelen. Alleen zo kan het duurzaamheidsstreven van biobased innovaties bijdragen aan de totstandkoming van een rechtvaardige bio-economie.

Dit proefschrift presenteert en past een benadering toe voor de ontwikkeling van duurzame en inclusieve biobased productiesystemen. Centraal staat de volgende onderzoeksvraag: *"Hoe kunnen we de prestaties van context specifieke, duurzame en inclusieve biobased waardeketens ontwerpen en evalueren, met een specifieke focus op maritieme biobrandstofproductie via hydrothermale liquefactie (HTL)?"*. Om deze hoofdvraag te beantwoorden, is het onderzoek opgebouwd rond de integratie van stakeholderperspectieven en contextuele kennis in het conceptuele ontwerp van waardeketens, gecombineerd met een duurzaamheidsbeoordeling. De motivatie, achtergrond en relevantie van dit onderzoek worden uiteengezet in **hoofdstuk 1**, waarin ook de toegevoegde waarde van het werk, de gehanteerde transdisciplinaire aanpak, het biohub-concept en de methodologie voor systematische selectie van casestudies worden besproken. Op basis van empirisch onderzoek wordt vervolgens onderzocht hoe sociale aspecten—zoals waarden, capaciteiten, behoeften, verwachtingen en doelen—kunnen worden geïntegreerd in het technische ontwerp van biohubs. Dit gebeurt door lokale stakeholders te betrekken en gebruik te maken van bestaande infrastructuren, met als casus de olijfolieproductieketen in Spanje. In **hoofdstuk 2** ligt de focus op de economische haalbaarheid en technische ontwerpkenmerken van biohubs die gebruikmaken van verwerkingsresiduen in een land in het Globale Noorden, waar al infrastructuren voor reststromen bestaan.

**Hoofdstuk 3** bouwt voort op deze inzichten en richt zich op de economische en ecologische prestaties van biohubs gebaseerd op veldresiduen in landen in het Globale Zuiden. Doel is hier het ontwikkelen van context specifieke en capaciteitsgevoelige biohubs in Spanje, Colombia, en Namibië, en het analyseren van hun prestaties. In **hoofdstuk 4** worden, aan de hand van de drie casestudielocaties, de technische, sociale en institutionele uitdagingen én kansen besproken voor de implementatie van duurzame en inclusieve biohubs in opkomende bio-economieën. **Hoofdstuk 5** presenteert de belangrijkste bevindingen van dit onderzoek en erkent tegelijkertijd de beperkingen ervan. Tot slot bespreekt **hoofdstuk 6** mogelijke richtingen voor toekomstig onderzoek en introduceert het een nieuw ontwerpkader voor duurzame en inclusieve biobased waardeketens.

**Hoofdstuk 1** van dit proefschrift presenteert de motivatie, achtergrond en onderzoeksvragen die ten grondslag liggen aan dit werk. Daarbij wordt ingegaan op de bijdrage van de scheepvaartsector aan de wereldwijde klimaatverandering en op het potentieel van "drop-in" maritieme biobrandstoffen als duurzaam alternatief voor conventionele brandstoffen op de korte tot middellange termijn. Vanuit commercieel perspectief worden de duurzaamheidsvoordelen van drop-in biobrandstoffen besproken, evenals de recente technologische vooruitgang op het gebied van verschillende thermochemische conversieroutes voor de productie ervan. Vanuit een systeemperspectief wordt duidelijk dat, ondanks de technologische rijpheid, de grootschalige implementatie van biobased waardeketens wordt belemmerd door uitdagingen rondom biomassa-mobilisatie en maatschappelijke acceptatie, vooral bij mondiale opschaling binnen de bio-economie. Vanuit maatschappelijk oogpunt wordt het conceptuele ontwerpproces van bioraffinaderijen beschouwd als een cruciale mogelijkheid om stakeholders, en in het bijzonder biomassaproducenten, actief te betrekken. In dit kader introduceert het proefschrift het concept van de biohub, een samenwerkingsmodel dat gericht is op het creëren van wederzijds voordeel tussen biomassaleveranciers en biobrandstofafnemers. Hierbij worden opbrengsten voor lokale biomassaproducenten expliciet geborgd, om zo de eerder genoemde knelpunten aan te pakken. Om deze benadering te operationaliseren, wordt een transdisciplinaire onderzoeksaanpak gehanteerd die de in de literatuur voorgestelde concepten in de praktijk toetst. Hierbij staat het vroegtijdig integreren van stakeholderperspectieven centraal bij het ontwerpen van context specifieke biohubs. Hoofdstuk 1 presenteert tevens een nieuwe, holistische en systemische methodologie voor de uitvoering van empirisch onderzoek aan de hand van zorgvuldig geselecteerde case studies. In dit proefschrift worden drie reststroomgebaseerde waardeketens onderzocht: de onderbenutte olijfresiduen in Spanje, koffiereststromen in Colombia en de biomassa op basis van woekergewas in Namibië.

In **hoofdstuk 2** wordt een aanpak gepresenteerd voor het verkennen van de ontwerpruimte van biohubs, met expliciete aandacht voor de capaciteiten en behoeften van betrokken stakeholders. De methodologische basis wordt gevormd door de concepten *Value-Sensitive Design* (VSD) en de *Capability Approach* (CA). Deze benadering wordt gevalideerd aan de hand van een case studie gericht op de productie van maritieme biobrandstoffen uit olijfresiduen in Andalusië in Spanje. Binnen een multidisciplinair onderzoeksteam zijn ontwerpvoorstellen (*Design Proposals*, DP's) ontwikkeld met behulp van participatieve methoden, waaronder een multi-stakeholder workshop. Hierbij is systematisch gebruikgemaakt van zowel technische als niet-technische inzichten, waaronder lokale contextuele kennis en stakeholderperspectieven. Op basis daarvan zijn meerdere conceptuele alternatieven voor biohubs ontworpen, die inspelen op uiteenlopende voorkeuren voor ontwerpvariabelen van lokale stakeholders. Het doel was om te komen tot context specifieke, duurzame en capaciteitsgevoelige ontwerpen voor de biohubs. Voor 21 verschillende biohub scenario's zijn procesmodellen opgesteld in Aspen Plus om massa- en energiebalansen te berekenen op basis van de vastgestelde ontwerpspecificaties. Aansluitend is een technisch-economische evaluatie uitgevoerd om de economische haalbaarheid van de voorgestelde biohubs te beoordelen. Uit de resultaten blijkt dat HTL-gebaseerde biobrandstofsystemen op basis van olijfresten een economisch haalbaar en milieuvriendelijk alternatief kunnen bieden voor de verwerking van vervuilende reststromen in het Middellandse Zeegebied, en zo kunnen bijdragen aan een duurzamere toekomst.

**Hoofdstuk 3** bouwt voort op de aanpak en inzichten uit **hoofdstuk 2**, maar past deze toe op een bredere en meer gevarieerde context. De lessen uit **hoofdstuk 2**, zoals het coprocessen van ruwe HTL-bio-olie, fractionering van eindproducten en het gebruik van biochar voor interne warmteopwekking, vormen de basis voor het verder ontwikkelen van biohub ontwerpen gericht op de valorisatie van veldresiduen. De scope van het onderzoek wordt in dit hoofdstuk verbreed naar drie landen met uiteenlopende commerciële archetypen, om zo het potentieel van biohub ontwikkeling in verschillende contexten te analyseren. De case studies richten zich op drie typen veldresiduen: snoeihout van olijfbomen in Spanje, koffiepulp in Colombia en overwoekerende struiken (*bush encroachment*) in Namibië. De ontwerpruimte werd verkend en ontwerpvoorstellen werden ontwikkeld via participatieve methoden en multi-stakeholder workshops. De duurzaamheidsprestaties van de verschillende ontwerpvarianten zijn beoordeeld met behulp van een technisch-economische analyse en een milieugerichte levenscyclusanalyse. Het onderzoek benadrukt het belang van context specifiek ontwerp. Factoren zoals de schaal en locatie van de bioraffinaderij, de keuze van grondstoffen, en de toegepaste voorbehandelingstechnieken bleken sterk afhankelijk van de lokale omstandigheden, waaronder de technische vaardigheden van de biomassaproducenten en de beschikbaarheid van infrastructuur.

**Hoofdstuk 4** reflecteert op de transdisciplinaire aanpak die in alle drie case studies is toegepast, met als doel het identificeren van kansen, knelpunten en uitdagingen voor de ontwikkeling van biohubs in opkomende bio-economieën, in het bijzonder vanuit het perspectief van ontwerpers. De focus ligt op de empirische fase van het *Value Sensitive Design*-proces, waarbij de gegenereerde ontwerpvoorstellen systematisch zijn geanalyseerd. De ontwerpkenmerken van de biohubs worden met elkaar vergeleken om zowel generieke elementen, zoals het vermogen om verschillende soorten residuen te verwerken, het gebruik van technologieën met laag waterverbruik, en eigendomsvormen van de bioraffinaderij, als context specifieke elementen zoals het type eindproducten of de locatie van de voorverwerking van de grondstof te identificeren. Op basis van een *SWOT*-analyse van de bestaande sectoren in de drie contexten worden cruciale factoren voor commerciële implementatie vastgesteld. Dit omvat onder meer maximale waarde toevoeging nabij de regio's waar biomassa wordt geproduceerd, de aanwezigheid van een verhandelbaar ankerproduct, en mogelijkheden voor capaciteitsopbouw. Daarnaast worden context specifieke doelstellingen geformuleerd, zoals het versterken van bestaande sectoren ten behoeve van duurzaamheid, het bijdragen aan lokale duurzame ontwikkelingsdoelen, en het verbeteren van energie- en materiaalsecuriteit. Het hoofdstuk belicht ook de spanningen en afwegingen die gepaard gaan met biohub ontwikkeling, waaronder mondiale versus lokale duurzaamheidsdoelen, efficiëntie versus inclusiviteit, en schaalvoordelen versus scopevoordelen. Tot slot wordt een aanbeveling gedaan voor een transdisciplinair kader dat niet-technische en technische aspecten vanaf de ontwerpfase integreert. Dit kader combineert inzichten uit de technische en sociale wetenschappen en beoogt de ontwikkeling en beoordeling van circulaire, inclusieve en duurzame systemen die mondiale problemen adresseren én lokale ontwikkeling stimuleren. Essentieel binnen dit kader is het gebruik van zowel kwalitatieve als kwantitatieve indicatoren, om de prestaties van de ontwikkelde systemen effectief te evalueren en relevantie voor de context zichtbaar te maken voor beleidsmakers en andere besluitvormers.

**Hoofdstuk 5** presenteert de algemene conclusies van het onderzoek, waarbij de belangrijkste bevindingen worden samengebracht en de beperkingen kritisch worden besproken. Tot de belangrijkste inzichten behoren onder andere: het economische voordeel van het co-processen van ruwe HTL-bio-olie, de positieve milieueffecten van het valoriseren van slecht beheerde of onderbenutte biomassa, en het belang van sociale duurzaamheid door middel van actieve betrokkenheid van lokale stakeholders bij het ontwerp van biohubs. Tegelijkertijd worden ook de beperkingen van het onderzoek erkend. Een belangrijke methodologische beperking betreft de selectie van case studies, die deels werd beïnvloed door reis- en contactbeperkingen tijdens de COVID-19-pandemie. Daarnaast is in het procesontwerp gebruikgemaakt van literatuurdata in plaats van experimentele gegevens voor HTL-processen en upgradingtechnologieën, wat invloed kan hebben gehad op de nauwkeurigheid van de simulaties en de economische en milieutechnische evaluaties.

**Hoofdstuk 6** doet aanbevelingen voor de verdere versterking van dit onderzoek en introduceert een kader voor duurzame en inclusieve ontwerpprocessen. Dit hoofdstuk beantwoordt de centrale probleemstelling door in te gaan op de drie deelvragen die in **hoofdstuk 1** zijn geformuleerd. Er wordt geconcludeerd dat het vroegtijdig betrekken van lokale contextuele kennis en stakeholderperspectieven in het conceptuele ontwerp van biobased waardeketens de risico's van commercialisering op vier manieren kan verkleinen. Ten eerste, een systematische benadering van case studie selectie, waarin zowel het behalen van het eindproduct als de maatschappelijke relevantie centraal staan, helpt bij het identificeren van waardeketen-specifieke kansen en uitdagingen. Deze aanpak houdt expliciet rekening met technische factoren (op product- en waardeketenniveau), sociale aspecten (zoals de contextuele status quo) en politieke duurzaamheidsdoelstellingen. Ten tweede, het het gezamenlijk ontwerpen van biohubs, met aandacht voor de lokale context en sociale factoren, kan nieuwe mogelijkheden identificeren voor het gebruik van grondstoffen. Door bestaande infrastructuren en praktijken optimaal te benutten, ontstaat een transitiepad dat minimale gedrags- of systeemveranderingen vereist van de betrokken stakeholders. Ten derde, een context specifieke en capaciteitsgevoelige benadering maakt het mogelijk om het mobilisatiepotentieel van onderbenutte of verkeerd beheerde veldresiduen op grotere schaal aan te boren. Dit draagt tegelijkertijd bij aan sociaaleconomische ontwikkeling in en rond biomassa producerende regio's. Ten slotte bevordert een transdisciplinaire en multi-stakeholderbenadering voor het gezamenlijk ontwerpen van commerciële biohubs de kennisdeling en vertrouwensopbouw tussen verschillende stakeholders. Dit verkleint de kloof tussen theorie en praktijk en ondersteunt geïnformeerde besluitvorming, waarmee conflicten en spanningen beter beheerst kunnen worden—binnen en tussen landbouwsystemen, regio's, sectoren en zelfs continenten. Op basis van deze inzichten wordt een integraal ontwerpkader voorgesteld voor de ontwikkeling van duurzame en inclusieve biobased waardeketens met actieve betrokkenheid van stakeholders. Dit kader combineert beleidsaspecten (zoals IMO 2020 en de Richtlijn Hernieuwbare Energie), commerciële vereisten (zoals brandstofspecificaties), duurzaamheidscriteria (zoals economische haalbaarheid, milieu-impact en sociale relevantie) en inclusieve participatie van stakeholders (zoals boeren, overheden, en technologieaanbieders). Het kader biedt handvatten voor het ontwerpen van context specifieke biohubs die inspelen op mondiale uitdagingen.

Hoewel dit proefschrift zich richt op de vroege, conceptuele fasen van het ontwerp, onderstreept **hoofdstuk 6** dat toekomstige studies zich ook moeten richten op de technische en commerciële haalbaarheid van biohub concepten op pilotschaal. Dit is essentieel om het voorgestelde kader verder te valideren en de wereldwijde, sociaal rechtvaardige ontwikkeling van de bio-economie te ondersteunen.


"If you want to walk fast, walk alone. But if you want to walk far, walk together"- Ratan Tata


I

# 1

# General Introduction

## 1.1 MOTIVATION

In the 21st century, Climate change is the biggest threat to humanity [1]. The Intergovernmental Panel on Climate Change (IPCC) Working Group 1 report, released in August 2021, supports the statement by providing a reality check on the *status quo* and anthropogenic activities' potential long-lasting and irreversible implications [2]. Some of these implications are severe drought, extreme weather patterns, floods, biodiversity loss, and sea level rise. The United Nations (UN) Secretary-General, António Guterres, referred to the message from the IPCC report as *"Code Red for Humanity",* indicating *"irrefutable"* evidence of human influence [3]. Since the Industrial Revolution, various anthropogenic activities, based on fossil fuel sources, have led to an increase in the concentration of atmospheric greenhouse gases (GHGs), mainly Carbon dioxide ($CO_2$), Methane ($CH_4$), Sulfur dioxide ($SO_2$), and nitrogen oxides ($NO_X$). These gases, by trapping the solar radiation in the Earth's atmosphere, cause a rise in surface air temperatures, also known as global warming. Left unchecked, the current trend in human activities, in the form of the production and consumption of materials and energy, will significantly increase global warming, affecting all life on Earth [4]. As shown in *Figure 1.1*, in 2023, six out of nine planetary boundaries assessed have already exceeded the threshold limit under which humanity can sustainably develop and thrive for generations to come. Furthermore, the expected rise in global population up to 10 billion by 2050 will only intensify the pressure on the demand for finite resources available on Earth for sustaining life.

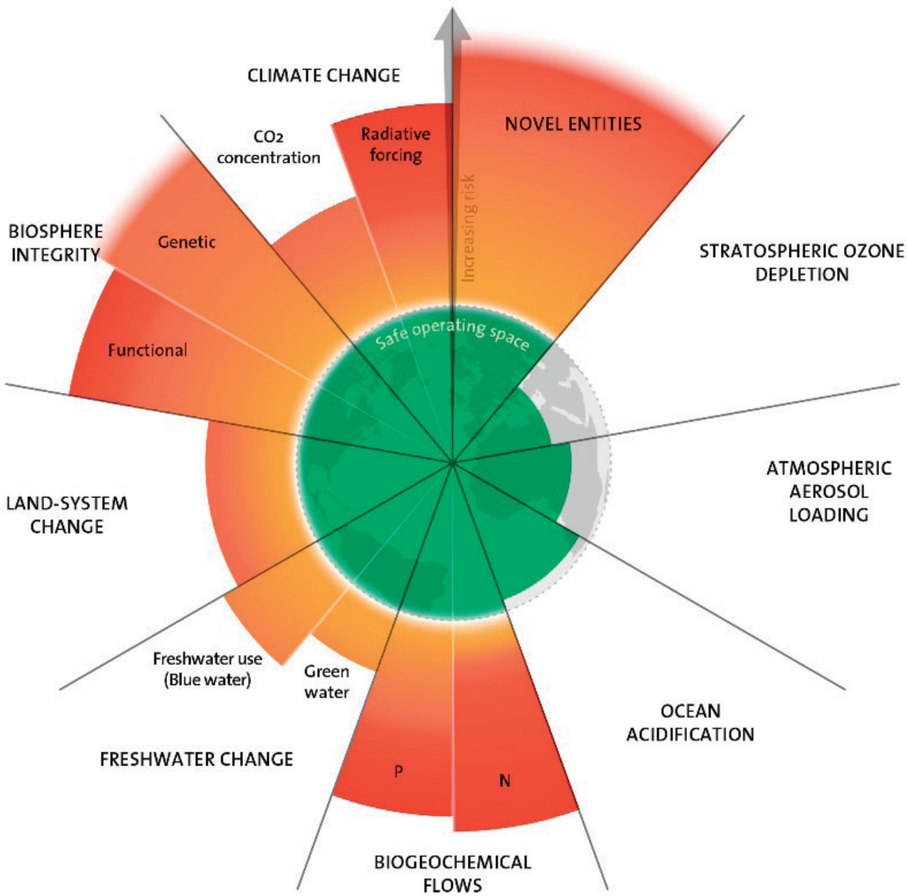


Figure 1.1: Human activities impact on the planetary boundaries as of 2023. Source: Azote for Stockholm Resilience Centre, based on analysis in Richardson et al. (2023) [4]

Globally, to combat climate change, various treaties and strategic goals, such as the Paris Climate Agreement [5] and the European Union (EU) Green Deal [6], have been set to achieve significant greenhouse gas reduction from numerous sectors to limit the rise of global temperatures to 1.5°C above pre-industrial levels. Hence, it is the need of the hour for various novel, holistic, sustainable, inclusive, and innovative strategies to reduce GHG emissions, and efficient resource utilisation by transitioning into a circular and fossil-free economy.

### 1.1.1 Role of the Transportation Sector in Climate Change

Regarding sectoral contribution, since modern globalisation, the transportation sector is the second leading source of greenhouse gas emissions, after electricity and heat [7]. In 2021, the global GHG emissions from the transportation sector accounted for 7.84

billion tons of carbon dioxide equivalents over a 100-year timescale [7]. In 2022, the global fossil-related emissions from the transportation sector increased to 7.95 billion tons of carbon dioxide equivalents, with road transportation accounting for 74% of the total emissions, followed by maritime (11.2%), aviation (9.8%), pipeline (4%), and railways (1%) [8]. Therefore, sustainable transport, which includes replacing fossil-based fuels with renewable alternatives in the transportation sector, can significantly contribute to climate change mitigation and adaptation.

Some of the renewable alternatives to fossil fuels in the transportation sector include electrification, biofuels (bioethanol, biogas, and biodiesel), methanol, ammonia, and hydrogen [9]. Each of the aforementioned alternatives has dedicated advantages and disadvantages in terms of technical, economic, environmental, and social aspects for global commercial implementation based on the targeted segment. For instance, in the road segment, decarbonisation strategies such as electrification and hydrogen are seen as potential alternatives for achieving an emission-free fleet [10]. Similarly, railways are predominantly electrified across the globe, which can be inferred from their share of GHG emissions [11]. On the contrary, unlike road and rail segments, which are either over short distances or integrated with electricity infrastructure, aviation and maritime segments are considered to be "hard to abate" sectors where decarbonisation strategies are posed with significant challenges [12]. Therefore, solutions for defossilisation of fuel sources are perceived to be promising, supplemented by decarbonising pathways such as improved operational efficiency through optimised fleet management. In this thesis, I will particularly focus on the shipping sector due to its nascent stage of replacing conventional fossil fuels for GHG emission reduction, in comparison to the aviation sector.

### 1.1.2 Shipping Sector and GHG emissions

The shipping sector is a part of the maritime industry, involving watercraft carrying freight or people. Some of the processes in this sector pertain to transporting commodities, merchandise goods, and cargoes by large waterbodies such as seas and oceans. Merchant shipping is considered "the lifeblood of the world economy", as it is responsible for handling, on average, 80% of the international trade, equalling 1200 million tons of freight worth 7 trillion USD [13]. During its functioning, globally, the shipping sector consumes more than 330 million tons of fossil fuels annually [13]. With the expected increase in global population and emerging economies requiring goods (raw materials, intermediates, and finished products), the shipping sector is naturally envisioned to grow in the future. Marine transportation is considered the most energy-efficient and least environmentally damaging mode of commercial transport [14]. Due to long distances, such as in merchant shipping, the $CO_2$ emissions per ton-kilometre are the least for shipping in comparison with airways or roadways. However, with an exponential rise in the shipping sector in the future, due to increasing demand for goods and energy, long-term sustainable growth is of vital importance for the global climate. Reducing emissions from the shipping sector will also contribute to the reduction in the environmental footprint of the traded goods on a life-cycle basis.

Concerning air emissions, the marine sector accounts for 2-3% of the global $CO_2$ emissions, the least of all commercial transportation in terms of per ton of cargo over a kilometre [14]. However, due to the (low-) quality of fossil fuels used, the sector contributes to 4-9% of global (non-GHG) Sulfur oxides (SOx) and 10-15% of all nitrogen oxides (NOx) emissions [15]. The sectors' contribution to climate change is expected to rise significantly if waterborne transport is allowed to expand at the current rate without any modifications and by maintaining the status quo. To address the same, the International Maritime Organization (IMO), in 2020, introduced a global regulation to limit the Sulfur content in ships' fuel to reduce the SOx emissions [16]. Also known as IMO2020, the regulation mandates the upper limit of Sulfur content present in the fuel to be 0.5% (against 3.5%) for all ships outside the Emission Control Areas, where the limit is set to 0.1% [16]. Likewise, to achieve the EU green deal, within the Fit for 55 law package, the FuelEU maritime law aims to reduce the GHG intensity of the energy used on board the shipping vessel by 6% and 80%, in comparison to 2020, by 2030 and 2050, respectively [17]. Therefore, there is a global imperative for the large-scale development and deployment of commercial volumes of sustainable marine fuels.

As a global industry, the shipping sector spans worldwide, but it is intricately connected to the regions of industrial activities. The development strategies to achieve sustainable shipping are highly dependent on the global market demand and supply for goods transport, environmental and regulatory aspects of the regions of seaports, and availability and supply of specific fuels for marine propulsion [13]. Furthermore, the institutional framework, such as policies and regulations, will dictate the economic feasibility of the alternative fuels, along with the technical development of propulsion systems to utilise the alternative fuels [18]. Therefore, understanding of the global shipping routes is a prerequisite for developing strategies for alternative, renewable, low-carbon or net-zero emissions fuels for the marine sector. Although a global industry, the shipping sector has some regions across the globe where the marine traffic for commercial ships is higher, such as the Panama Canal, Gibraltar, etc. These regions of high commercial ship density are commonly referred to as primary chokeholds. *Figure 1.2* shows the global marine transport route, which indicates the regions of primary and secondary chokeholds.

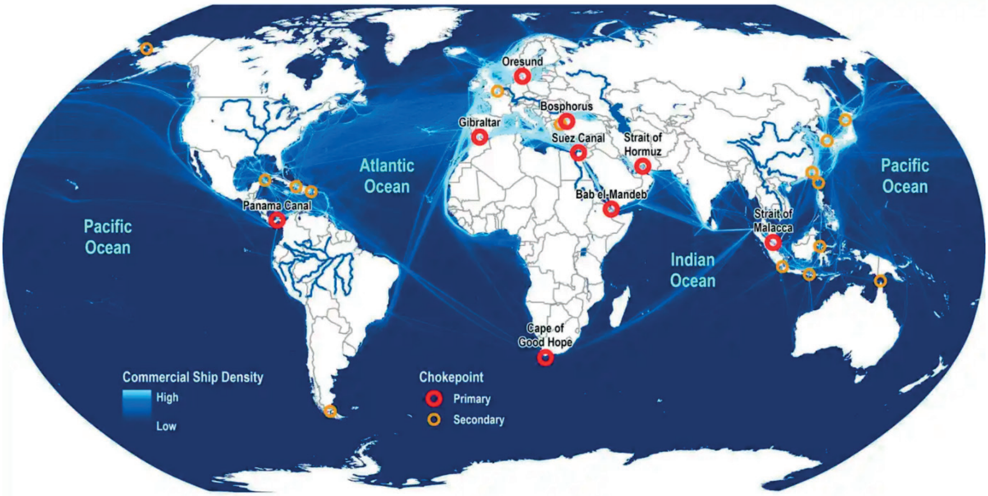


Figure 1.2: Global shipping route with primary and secondary chokepoints. Source:[19]

### 1.1.3 Alternative Energy Carriers for the shipping sector

In recent decades, various energy carriers have been identified as potential substitutes for fossil-based fuels in the shipping sector. These can be classified into low-carbon, carbon-neutral, and zero-carbon alternative fuels [20]. Some of the possible energy carriers to substitute the conventional sulphur-intensive heavy fuel oil in the large ocean-going vessels are ammonia, diesel, natural gas, hydrogen, methanol, electricity, ethanol, Dimethyl Ether, Metal carriers, and hydrogen carriers (such as formic acid) [21]. The energy sources for these carriers range from biomass, renewable electricity (such as wind, solar, hydro, geothermal, etc.), and metals (such as Uranium) [20], [21]. Based on the numerous factors involved during the life cycle of the alternative fuel, each of the energy source-carrier-combustion fuel pathways emits a different amount of GHG emissions, as can be seen in Figure *1.3*. It can be inferred from *Figure 1.3* that, predominantly, alternative fuels from most of the non-fossil energy source-based pathways were able to achieve at least a 50% reduction in GHG emissions, showing promising potential.

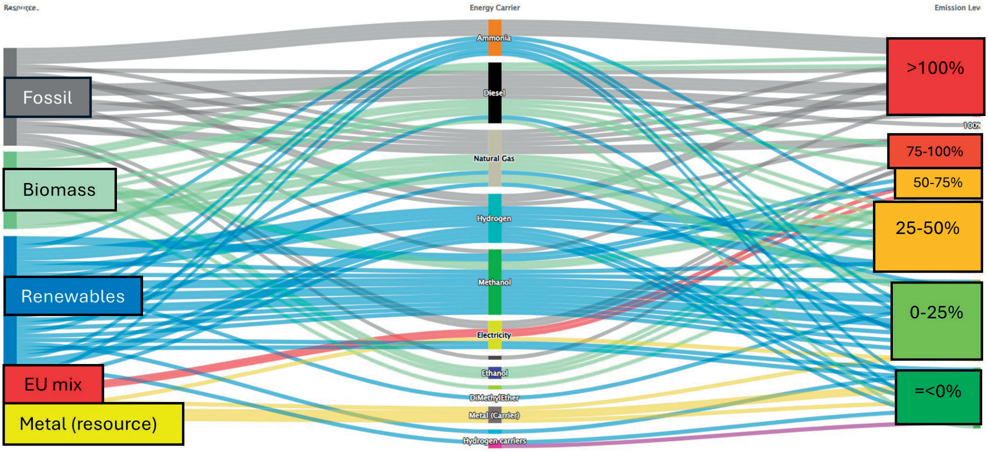


Figure 1.3: Sustainable Energy sources (left) and carriers (middle) for the Shipping sector with potential reductions in emissions (right side) in comparison with fossil fuels, with base for relative emissions with Marine Gas Oil as reference (100% emissions). Source: Modified from [21]

However, the viability of large-scale deployment of sustainable alternative fuels in the shipping sector is determined by much more than their potential to reduce environmental emissions. Some of the other crucial parameters determining the technical viability, economic feasibility, and social acceptance for commercial-scale uptake are energy density of the fuel, on-board storability and stability of the fuel, maturity level of the conversion technology, energy costs, capital costs, bunkering availability, requirement of new infrastructural development at ports, modifications to the vessels, and the physio-chemical properties for combustion along with the potential for global availability of the fuel [22]. For instance, green hydrogen is considered a non-toxic, net-zero emission fuel with no GHG emissions on combustion. However, its global availability requires significant new or modified infrastructure for global production supply using renewable electricity, bunkering facilities, on-board storage, and combustion in the vessels [23]. Based on literature reports, *Table 1.1* shows the summary of the overall readiness of different alternatives to substitute heavy fuel oil in the shipping sector based on literature reviews [18], [24], [25], [26], [27], [28].

Table 1.1: Overview of pros and cons of alternative fuels as short-term solutions in the shipping sector. Red: Positive Performance, Orange: Positive performance but requires significant research and modifications, Red: Severe concerns, N/A: Not Applicable

| | Safety | Air Emissions (well to wake) | (upstream) availability | Bunkering infrastructure | Energy density | Operating costs | On-board storage | Technology readiness level |
|---|---|---|---|---|---|---|---|---|
| Fossil fuels | Green | Red | Green | Green | Green | Green | Green | Green |
| Fossil LNG | Orange | Orange | Green | Orange | Orange | Orange | Orange | Green |
| Biofuels | Green | Green | Orange | Green | Green | Orange | Green | Green |
| e-Ammonia | Orange | Green | Red | Red | Orange | Red | Red | Red |
| e-biomethanol | Orange | Green | Orange | Red | Orange | Orange | Orange | Orange |
| e-hydrogen | Orange | Green | Red | Red | Red | Red | Red | Orange |
| Energy storage systems (such as batteries) | Green | Green | N/A | Red | Red | Green | Red | Green |
| Electrical shore power | Green | Green | Orange | Red | N/A | Orange | N/A | Green |
| Nuclear | Red | Green | N/A | N/A | Green | Green | Green | Red |

Due to variation in global fleet concerning the size of the vessels, transport distances, routes, and purpose, a combination of alternative fuels is required to achieve GHG emission-free shipping. Although zero-carbon fuels, such as green hydrogen and green ammonia, can achieve a significant reduction in GHG emissions, they are considered to be long-term solutions. This is mainly due to the time needed to develop global infrastructure and fleet modification, to ensure global availability of the fuel and its uptake (onboard storage facility and engine modifications) in the vessels [29]. Furthermore, with the use of zero-carbon fuels, the shipping sector will face stiff competition from the fossil-intensive "hard-to-abate" petrochemical industry, which can offer sustainable, high-value-added products in comparison to the transportation sector [23]. Currently, the shipping companies are installing on-board gas scrubbing systems or replacing heavy fuel oil (HFO) with low-carbon fuels such as fossil-based liquified natural gas (LNG) or fossil-based methanol, as short-term solutions, to achieve the IMO2020 targets for Sulfur and nitrogen emissions to the air [13]. However, the new FuelEU maritime law requires significant carbon emissions reduction by 2050. So, Carbon-neutral fuels, such as liquid biofuels, that benefit from the existing infrastructure, with proven potential to reduce GHG, Sulfur, and Nitrogen emissions, are seen as crucial candidates to act as short- to mid-term solutions [13]. However, significant technical, economic, and social challenges need to be addressed to fully valorise the potential of climate-neutral fuels as a commercial replacement for Heavy Fuel Oil (HFO) in the shipping sector. In this thesis, I will focus on marine biofuels as an alternative for the shipping sector.

## 1.2 THEORETICAL BACKGROUND

### 1.2.1 Biofuels and their classification

Biofuels are one of the primary energy carriers known to humans, which are produced from biobased sources. Based on their physical state, biofuels are classified into solid biofuels (such as biochar, firewood, etc.), liquid biofuels (such as bioethanol, biodiesel, and biomethanol), and gaseous biofuels (such as biomethane and bio-hydrogen). Globally, bioethanol and biodiesel are the commonly produced commercial biofuels, although primarily consumed by the road segment of transportation [13]. Based on their potential to mitigate GHG emissions, in the recent decade, the use of biofuels as sustainable aviation fuel (SAF) has also gained immense spotlight from the scientific community and industries alike [30]. Compared to the road and aviation sectors, marine fuels are of lower quality, have higher viscosity, and are less refined, making them the "low-hanging" end-user segment for commercial-scale, global biofuel implementation at lower processing costs due to eliminating the need for advanced refining [31]. Moreover, biomass is a renewable resource containing very little or no Sulfur content, and liquid biofuels derived from biomass have immense potential to become part of the sustainable fuel mix in the shipping sector.

The global availability potential and sustainability performance of biofuels are primarily dependent on the nature of the biomass source [32]. Based on the nature of biomass source, the biofuels are classified into various generations: first (from edible biomass such as sugars and vegetable oils), second (from non-edible lignocellulosic materials such as agricultural residues), third (from aquatic biomass such as algae and cyanobacteria), and fourth (with the use of genetically modified organisms) [33]. Currently, the majority of the liquid biofuels used in the road segment are first-generation biofuels, also known as conventional biofuels, produced from either corn, soy, or sugarcane. However, with the use of edible biomass as feedstock, the conventional biofuels have been under scrutiny for their sustainability [34]. Although conventional biofuels are proven to reduce $CO_2$ emissions, at larger volumes such as needed for the marine sector, they cause non-GHG related sustainability concerns such as limitations in feedstock supply, food security, and undesired land use changes [35]. On the other hand, advanced biofuels such as the third and fourth generation biofuels are still in their infancy stages, requiring significant technological development and infrastructure for raw material cultivation. Therefore, second-generation biofuels, derived from non-edible biomass sources, are expected to play a crucial role in satisfying the large-scale global demand for bioenergy in various sectors, including transportation.

Second-generation biofuels are advanced biofuels produced from non-food lignocellulosic material as feedstocks [33]. These feedstocks range from residues from the agricultural and forestry sectors, ecological energy crops, and waste streams from food and processing industries, such as used cooking oil. As a pathway for residues and waste valorisation, 2nd-generation biofuels promote the concepts of green chemistry, sustainability, and circularity [36]. Despite their promising potential for GHG emission reduction, the advanced biofuels are still far from commercial deployment, facing substantial challenges in terms of low technology readiness level (TRL) of conversion pathways, high capital and operating expenses, low public acceptance, and lower investment confidence [37]. Technically, due to the heterogeneous and recalcitrant properties of the feedstock, the biomass conversion pathway requires various advanced upstream (such as complex pre-treatment) and downstream (for product separation and purification) processes at the biomass conversion stage [38]. At a large scale, due to technical constraints (such as lower process yields) and feedstock price, the second-generation biofuels become expensive in comparison with either fossil fuels or first-generation biofuels [39]. This is translated into reduced market competitiveness of the alternative fuels.

Based on the physio-chemical properties, (second-generation) biofuels can be classified into "dedicated" and "drop-in" biofuels. Due to the different and distinct physio-chemical properties, the "dedicated" types of biofuels (such as bioethanol and fatty acid methyl esters) cannot fully benefit from the existing petroleum processing and distribution infrastructure [31]. Also, bioethanol and biodiesel are unsuitable for long-distance trucking, marine, and aviation sectors as they do not meet the threshold of fuel properties such as density. Unless engines are modified, these conventional "dedicated" second-generation biofuels can only be blended to a certain percentage (15% for bioethanol, and 20% for biodiesel) [31]. Therefore, novel and innovative technological strategies are needed to promote biofuels as a viable and sustainable alternative fuel source.

Drop-in biofuels, defined as *"liquid bio-hydrocarbons that are functionally equivalent to petroleum fuels and are fully compatible with existing petroleum infrastructure"*, can be a potential solution for introducing second-generation biofuels into the market [34] . As opposed to conventional "dedicated" biofuels (such as bioethanol or fatty-acid methyl esters) that have a distinct chemical composition, drop-in biofuels consist of a mixture of hydrocarbons and are characterised by the functionality of the mixture, analogous to that of fossil crude. Due to their resemblance to physio-chemical properties with petroleum fuels, the “drop-in” biofuels can be directly blended with conventional fossils, in higher percentages. Due to the potential possibility for co-processing along with fossil fuels in existing petrochemical refineries, especially for the downstream activities, and integration with existing combustion engines without modifications, “drop-in” biofuels can significantly benefit technically and economically, enabling market penetration [34]. However, significant technological barriers, in terms of maturity and fuel properties, have to be addressed to fully realise the potential of “drop-in” biofuels.

In terms of sustainability, to avoid concerns, such as those in the first generation biofuels, various certification schemes have been introduced at the national or continental level, across the globe, to ensure that biofuels are produced sustainably according to various sustainability criteria. For instance, in the EU, the sustainability criteria for alternative fuels are well established under the Renewable Energy Directive (RED), revised in 2023, also known as RED III [40]. It provides an overarching regulation for the promotion and use of sustainable fuels in the EU, including the sustainability criteria for various biomass-technology-biofuel pathways. Various biomass certification schemes, such as International Sustainability and Carbon Certification (ISCC), Roundtable on Sustainable Biofuels (RSB), are developed voluntarily to ensure the sustainable production of biofuels [41]. Based on the nature of the feedstocks, the biomass raw materials is classified as Part A (feedstocks that are not directly from food or feed crops and are often considered to be more sustainable in terms of land use and environmental impact, such as residual biomass from agriculture and forestry sectors) and Part B (feedstocks containing lipids such as used cooking oil and animal fats). Under RED III, the combined share of advanced biofuels and biogas from feedstocks from Part A and Part B of Annex IX should be 5.5% and 1.7%, respectively.

Due to the foreseen limited availability of feedstocks classified under Part B of Annex IX (such as animals fats and used cooking oil) and the requirement of large volumes for the marine sector, this thesis will focus on “drop-in” marine biofuels based on lignocellulosic residues that belong to Part A of Annex IX under RED III [40].

### 1.2.2 “Drop-in” biofuel production technologies and economics

Over the past decade, the “drop-in” biofuels have gained immense spotlight from both academia and industry alike [34]. Drop-in biofuels are being developed to replace fuels in all forms of transportation, namely road (for heavy-duty trucking), aviation, and the shipping sector [42]. The production platforms can be classified based on the nature of the feedstock and mode of biomass conversion, namely oleochemical (based on oil-rich feedstocks), thermochemical (heat treatment of lignocellulosic biomass), biochemical (using microbial fermentation of lignocellulosic biomass), and hybrid platforms (using combination of technologies to convert platform chemicals into fuels) [43]. *Figure 1.4* shows the different technological pathways for "drop-in" biofuel production to attain "drop-in" sustainable aviation fuels as an example.

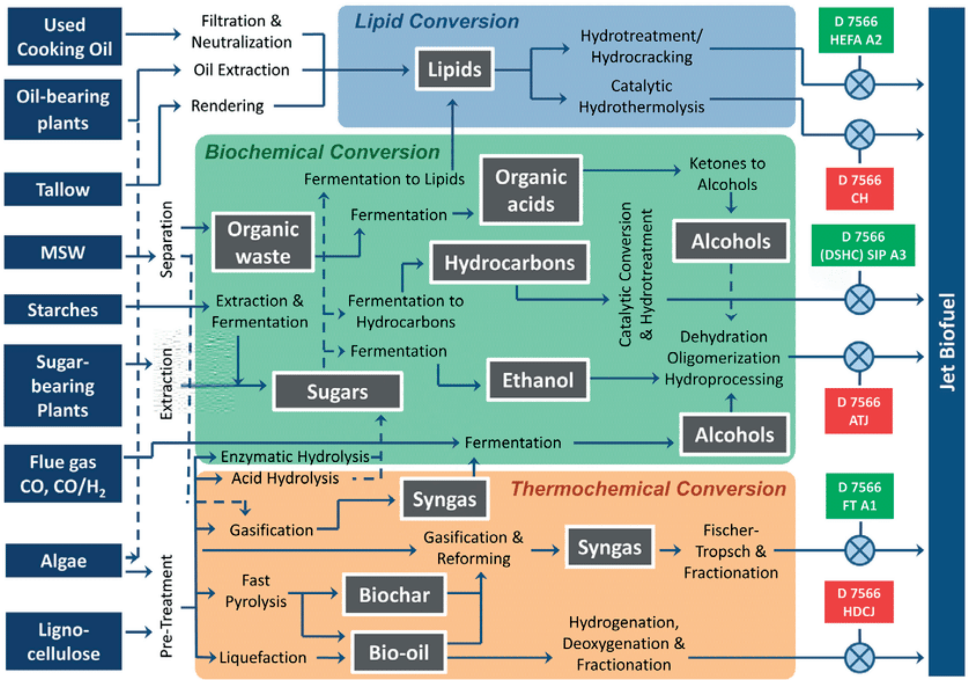


Figure 1.4: Overview of technology pathways for drop-in "jet" biofuels and ASTM status. ATJ, alcohol to jet; CH, catalytic hydrothermolysis, not yet approved; DSHC, direct fermentation of sugars to hydrocarbons, approved; FT, Fischer-Tropsch process, approved; HDCJ, hydrotreated depolymerised cellulosic to jet, not yet approved; MSW, municipal solid waste; HEFA, hydro processed esters and fatty acids, approved. Source: [43]

The oleochemical platform, which produces renewable diesel (also known as hydrotreated vegetable oil, HVO or hydrotreated esters and fatty acids, HEFA) as the "drop-in" fuel after hydrotreatment of oil-rich feedstocks such as used cooking oil and tall oil, is the most commercial process to date [34]. This platform has pioneered the "drop-in" biofuels market due to its relatively easier process of upgrading the feedstocks with lower oxygen content (11% max.) and high hydrogen to carbon ratio (1.8:1) [34]. However, this platform is only perceived as a short-term solution, enabling transition to other drop-in biofuels platforms due to the high costs, limited global feedstock availability, and sustainability concerns of the oleochemical feedstocks, which is also reflected in the targets under RED III [40].

On the other hand, the biochemical platform and the hybrid platform convert alcohol to drop-in fuels using deoxygenation techniques such as dehydration, hydro processing, and oligomerisation. The pathway of alcohol production determines the nature of the platform, biomass-based (such as cellulosic ethanol or methanol from bio-based syngas fermentation) for biochemical platform, and power-based (methanol from carbon capture and green hydrogen) in a hybrid platform [42]. Although these pathways have the potential to significantly reduce the carbon intensity of the "drop-in" fuels and do not possess adverse sustainability concerns, the global technology readiness level, infrastructure development needed, and lower availability of high-cost feedstock (namely alcohol) make these pathways economically unattractive and an option for a long-term solution [42]. Furthermore, drop-in biofuels from these pathways could be beneficial for aviation and the road segment due to the high quality of the end-product, which is not a requirement for the marine sector. Therefore, drop-in biofuels obtained through the thermochemical platform can suit the needs of the shipping sector [13].

Thermochemical platform includes biomass conversion processes which implement high energy (in the form of temperature and pressure) to convert any form of lignocellulosic feedstock into carbon-rich streams (namely solid, liquid, and gas) either in the presence or absence of catalysts [34]. Gasification and liquefaction are the two main routes involved in this platform, where either a gaseous (namely, syngas) or liquid (namely, biocrudes) intermediates are obtained, respectively. The intermediates are further processed into drop-in fuels using either the Fischer-Tropsch process (for syngas) or hydrotreatment (for biocrudes) in a stand-alone facility or by co-processing the intermediates in an existing petroleum refinery. Due to their ability to process a wide range of biomass feedstocks with sustainability certifications, overcoming the availability and sustainability concerns related to feedstocks, thermochemical routes have gained significant momentum in technological development from academia and industry alike [44]. Furthermore, the liquefaction routes are divided into two categories based on the processing conditions (temperature, pressure, and process medium), namely, pyrolysis and hydrothermal liquefaction (HTL). *Table 1.2* compares the three thermochemical conversion techniques, gasification, pyrolysis, and HTL, based on technical criteria such as feedstock quality requirement, severity of process conditions, product yield and quality, and Technology Readiness Level (TRL). We ranked the conversion pathways based on each criterion using the symbols "+" (more suitable), "+/-" (neutral), and "-" (less suitable) to indicate their relative performance.

Table 1.2: Technical comparisons of thermochemical conversion pathways for marine biofuel production. Sources: [45], [46], [47]

| **Criteria** | **Gasification** | **Pyrolysis** | **HTL** |
|---|---|---|---|
| Quality of feedstocks | +/- | - | + |
| *Moisture content* | 10-20 wt.% | <10 wt.% | Not applicable |
| *Particle size* | <2-2.5 inch | <3 mm | <3 mm |
| *Nature of commonly investigated feedstocks* | Forestry wastes, woody plantations, and agricultural wastes. | Plastics, Forestry, and agricultural residues | Wastewater Sludge, Municipal Solid Waste, Algae, food and animal waste, crops, and their residues |
| Process conditions | +/- | + | - |
| *Temperature* | 600-1000°C | 400-500°C | 250-370°C |
| *Pressure* | 20-70 atm | 1 atm | 100-250 atm |
| *Catalysts requirement* | No | No | Maybe |
| Product characteristics | +/- | - | + |
| *Type* | Syngas | Bio-oil | Bio-oil |
| *Yield* | 1.54 - 2.41 $m^3$/kg biomass | 50-70 wt.% | 30-40 wt.% |
| *Oxygen content* | N/A | 35-40 wt.% | 5-15 wt.% |
| *Higher heating Value* | N/A | 16-18 MJ/kg | 30-38 MJ/kg |
| *Upgrading step* | Cleanup and reforming | Hydrotreating | Could be co-processed with crude oil |
| Technology scale | - | + | +/- |
| *# of Demonstration facilities* | 6 | 9 | 6 |
| *# of Commercial facilities* | Not Applicable | 10 (out of which three are under development) | 1 (under development) |
| *Technology readiness level* | 5-7 ($CO_2$ based gasification)<br>8-9 (steam-based gasification) | 7-9 | 6-8 |

Based on various literature sources indicating the promising potential for technical performance and environmental footprint of the thermochemical routes based drop-in fuels, various techno-economic assessments have been performed in the recent decade for their economic feasibility. *Table 1.3* summarises some of the results of techno-economic studies for the thermochemical-based drop-in biofuels for the transportation sector at various scales and different technology readiness levels (state of the art, pioneer or commercial, $N^{th}$ kind).

Table 1.3: Techno-economic evaluation studies reported on the thermochemical conversion of lignocellulosic biomass to advanced "drop-in" biofuels.

| Technology | Region | Type of Plant | Capacity (in DTPD) | Biomass feedstock | Products | CAPEX (in million $) | MFSP ($/kg) | Reference |
|---|---|---|---|---|---|---|---|---|
| Gasification (with Fischer Tropsch) | Brazil | Pioneer | 500 | AR | MB | 219-279 | 2.9-8.6 | [48] |
| | Sweden | Pioneer | 500 | AR | MB | 214-237 | 2.4-4.0 | [48] |
| | US | $N^{th}$ Kind | 2000 | PWC | D | 379-537 | 0.93 [a] -1.05 [a] | [49] |
| Pyrolysis | Brazil | Pioneer | 500 | AR | MB | 208-255 | 1.8-3.1 | [48] |
| | Sweden | Pioneer | 500 | AR | MB | 173-214 | 1.6-2.9 | [48] |
| | US | $N^{th}$ kind | 2000 | PWC | G, D | 332 | 0.69 [a] | [49] |
| HTL | Brazil | Pioneer | 500 | AR | MB | 250-283 | 1.8-4.0 | [48] |
| | Sweden | Pioneer | 500 | AR | MB | 217-262 | 1.5-2.0 | [48] |
| | US | Pioneer; $N^{th}$ Kind | 2000;2000 | WC | G, D | 512; 468 | 1.68 [a]; 0.96[a] | [50] |
| | US | $N^{th}$ Kind | 1339 | MA | N, D | 468 | 1.63 [a] | [51] |
| | US | $N^{th}$ Kind | 110 | SS | N, D | 36.2 | 0.86 [a] | [52] |

IRR: Internal rate of return; MFSP: Minimum fuel selling price; DTPD: Dry tonne biomass per day; AR: Agricultural residues; WC: Wood chips; SS: Sewage Sludge; MA: Micro Algae; PWC: Poplar wood chips; N: Naphtha; D: Diesel; G: Gasoline; MB: Marine biofuel. Conversion factors [53]: *[a] 1 gallon = 3.78 L, density of upgraded HTL bio-crude = 0.77kg/L, density of upgraded FT diesel = 0.8 kg/L, density of upgraded Pyrolysis bio-crude = 0.95 kg/L.*

As can be inferred from *Table 1.3*, the direct thermochemical liquefaction (DTL) pathways are considerably less expensive than the gasification routes, however, the minimum fuel selling price is still significantly more than the fossil fuels ( between 2007-2012, the U.S. gasoline wholesale price was in the range of USD 0.47 -0.78/kg,[54]). Moreover, the biocrudes obtained from the liquefaction routes still need to be upgraded due to their high moisture and oxygen content, which is undesirable for a transport fuel [55]. In terms of biocrude upgrading, the HTL biocrudes are found to be easier to upgrade with mild hydrotreatment as opposed to severe conditions required for pyrolysis-based biocrudes [56]. This is primarily due to the reduced oxygen and moisture content of the high-quality biocrudes obtained from hydrothermal liquefaction at subcritical temperatures. Moreover, the HTL offers significant benefits in terms of its ability to process wet feedstocks, high energy efficiency, and economic performance in comparison to pyrolysis [56]. In addition, HTL biocrudes have shown better blending properties with the fossil fuels, indicating better prospects for co-processing either in a fluidised catalytic converter (FCC) or hydrotreater in an existing petrochemical refinery based on the desired fractions of transportation fuels [34].

To realise the full global potential of DTL-based drop-in biofuels and commercialise the technological pathway, leading institutions, such as the Pacific-Northwest National Laboratory (PNNL) and the International Energy Agency (IEA), have dedicated activities addressing the technical, economic, and environmental aspects of the DTL pathway. For instance, Task 34 of the IEA Bioenergy technology collaboration programme aims at technological advancement for better economic performance and standardisation of biofuels for market penetration [57]. Recently the Task 34 investigated the commercial status of DTL technologies [58] and also the potential for using DTL for producing chemicals and materials [59]. Furthermore, Task 39 of the IEA Bioenergy complements Task 34 by assisting in the development and deployment of biofuels as a commercial, sustainable transport fuel [57]. Recently, the teams of Task 39 reported means to increase the use of biofuels in the marine sector [60] However, an existing knowledge gap in the global activities is the understanding of systemic challenges (such as large-scale biomass mobilisation, producing advanced biofuels from lignocelluloses in an economically feasible and environmentally friendly manner, investment risks for commercial scale implementation, etc.) and opportunities (such as local rural development at biomass production site, transitioning to a fossil-free economy, etc.) present in developing a value chain with integration of upstream (biomass supply), biomass conversion technology (such as HTL), and downstream (end-user segment) for HTL-based biofuels from bio-based feedstocks in different regions of the globe.

To supplement the global activities, this thesis aims to develop and assess bio-based value chains for drop-in marine biofuel production in three countries using lignocellulosic materials via hydrothermal liquefaction.

### 1.2.3 Biobased value chains (BBVCs) – Opportunities and Challenges of the *status quo*

Bio-based value chains (BBVCs) are supply chains where biomass is transformed into valuable end products with potential market applications. BBVCs are socio-technical systems (STS) where technical components are embedded within the social elements prevailing in the region of implementation [61]. In principle, any BBVC consists of 5 different nodes: biomass production, biomass pre-treatment, biomass conversion in biorefineries, bioproduct distribution, and end use. Given the nature of activities performed at each of the aforementioned nodes, BBVCs are multi-stakeholder systems requiring collaboration among diverse expertise ranging from crop cultivation, complex biorefinery technologies, logistics, and policies. Furthermore, due to the geographical distribution of the biomass and based on the size of the targeted end-market, the BBVCs can span over a certain region, country, or even different continents. *Figure 1.5* depicts various aspects of a conventional BBVC. Figure 1.5a shows the different nodes of a biobased value chain for biofuels with the corresponding design variables. Figure

1.5b shows the different levels of decision making involved during the development of a BBVC, based on the durational impact of the decisions (short term to long term). Finally, Figure 1.5c shows the different direct and indirect stakeholders involved in a conventional biobased value chain for biofuel production.

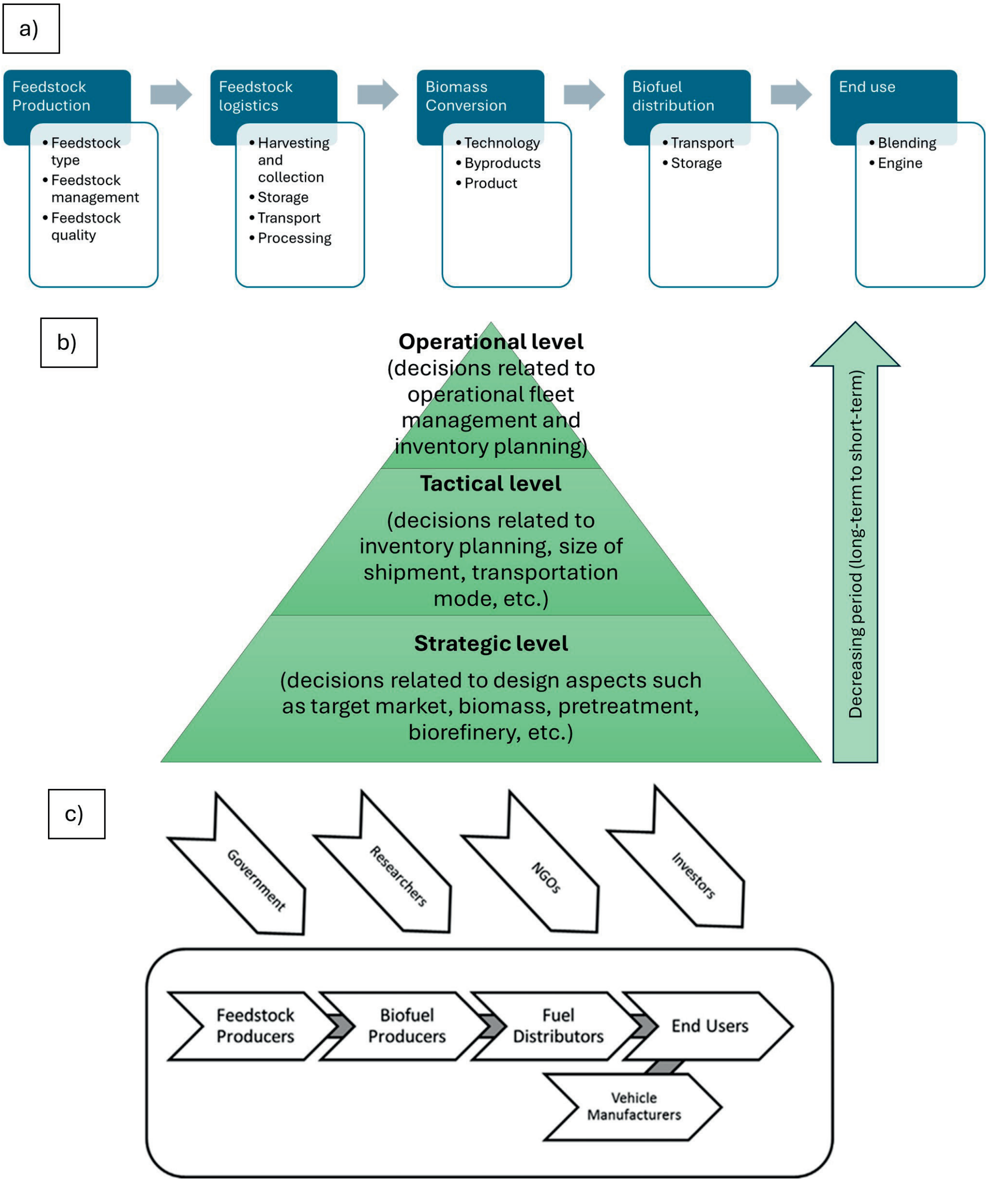


Figure 1.5: Elements of a biobased value chain. a) nodes of a BBVC [62], b) decisions involved in BBVC development [63], c) stakeholders involved in a BBVC [64]

BBVCs can play a vital role in transitioning from a fossil-based economy into a biobased economy, also known as the bioeconomy [65]. As a socio-technical system, BBVCs can enable a sustainable, circular, and just transition. In past decades, numerous studies have been conducted on the conceptual process and supply chain design for producing biobased products (such as bioenergy and biochemicals) based on diverse biomass feedstocks [66], [67]. However, despite the promising environmental performances and decade-long academic optimisation for improving economic performance, BBVCs are still facing various strategic, tactical, and operational challenges for large-scale global commercial deployment [68], [69], [70], [71]. Some of these challenges are discussed below,

Firstly, the techno-economics of lignocellulosic-based bioproducts, at large volumes, are still unfavourable in comparison with their fossil counterparts [26], [72], [73], [74]. This is mainly due to the various technical challenges involved in the BBVCs. In terms of upstream activities, biomass mobilisation, i.e., concerning the secure and constant supply of good-quality feedstocks, the lignocellulosic materials, such as agricultural residues, are produced seasonally based on the harvest calendar, and the available volumes are vulnerable to climate change and crop failures. This raises uncertainties for developing commercial-scale biorefineries, which require a large quantity of feedstocks. Focusing on the biomass, due to the complex, heterogeneous, and recalcitrant nature of lignocelluloses combined with low energy-dense and high bulk density properties, intense pre-treatments, such as steam explosion or pelletisation, are required before biomass conversion. In case of high moisture content feedstocks, a (non-renewable energy-based) energy-intensive drying step is required to improve the shelf life and energy content of the feedstock. The necessity of these pretreatment steps, combined with high feedstock and transportation costs, makes the biochemical pathways inherently expensive. In the biomass conversion stage, the overall process yields of bioprocesses are relatively lower (varies based on chosen technology), in comparison with fossil-based chemical processes, even after numerous downstream purification activities, thereby consuming more feedstocks to produce the same quantity of products. Upon scale-up, the above-mentioned technical complexity rises exponentially, making the bioprocesses resource-intensive and further reducing the economic and environmental performance of the bioproducts. Although some of these technical challenges, such as eliminating the need for a drying step, are inherently addressed by opting for hydrothermal liquefaction for drop-in biofuel production, strategies to mobilise large volumes of biomass are still to be addressed.

In recent years, various studies have proposed decentralised configurations, also commonly referred to as the hub and spoke model, as a potential way to mobilise biomass feedstocks by achieving the trade-off between economies of scale and economies of numbers [75], [76]. In a recent study, published by the IEA, one such configuration, referred to as biohubs, is seen as a key to successful biomass supply integration for achieving bioeconomy [77]. In the biohubs, or any hub and spoke configuration of BBVCs, biomass is collected and pretreated at various pre-processing facilities located near the biomass production sites, before transporting it to biorefineries [78]. Likewise, the concept of cascading, where biomass resources are used and recycled for as long as possible, and allocated to the high-value-added purposes possible at each stage, is implemented as a strategy for improving the efficiency and sustainability of BBVCs. However, the current approach for BBVCs development is primarily focused on overcoming the technical barriers concerning technologies, but does not account for contextual knowledge (for strategic, tactical, and operational decisions) prevailing in the region of interest, which predominantly determines the intricacies of implementation [78], [79]. Therefore, there is a need for a multi-disciplinary approach, as opposed to a one-dimensional designer approach, for designing BBVCs for a holistic viewpoint to identify potential opportunities and showstoppers at the conceptual stage for commercial development [76].

Secondly, as a socio-technical system and as a means to achieve a just bioeconomy, BBVCs are expected to enhance the local rural development at or near the biomass production sites. In the conventional approach of BBVCs development, by designers, although a multi-stakeholder system, most often, the stakeholders situated upstream of biorefineries, the so-called biomass suppliers, are neglected or overseen during the conceptual design phase [80]. Furthermore, the commercialisation process is driven by stakeholders with a technical background located in different regions, countries, or continents, such as technology providers or end-users, who lack expertise in the identification and incorporation of contextual knowledge of biomass production [81]. Therefore, despite the proven potential positive socio-economic impacts, bio-based projects frequently face challenges pertaining to public acceptance during the project implementation phase [80]. This highlights the presence of a blind spot in the conventional approach and the need to identify and incorporate non-technical aspects of value chain development at the early stage of the conceptual design process.

Some non-technical aspects about BBVCs include stakeholders' values, necessities, needs, skillsets, capabilities and capacities. These non-technical aspects are often overlooked and disregarded in scientific literature and other major research arenas like IEA's Tasks 34 and 39 [81]. Although not common in bio-based value chains, the concept and practice of including stakeholders' perspectives in the technological design is well established in other socio-technical studies (STS) domains such as urban planning and Information systems. In the fields of Engineering Ethics and Science and Technology Studies, various theoretical frameworks have been developed, such as Constructive

Technology Assessment (CTA), Mid-stream Modulation (MM), Value Sensitive Design (VSD), and Capabilities Approach (CA), to combine the technical and non-technical aspects during technology development for societal benefits [82], [83]. In recent times, the integration of qualitative social aspects in the BBVC designs has gained attention among the scientific community.

Social sustainability and inclusion are two crucial aspects to ensure social welfare due to the introduction of BBVCs. In terms of social sustainability, Parada *et al.* (2018) proposed an approach to setting the design space and design propositions of biorefineries through values related to sustainability, for promoting the concept of design for values [82]. In a follow-up study, Palmeros Parada *et al.* (2021) showed, from a researcher's perspective, the implementation of VSD for developing biorefineries through integrating stakeholders' value consideration in the decision-making process, to argue the necessity of openness and flexibility during the conceptual phase [84]. With the establishment of the need and framework for stakeholder inclusion in the conceptual design of BBVCs, Robaey *et al.* (2022) investigated three BBVCs, namely corn stover in the USA, sugar cane in Jamaica, and sugar beet in the Netherlands, to identify practices for achieving inclusive biobased value chains [85]. The choice of feedstocks, biorefinery designs, and contracts is identified to be one of the different means of inclusion. However, the needs and means of inclusion alone do not provide a guarantee for stakeholders' participation and inclusion in decision-making. Therefore, with a special focus on the inclusion of resource-poor upstream stakeholders, Asveld *et al.* (2023) combined the concept of stakeholder capabilities through the capability approach with inclusion to attain a context-sensitive design of BBVCs [83].

Although the aforementioned works of literature addressed the knowledge gap of incorporating non-technical aspects into the technical design, an empirical study implementing the proposed frameworks, from a technical designer's perspective, with an outcome of conceptual design of sustainable and inclusive biobased value chains for commercialisation, is yet to be explored [83], [84], [85]. To address the knowledge gap of the real-time challenges and opportunities in operationalising the theoretical social frameworks to design inclusive biobased value chains based on empirical case studies, this thesis aims to answer the overall problem statement:

*"How can we design and evaluate the performance of context-specific sustainable and inclusive bio-based value chains, with a special focus on marine biofuel production through hydrothermal liquefaction (HTL)?"*

## 1.3 NOVELTY AND RELEVANCE OF THE RESEARCH

### 1.3.1 Trans-disciplinary approach

The novelty of this research lies in the interdisciplinary work of a multidisciplinary team using a transdisciplinary approach for developing biobased value chains. The novel approach aims to identify and integrate the non-technical, local context-specific, social aspects (such as stakeholders' perspectives), using theories in social sciences (such as Value Sensitive Design and Capability approach) into the technical conceptual design of biohubs at the early stages of development. This PhD is a part of the consortium, "*CLEAN SHIPPING – Thermo-chemistry and inclusive supply chains design for sustainable production of biofuels in the maritime transport industry*". The consortium's main goal is to develop inclusive and sustainable value chain concepts for the large-scale production of drop-in shipping biofuels from residual lignocellulosic biomass, with hydrothermal liquefaction (HTL). The project team aims to provide a holistic approach for the circular bio economy by creating multi-dimensional scenarios where various limiting factors are addressed at the same time. The investigation addresses the technical challenges associated with the value chain, mainly focusing on the conceptual design of processes and supply chains, which will be combined with integral sustainability assessment methods such as techno-economic evaluation and environmental life cycle assessment (e-LCA). In addition to sustainable design, the value chains are aimed to be inclusive by considering the capacities, values, skills and knowledge of all potential stakeholders in the conceptual design of value chains. As a part of the consortium, this research was performed in close collaboration with social scientists working on the aspects of societal and institutional challenges within the consortium. The research consists of three empirical case studies, where a multi-actor approach was used to co-develop the inclusive and sustainable conceptual designs of BBVCs, with stakeholder participation using various participatory techniques such as field visits, semi-structured interviews, and multistakeholder workshops for enabling early-stage consideration of stakeholders' perspectives and values. In *Figure 1.6* the empirical approach followed during the case studies, to combine technical and non-technical aspects of BBVCs development through a transdisciplinary approach by a multidisciplinary team.

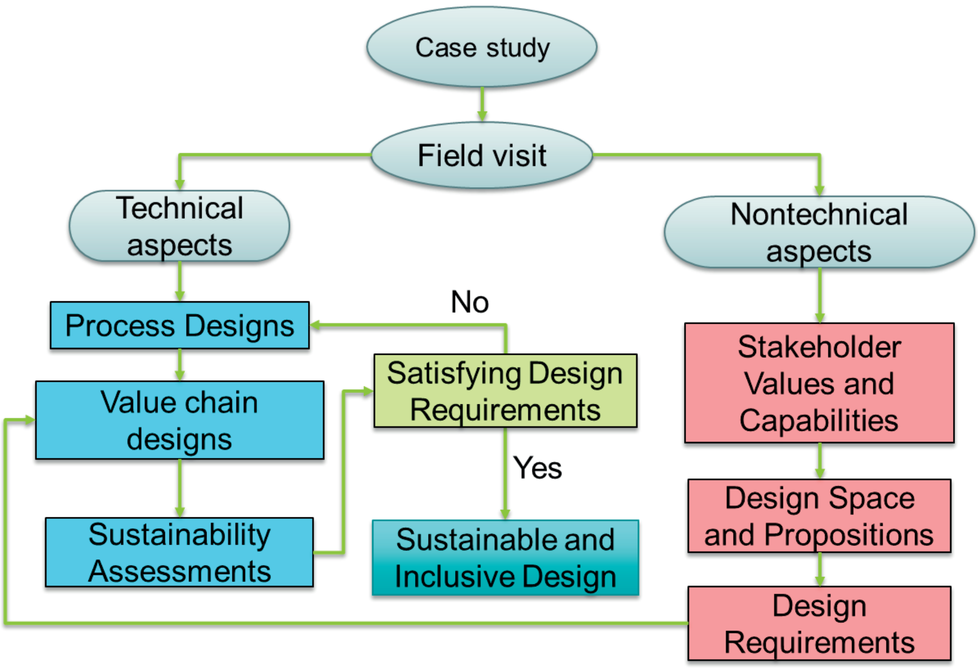


Figure 1.6: The empirical approach followed for combining technical and non-technical aspects during BBVCs development. Light blue boxes indicate the technical aspects of the design process, pink boxes indicate the non-technical aspects and their translation into technical design, and green box indicate the (stakeholder) validation for obtaining sustainable and inclusive design.

The biobased value chains, BBVCs, are hereby developed as a "biohub" concept. However, unlike IEA's biohubs (referred to as an intermediate place where farmers/growers can deliver their by-products web [76]) CLEANSHIPPING's biohubs are defined as a concept of secure, inclusive, and sustainable supply of feedstocks for biomass that integrates various elements of a socially acceptable, profitable, and sustainable bioeconomy into a modular system that can be adapted to the local context. A bio-hub is a circular system where private and public actors cooperate to 1) source bio-based streams and wastes, and transform them into marketable products, 2) improve the sustainability of local farming practices and traditional biomass use, 3) fulfil local needs, including energy and clean water, and 4) fairly distribute costs, benefits, risks and opportunities. The bio-hub is very context-specific, and the scale, type of biomass, variety of benefits, complexity of technologies, etc., can differ in each context. *Figure 1.7* visualises the proposed concept of biohubs with HTL as the conversion technology for producing marine biofuels using second-generation feedstocks.

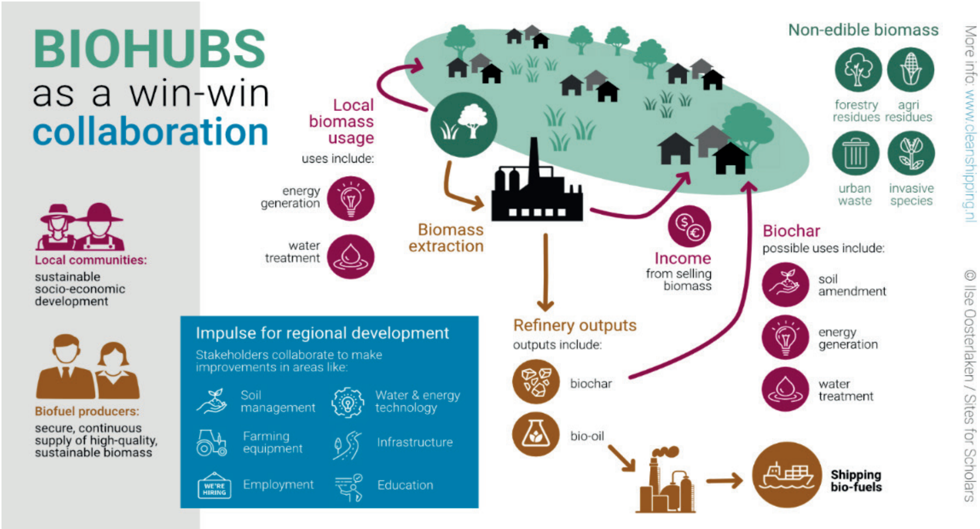


Figure 1.7: Visualisation of the Biohub concept envisioned by the CLEANSHIPPING consortium [86]

The biohub concept is developed as a modular system, which is independent of the choice of biomass conversion technology and can act as a technology "plug-in" model. Furthermore, this research develops biohubs for a novel perspective

i. to promote social sustainability for just bioeconomy by focusing on context-specific issues and stakeholders' capabilities at the biomass production regions instead of the conventional approach of optimising for economic and GHG emission reduction potential, and
ii. to meet the commercial demand of an end-user segment (shipping sector) rather than focusing on maximum valorisation of biomass feedstocks through cascading principles.

### 1.3.2 Contributions of the research

The contributions of the research can be classified into the conceptual phase and the empirical phase. In the conceptual phase, the work undertaken aims to develop sustainable and inclusive biohubs for marine biofuels using hydrothermal liquefaction. Firstly, this research implements a "first-of-a-kind" systematic protocol for case study selection for the conceptual design of BBVCs by combining various sustainability criteria and stakeholder participation. Secondly, the choice of feedstocks (from a specific region)-HTL combination is novel, thereby making the process design, value chain design, and integral sustainability assessments for a new biomass value chain, which has never been reported in the literature. Thirdly, this thesis aims to combine engineering concepts with social sciences to incorporate local contextual knowledge in the region of biomass production and the prevailing social aspects (such as stakeholder values and capabilities) at the early stage of the conceptual design process to co-develop sustainable and inclusive value chains. In the empirical phase, this research showcases the methodology for conducting transdisciplinary work to incorporate context-specific non-technical knowledge (such as stakeholders' perspectives, cultural values, etc.) with the technical elements during the conceptual design to co-develop biohubs. Finally, this thesis tests the concepts proposed in previous pieces of literature for implementing stakeholder participation to develop inclusive value chains while ensuring local rural development in the biomass-producing region [82], [83], [85], thereby enabling sustainable socio-economic development of communities.

The aforementioned contributions of this thesis could even be related to some of the efforts carried out by international agencies such as the IEA Bioenergy tasks. To develop sustainable and inclusive biohubs for marine biofuels use hydrothermal liquefaction (HTL) technology, the scope of this research can be complementary to the activities of Task 34 (Liquefaction), Task 39 (Transport biofuels), Task 42 (Biorefining), Task 43 (biomass supply), and Task 45 (Climate and Sustainability).

As shown in *Figure 1.8*, by investigating a novel thermochemical liquefaction technology, HTL, for converting "first-of-a-kind" biomass such as olive residues in Spain, Coffee residues in Colombia, and Acacia in Namibia, the CLEANSHIPPING project in general contributes to the value addition of the potential of new feedstocks from unexplored regions, complementing Task 34. With the chosen end product of marine biofuels, with the possibility to produce other transportation fuels, the conceptual process and biohub designs, along with techno-economic evaluation, can provide insights to Task 39. By focusing on the utilisation of mismanaged and underutilised field residues, along with environmental impact assessment over the life cycle of the HTL biofuels, the results from this research could be compared with the value chains assessed by Task 45. With the modified definition of biohubs, with the inclusion of social aspects, the performed work, similar to Task 43, addresses the potential opportunities and challenges for continuous, secure, and sustainable biomass mobilisation and supply. Finally, with the aim of promoting bioeconomy, this thesis and the CLEANSHIPPING project in general align with the scope of Task 42, biorefining. The dissertation integrates the activities of different tasks into a value chain and investigates the systemic performance, challenges, opportunities, and threats which are often overlooked by specialised or focused tasks. However, the above-mentioned tasks are focused on the technical aspects of the biobased value chains. On the contrary, this thesis actively aims to combine the technical aspects with non-technical aspects of biobased value chains into the conceptual design of biobased value chains, such as the inclusion of stakeholders' perspectives, social values, capabilities, needs, etc. thereby creating a niche of its own by contributing to existing research domains in the field of bioeconomy.

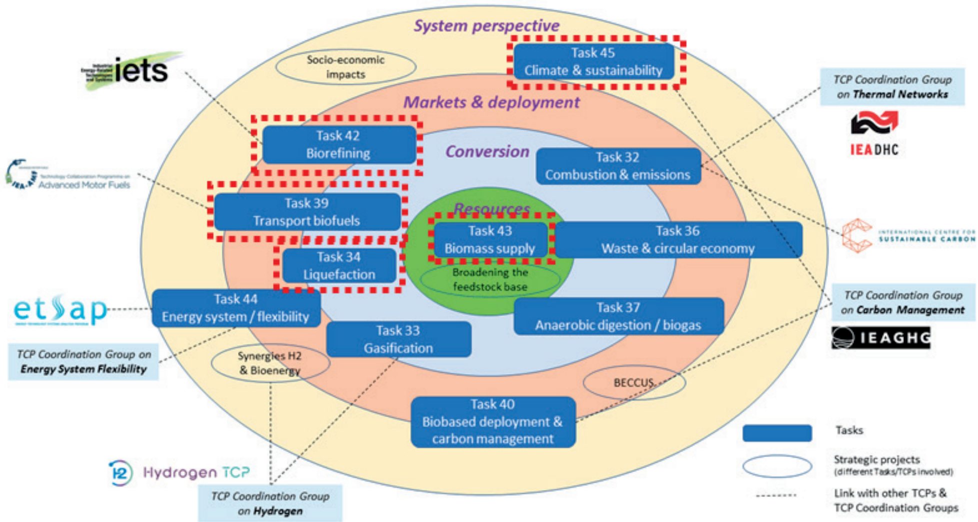


Figure 1.8: Activities performed by the IEA Bioenergy program with scope related to the CLEANSHIPPING project highlighted in brown dotted lines. Source: [57]

### 1.3.3 Case study selection methodology

In 2021, the research was initiated with a case study selection for developing marine biofuel value chains using lignocellulosic materials. A novel systematic selection protocol was implemented using various selection criteria to standardise the selection protocol as recommended by Tassinari *et al.* (2021) [87]. In principle, the selection of cases is an essential part of case study research design. As an exploratory research, the cases are ideally selected strategically to generate as much information as possible about the research objective. Therefore, the case selection methodology implemented the diverse case study method to have representation of different archetypes to capture the diversity in contexts for maximum knowledge generation (which includes opting for feedstocks with minimal experimental data available, as the project consortium included an experimental team). As fieldwork and participatory techniques were to be used in the case study locations, especially during the COVID-19 pandemic, the selection criteria were based on both literature and practical matters, such as accessibility and connections. The case study methodology with different phases involving stakeholder participation is shown in *Figure 1.9*.

In the first phase, the so-called divergent phase, regions along the primary chokepoints in the global maritime routes (as indicated in Figure *1.2*) and with a large availability of lignocellulosic biomass were selected. An initial selection of 23 countries with over 100 feedstocks was made (refer to Appendix I, in section 7.1)

During the second phase, the convergent phase, selection criteria were identified using various literature works reported on the sustainability criteria of biobased supply chains. Furthermore, interviews with experts and project partners were conducted to identify feedstocks with potential opportunities or concerns. The chosen selection criteria were aimed at de-risking the commercial implementation of the potential hypothetical biobased value chain to be investigated. Therefore, the selection criteria were selected across all the dimensions of sustainability, namely technical, environmental, social, and institutional. The list of criteria used is mentioned below

1. Connection to local institutions that are willing to collaborate.
2. Biomass availability (area harvested, yield, productivity, residue-to-crop-ratio).
3. RED II approved.
4. Literature reporting HTL of the feedstock.
5. Political stability (World Bank indicator: political stability and absence of violence).
6. Infrastructure (existence of bio-based industries).
7. Local policy promoting bioenergy development.

Based on the findings, the 10 shortlisted countries were analysed in detail for the contextual knowledge based on data reported in the literature, national databases, and meetings with the local knowledge experts. The features analysed are mentioned below

1. Source of feedstock (Agri-residue, forest residue, energy crop, invasive species).
2. Geographical location (continent).
3. Scale of farming (small-scale, large-scale, combination).
4. Human Development Index (low, medium, high, very high).
5. Type of potential impact to the biomass producing region due to feedstock valorisation (economic, social, environmental).
6. Existing crop in cultivation/new crop to be incorporated.
7. Type of cultivable land (marginal land, wasteland, forest, pastured land).
8. Current utilisation of feedstock (underutilised, exploited partially, exploited fully).

In the third phase, the selection phase, during the project consortium meeting, the project partners were asked to shortlist 3 case studies by voting based on the contexts. The selected case studies were the Olive sector in Spain, the Coffee and Cacao sector in Colombia, and encroacher bush in Namibia. shows the list of countries considered in Phase 1 and selected after Phase 3 for performing case studies.

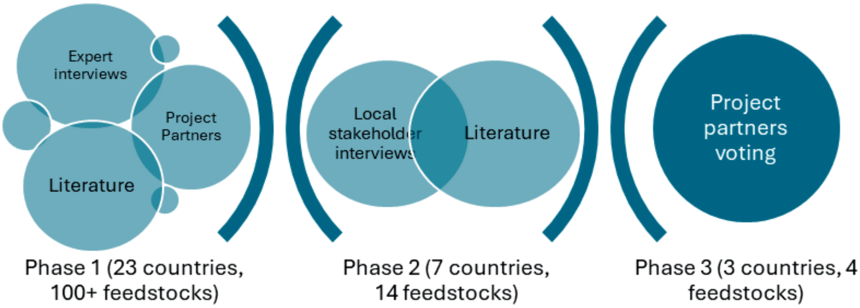


Figure 1.9: The case study selection procedure indicates different phases along with the stakeholder interaction for gathering data for criteria (in Phase 1), context features (in Phase 2), and final selection (in Phase 3).

*Figure 1.10* shows the list of countries considered in phase 1, along with final case studies chosen after Phase 3 of the case study selection methodology.

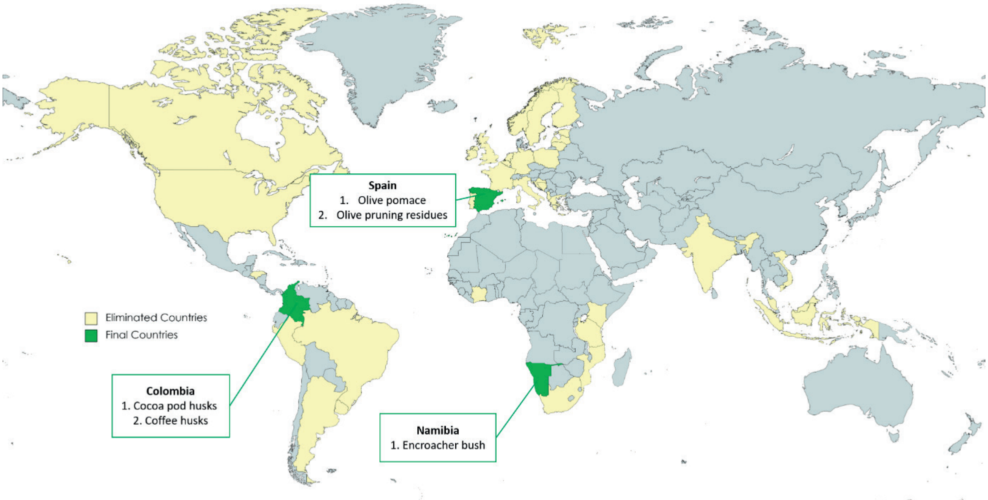


Figure 1.10: Overview of countries initially considered and the final selected countries for the case study in the CLEANSHIPPING consortium

## 1.4 RESEARCH APPROACH

The research approach followed in this thesis is discussed in this subsection. Based on the previous literature works and knowledge gaps identified on the concepts discussed above, this thesis aims to position itself and make further contribution by addressing the main problem statement: *"How can we design and evaluate the performance of context-specific sustainable and inclusive bio-based value chains, with a special focus on marine biofuel production through hydrothermal liquefaction (HTL)?"*. For this purpose, three sub-research questions (RQs) were defined within the scope of early-stage integration of stakeholders' perspectives into the conceptual design of biohubs, evaluating their economic and environmental performance, and ultimately reflecting on the transdisciplinary approach for developing and establishing sustainable and inclusive biohubs for emerging bioeconomies. The three sub-research questions, along with their specific objectives, are as follows,

In Chapter 2, the RQ 1: *"Can we, and if so under what conditions, design socially just and economically feasible biohubs for marine biofuel production based on olive residues in Jaén via hydrothermal liquefaction (HTL)?"* is addressed.

The specific objectives (SO) involved in this research question are,

*SO 1.1* Application of capability sensitive design by bringing considerations of stakeholders' context and capabilities during the conceptual design of the biofuel value chain, with the focus on the design outcome (the biohub or biorefinery concept),

*SO 1.2* Estimation of capital and operational expenses of producing HTL marine biofuels from olive residues in Jaén based on various value chain designs (incorporating stakeholder values and capabilities) and calculating the minimum fuel selling price (MFSP),

*SO 1.3* Comparison of the calculated MFSP of HTL biofuels with general values reported in literature for fossils and other biomass-based HTL biofuels, and

*SO 1.4* Sensitivity analysis on the key parameters that influence the MFSP of HTL biofuels.

The scope of this question is focused on the techno-economic feasibility of biohubs designed by combining or embedding the social aspects with the technical design choices. Therefore, aspects of early-stage social inclusion, technical aspects related to technology, and economic assessments are the key areas of investigation. The methodology implemented to address this question involves a transdisciplinary, multi-actor approach, based on capability-sensitive design for socially just biohubs. With a novel technology, such as hydrothermal liquefaction, various technological aspects were focused on developing the design alternatives. This was achieved through developing various design scenarios based on design propositions, derived from stakeholder interviews and a multistakeholder workshop, for selecting design variables of various elements of biohubs (such as feedstocks, transportation, etc.). The design alternatives, based on stakeholders' capabilities and the prevailing context of the olive sector in the Andalusian region, were evaluated for their technical and economic performance.

As a result, various possible technical biohub configurations, using existing infrastructure, were developed. The local stakeholders opted for a novel residual stream, crude olive pomace (COP), a slurry-like processing residue with high moisture content, as the primary feedstock for the biohubs. The general characteristics of technical configurations of biohubs, based on HTL, that can be economically viable were deduced. The effect of technological choices to incorporate social preferences on the economic performance of the end product was showcased.

However, the nuances of implementing this approach for field residues, especially with a focus on the Global South countries where the infrastructure is not well established, are to be investigated. Therefore, in Chapters 3 and 4, the approach of early-stage stakeholder inclusion is tested for Global South countries. The challenges and perspectives of valorising field residues are crucial as they are the common form of lignocellulosic materials in the low- and middle-income countries. Moreover, the economic feasibility of biohubs should be complemented with the environmental assessment for a better understanding of broader aspects of sustainability. Therefore, the scope of this approach is broadened in the following research question to valorise the field residues from the olive sector in Spain, the coffee sector in Colombia, and the encroaching bush in Namibia, which are currently being underutilised or mismanaged.

Chapter 3 discusses the RQ 2: *"What are the economic feasibility and environmental impacts of the co-designed inclusive field residue-based biohubs for marine biofuel production in Spain, Colombia, and Namibia?"*

The specific objectives of this research question are,

*SO 2.1* Application of capability sensitive design, through Design Propositions by bringing considerations of local context, stakeholders' perspectives and capabilities during the conceptual design of the biofuel value chain, with the focus on the design outcome (the biohub concept)

*SO 2.2* Estimation of capital (CAPEX) and operating (OPEX) expenses of biohubs in Spain, Colombia, and Namibia for producing HTL marine biofuels;

*SO 2.3* Estimation of the minimum fuel selling price (MFSP) of the HTL biofuels, *SO 2.4* Comparison of the calculated MFSP of HTL biofuels from field residues with general values reported in literature for fossils and other biomass-based HTL biofuels,

*SO 2.5* Determination of environmental impacts, especially the global warming potential (GWP100) of HTL biofuels, and

*SO 2.6* Key parametric sensitivity analysis that influences the MFSP of HTL biofuels.

This research question encompasses the facets of early-phase social inclusion, along with the technical, economic, and environmental dimensions of sustainability. To tackle this research question, a similar methodology and approach were implemented as in RQ1. The insights gained from RQ1, such as technical configuration for economic viability, served as a foundation for this segment of the research. However, the scope of this investigation concentrated on field residues in three distinct countries, each representing an archetype in terms of infrastructure and local context. The technological aspects of biohubs also included strategies for the collection, logistics, and pre-processing of lignocellulosic materials from fields, either employing existing systems or proposing novel infrastructure. An attributional e-LCA was conducted alongside the techno-economic analysis for the co-designed context-specific biohubs. The environmental impact assessment highlighted the need to prioritise non-monetary impacts (such as reducing particulate emissions, decreasing fossil depletion, preventing GHG emissions, avoiding soil or air pollution due to the valorisation of mismanaged field residues, etc.) in sustainability analysis.

This research work indicates the potential for unlocking the mobilisation potential of field residues, especially across the Global South, when contextual knowledge is considered during the design stages of bio-based value chains. Moreover, the work also indicates the need for a macro socio-economic impact study to understand the effectiveness and impacts of early-stage social inclusion in the technical design through quantitative indicators. Furthermore, local stakeholders' validation is recommended for selecting context-relevant and meaningful sustainability performance indicators for multi-criteria decision analysis to understand the trade-offs and conflicts of design choices for local regional development.

As discussed in previous sections, integral sustainability assessments in terms of economic, environmental, and social aspects combined are crucial for biorefinery and bio-based value chains development. However, after decades of research, the global deployment of commercial-scale bioeconomy is still far from realisation, indicating blind spots in the conventional design approach. Biomass mobilisation is considered a key limiting factor for large-scale biorefineries [88], and many projects (such as Abengoa and Beta Renewable's Crescentino in Italy) were unsuccessful in establishing the same [89], [90]. The failure of the projects can be attributed to various factors, including social aspects such as the lack of contextual awareness of biomass-producing regions for the development of sustainable and inclusive bio-based value chains. Therefore, looking back at the transdisciplinary approach and results of RQ1 and RQ2, the general and context-specific challenges and the opportunities for commercial implementation of the co-designed biohubs, across the three case studies, are to be analysed for developing a business case. Therefore, in Chapter 4, the following research question aims to address,

RQ 3: *"What are the empirical outcomes of operationalising early-stage regional multi-stakeholder inclusion on the conceptual design of bio-based value chains across three different case study locations?"*

Especially aiming at the specific objectives of

*SO 3.1* Performing a comparative analysis and identifying common desired biohubs characteristics,

*SO 3.2* Identifying context-specific enablers for biohubs development, with the help of a "SWOT" assessment of the three locations for the potential to implement a sustainable and inclusive biobased value chain development

*SO 3.3* Finding context-relevant purposes of biohubs implementation for local socio-economic development at biomass producing regions, and

*SO 3.4* Identifying conflicts and trade-offs for sustainability due to early-stage stakeholder inclusion into the conceptual design process

The effectiveness of the approach was analysed from a designer's perspective. The biohub characteristics, across the three case studies, were analysed from the aspects of biomass (such as the choice of nature of feedstock, feedstock transportation mode, etc.) and biorefineries (biomass conversion technology, byproducts valorisation, etc.). With the help of a SWOT analysis of the existing sectors to develop biohubs, various enablers (such as maximum value addition near the biomass producing region, marketable anchor product, capacity building, etc.) for biobased value chains were identified. The roadmaps to achieve the successful implementation of biohubs were found to be based on the ability to achieve context-specific purposes (such as strengthening the existing sector for sustainability, contributing to the local sustainable development goals, improving energy and material security, etc.) for local socio-economic development in the biomass-producing region. The analysis also highlighted the sustainability conflicts and opportunities for addressing the trade-offs while performing a transdisciplinary approach to promote sustainability and inclusion in the conceptual design of biohubs, with the end goal of commercial real-life implementation.

In Chapter 5, the overall conclusions are discussed by presenting the study findings (such as the economic benefit of co-processing, environmental impact of valorising mismanaged or under-utilised biomass, addressing social sustainability by including local stakeholders in co-designing biohubs), and recognising the limitations (such as restriction in case study selection methodology due to the COVID-19 pandemic, use of literature data for process simulations instead of actual experimental data for HTL and upgrading processes).

Finally, in Chapter 6, recommendations for future work are provided, followed by proposing a framework which enables early-stage consideration of the concepts of responsible research and innovation into the technical design choices of the biobased value chain and their assessments for sustainability. The framework aims at addressing the limitations of the study and recommendations for future research to enhance the interaction of social sciences with engineering disciplines for developing a truly sustainable, inclusive, and circular bioeconomy for all.

## 1.5 AUTHOR CONTRIBUTIONS

The author of this dissertation has written all the chapters. The case study selection was performed together with another PhD candidate of the CLEANSHIPPING project, with equal contribution. The status of the Chapters is mentioned below

1. Chapter 2: Published in the Journal of Energy Conversion and Management: X

Contribution of (co-)author(s): **S. Chandrasekaran:** Conceptualisation, Data curation, Formal analysis, Investigation, Methodology, Software, Visualisation, Writing – original draft. **A. M. Vidal:** Investigation, Writing – review & editing. **E. Castro:** Methodology, Investigation, Resources, Writing – review & editing. **P. Osseweijer:** Conceptualisation, Methodology, Writing – review & editing, Supervision, Funding acquisition. **J. Posada:** Conceptualisation, Formal analysis, Writing – review & editing, Supervision, Project administration, Funding acquisition.

2. Chapter 3: Manuscript under review in the Chemical Engineering Journal

Contribution of (co-)author(s): **S. Chandrasekaran:** Conceptualisation, Data curation, Formal analysis, Investigation, Methodology, Software, Visualisation, Writing – original draft. **P. Osseweijer:** Conceptualisation, Methodology, Writing – review & editing, Supervision, Funding acquisition. **J. Posada:** Conceptualisation, Formal analysis, Writing – review & editing, Supervision, Project administration, Funding acquisition.

3. Chapter 4: Manuscript submitted to the peer-reviewed journal of Technological Forecasting and Social Change

Contribution of (co-)author(s): **S. Chandrasekaran:** Conceptualisation, Data curation, Formal analysis, Investigation, Methodology, Visualisation, Writing – original draft. **S. van der Veen:** Methodology, Data curation, Formal analysis, Investigation, Writing – review & editing. **A. M. Vidal:** Investigation, Writing – review & editing. **E. Castro:** Methodology, Investigation, Resources, Writing – review & editing. **D. C. Meza-Sepúlveda:** Methodology, Investigation, Resources, Writing – review & editing. **E. Andreas:** Investigation, Writing – review & editing. **P. Kashandula:** Resources, Writing – review & editing. **L. Asveld:** Writing – review & editing, Funding acquisition., **P. Osseweijer:** Conceptualisation, Writing – review & editing, Supervision, Funding acquisition., and **J. Posada:** Conceptualisation, Methodology, Writing – review & editing, Supervision, Funding acquisition.

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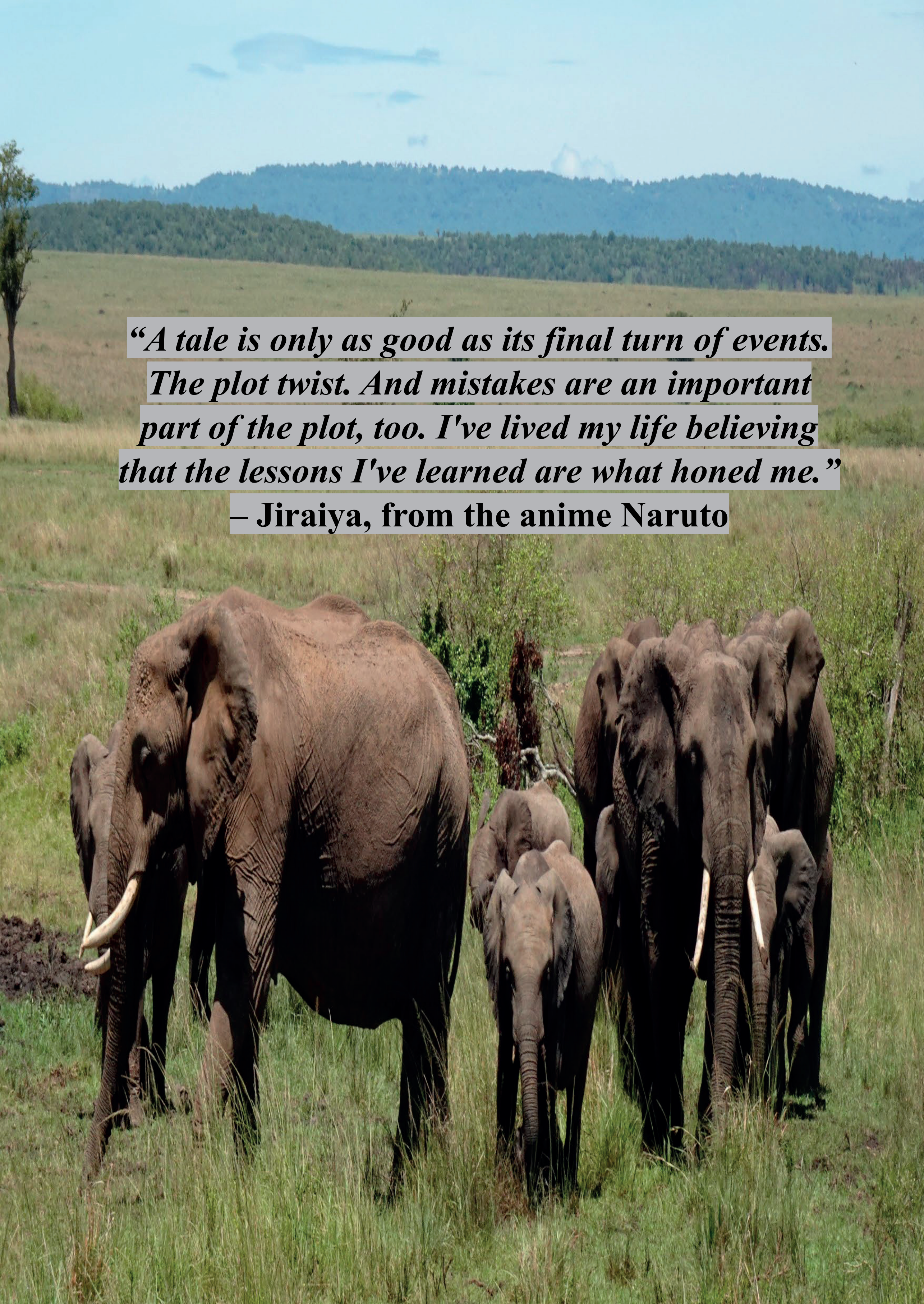
*“A tale is only as good as its final turn of events. The plot twist. And mistakes are an important part of the plot, too. I've lived my life believing that the lessons I've learned are what honed me.”*
**– Jiraiya, from the anime Naruto**


2

# 2

# Techno-economic feasibility of olive residue-based biohubs for marine biofuel production: a capability-sensitive and context-specific approach in the Mediterranean Region

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## 2.1 INTRODUCTION

In 2021, the European Union (EU) adopted the "Fit for 55" plan, which aims to reduce the EU's emissions by at least 55% by 2030 and make the EU climate-neutral by 2050 [1]. Under FuelEU maritime, various targets will ensure that the greenhouse gas (GHG) intensity of fuels used in the sector will gradually diminish, starting from a 2% reduction by 2025 and eventually leading to an 80% reduction by 2050 [2]. According to the International Energy Agency (IEA), "drop-in" advanced biofuels (AB) can be a promising alternative as they can function as short-term to mid-term solutions for the green transition of the hard-to-defossilise, carbon-intensive marine sector [3]. With approximately 1 billion dry tonnes of sustainable biomass potential in Europe from the agriculture, forestry, and other biowaste sectors, the EU is expected to be a front-runner in the deployment of commercial bioenergy pathways [4].

With 5 million hectares of land under cultivation, the olive sector is one of the major agricultural sectors in the EU, with Spain as the leader (63%), followed by Italy (17%), Greece (14%), and Portugal (5%). The European Union (EU) has been the leading producer of olive oil in the world, contributing 69% of the global share [5]. However, olive oil production is a resource-intensive process with a high undesired environmental impact associated with water and soil pollution and carbon dioxide emissions. Annually, the EU olive sector produces a total of 21.4 million tons of waste (in the form of wood, leaves, and branches) and byproducts (such as wet olive pomace and olive mill wastewater) [6]. Currently, in regions of Spain and Italy, the wet pomace is processed in a secondary extraction mill to extract its residual oil content via an energy-intensive, unsustainable chemical extraction. Most of these mills are privately owned and are seen as the only method for disposing of wet pomace due to the lack of other alternatives [7]. On the farms, some farmers chip the olive tree pruning to burn it in the field, causing a fire hazard. Hence, valorising these large volumes of underutilised residues that are found all over the Mediterranean region to produce advanced "drop-in" biofuels for the marine sector, which has never been investigated before, offers tremendous potential which remains to be explored.

Hydrothermal liquefaction (HTL) is one of the "Biomass to Liquid" (BtL) thermochemical conversion pathways that directly transforms wet biomass into liquid bio-oil under moderate temperature (280- 370°C) and high pressure (10-25 MPa), with or without the presence of a catalyst. This eliminates the requirement for energy-intensive feedstock drying prior to biomass conversions such as in conventional gasification and pyrolysis [8], [9]. Due to the superior physio-chemical quality of bio-oil, such as lower oxygen content (5-15 wt.%) and higher heating value (30-37 MJ/kg), and potential ability to be co-processed with crude oil in a refinery, HTL has attracted wide interest in research from academia and industries with various feedstocks including municipal solid wastes (MSW), sewage sludge (SS), and micro-algae [10], [11], [12]. Over the past decade, the Pacific Northwest National Laboratory (PNNL) in the United States has investigated the economic performance of common thermochemical conversion pathways using diverse feedstocks across various scales (from state-of-the-art technology (SOT) to $N^{th}$ kind plant) [13], [14], [15]. Tanzer *et al.* (2019) reported that liquefaction pathways (fast pyrolysis and HTL) had better economic performance across all considered feedstocks over the gasification-based route owing to high capital expenditures (CAPEX) and the use of expensive chemicals in gas processing. In the work conducted by Tews *et al.* (2014), the minimum fuel selling price (MFSP) of upgraded fuel from fast pyrolysis was estimated to be $1.1/kg in comparison with $0.7/kg for upgraded fuel via the HTL route [16]. Y Zhu *et al.* (2014) investigated the effect of processing capacity and the learning curves of technology development on the economic performance of HTL-based fuel systems [14]. The investigation also included the impact of system configuration (stand-alone facility vs decentralised HTL facility + central upgrading facility) and learning curve of the technology (pioneer (SOT) state-of-the-art technology or commercial "$N^{th}$" kind) on the MFSP of the product. They identified that the production cost of the $N^{th}$ kind plant was almost 43% lower than the SOT case. Also, the MFSP of the decentralised system was 26% and 44% less than the $N^{th}$ kind and standalone case, respectively. This was due to the reduced capital costs with a minimal plant size of 150 dry metric tons per day (DTPD) of biomass. Environmentally, HTL biofuels perform better, with less GHG emission from the process, with up to 90% reduction, in comparison to fossil fuels [17], [18], [19], [20]. S. Chandrasekaran *et al.* (2023) reported that advanced biofuels from olive residues in Jaén can achieve significant GHG emission reduction in comparison with conventional marine fuels [21]. However, the economic potential of HTL to valorise olive residues to produce biofuels remains unknown to the scientific world.

Albeit the advantages of significant feedstock availability, the ability to integrate with existing production and consumption infrastructure, and various conversion pathways, advanced biofuels are still far away from being deployed commercially in vast quantities globally. Some of the key reasons are significant differences between the reported theoretical and practical feedstock availability, lack of capacity in terms of coordination and infrastructure to mobilise massive quantities of biomass, social inclusivity and acceptance of the project, and institutional frameworks to enable the establishment of biobased value chains. The conventional social- and context-exclusive approach to value chain design has always had shortcomings in a) identifying a robust, holistic, sustainable biobased business case and b) flagging crucial showstoppers that are often the reasons for failure to establish successful biobased projects. It is argued, therefore, that early-stage combined incorporation of technical (process, logistics, and infrastructures), environmental (resources sourcing and consumption), and social (contextual and cultural) elements is required during the conceptual design. Value-sensitive design (VSD) and Capability-sensitive design (CSD) are two novel approaches under the Responsible Research and Innovation (RRI) theme that combine technical and non-technical components in a value chain. VSD and CSD are approaches to proactively design by considering stakeholders' values and capabilities, respectively. Palmeros Parada *et al.* (2017) proposed an analysis for explorative VSD research to investigate stakeholders' values and generate project-specific principles for the early-stage design of biorefineries [22]. In a following study, Parada *et al.* (2018) validated this analysis by performing empirical work focusing on the design process to promote the consideration of social aspects during the midstream modulation of the research phase [23]. Furthermore, Veen *et al.* (2024) broadened the approach by combining the VSD approach with the capability approach (CA) into the capability-sensitive design (CSD) to include ethical consideration and to enhance human capabilities through opportunities in new biobased value chains [24]. To address the real-world challenges of climate change, value chain designs should effectively and inclusively integrate technical and non-technical aspects of supply chain development simultaneously from the early stages of conceptualisation.



Therefore, this study investigates the economic feasibility of a "first-of-a-kind" novel approach to a social context-sensitive value chain design to valorise olive residues for producing alternative renewable fuels for the shipping sector. The context-specific and capability-sensitive designs bring the much-needed integration of social non-technical elements within the technical domain of process development. This study aims to address the problem statement *"Can we, and if so, under what conditions, design socially just and economically feasible biohubs for marine biofuel production based on olive residues in Jaén via HTL?"*. In this study, we define biobased value chains through the concept of biohubs. A bio-hub is a circular system where private and public actors cooperate to 1) source bio-based streams and wastes, and transform them into marketable products, 2) improve the sustainability of local farming practices and traditional biomass use, 3) fulfil local needs, including energy and clean water, and 4) fairly distribute costs, benefits, risks and opportunities. In this investigation, we co-designed various biohubs design configurations by implementing participatory techniques (such as stakeholder interviews and a multistakeholder workshop) using the CSD approach. The economic and technical feasibility was further analysed by a techno-economic evaluation of the designs to understand the impact of key parameters on the feasibility of the designs. The following points were addressed in this study: a) validation/application of CSD by bringing considerations of stakeholders' values and capabilities during the design of the biofuel value chain with the focus on the design outcome (the biohub or biorefinery concept), b) estimation of capital and operational expenses of producing HTL marine biofuels from olive residues in Jaén based on various value chain designs and calculating the minimum fuel selling price (MFSP), c) comparison of the calculated MFSP with general values reported in literature, and d) sensitivity analysis on the key parameters that influence the MFSP of HTL biofuels. The "methodology" section presents the approach and techniques implemented in designing and evaluating biohubs. The results are shown and discussed in the "Results" section, followed by a conclusion for the limitations of the study and future recommendations.

## 2.2 METHODOLOGY

### 2.2.1 System and Scenarios

#### *2.2.1.1 Spanish Olive sector and residues availability in Jaén*

In this work, the Andalusian region, located in the south of Spain, is considered for investigation. With almost 60% of the national olive cultivation present in the region, concentrated in the provinces of Jaén, Cordoba, and Seville, around 80% of Spain's olive oil is produced in Andalusia [25]. As a result, various (field and processing) residues are generated across the value chain in this region. Olive tree pruning biomass (OTPB), the largest field residue in the traditional cultivation practice, is generated at the cultivation stage in the farms during the biannual pruning season. During olive processing at (Cooperative and privately owned) primary mills, crude olive pomace (COP), olive stones (OS), olive leaves (OL), and olive mill wastewater (OMWW) constitute the residue generation. In Spain, the COP is further treated in specific (private) industries to extract the residual oil content via a chemical extraction technique to produce exhausted olive pomace (EOP) and pomace olive oil (POO). An overview of the material flows in the olive sector and the characteristics of residual streams are represented in *Figure 2.1* and *Table 2.1*, respectively.

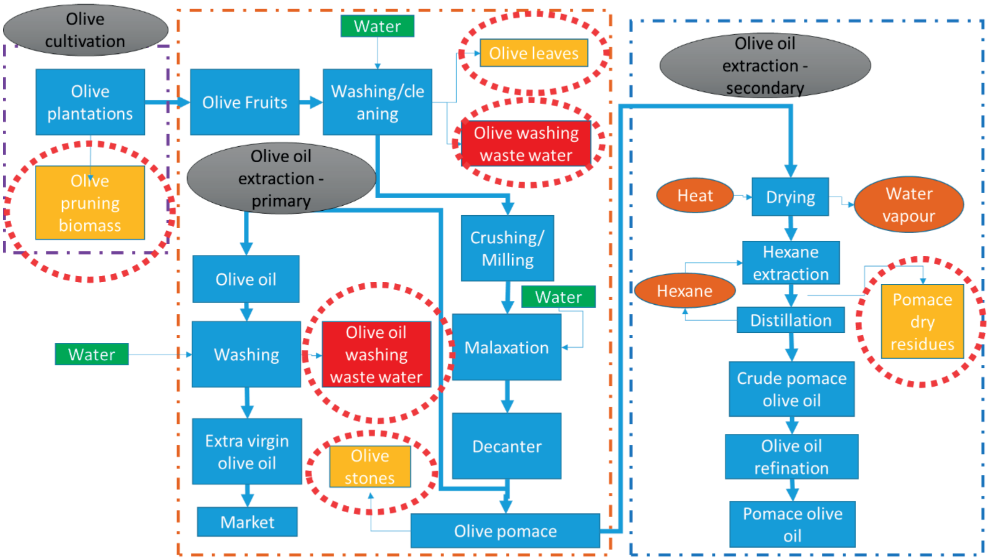


Figure 2.1 Stages (purple dashed box – olive cultivation, brown dashed box – primary olive oil mill, blue dashed box – secondary extraction mill) in olive oil production with residue (highlighted in red dots) generation.

Table 2.1: Overview of residue from the olive sector in the region of Andalusia. Sources: [7], [26], [27], [28], [29]

| Residue Type | Source location | Estimated production | Residue availability in Andalucia (in million metric tons) | Energy content (in MJ/kg) | Current utilisation |
|---|---|---|---|---|---|
| OTPB | Field | 1.5-3 t/ha | 1.3 | 16.7-19.8 | Direct burn |
| OL | Primary mills | 5-10% w/w of olives | 0.2 | 18.8-20.9 | Animal feed |
| COP | Primary mills | 50-60% w/w of olives | 4.5-5.5 | 18.6 | Extraction of pomace oil |
| OS | Primary mills | 8-12% w/w of olives | 0.4 | 20.7 | Energy |
| EOP | Secondary mills | 20% w/w of COP | 0.9 | 13.8-15.8 | Energy |
| OMWW | Primary mills | 50-100% w/w olive oil | 0.8-2 | 16-20 | Evaporated in open ponds |

The province of Jaén is identified as a suitable region to develop olive (residue) based biohubs due to: a) abundant availability of olive residues (within a 30 km radius), b) existing biomass handling infrastructure, and a less fragile environment, c) access to existing oil refinery infrastructure for bio-oil upgrading at Compañía Española de Petróleos, Sociedad Anónima (CEPSA) oil refinery with a crude distillation capacity of 240,000 barrels per day located in Cadiz, on the northern shore of the Bay of Algeciras, and d) access to regional markets for marine biofuel at either Port of Algeciras or Port of Gibraltar [30] . The location chosen for investigation is shown in *Figure 2.2*. The list of primary and secondary olive mills in the chosen regions of investigation is indicated in the Appendix 7.2.1.

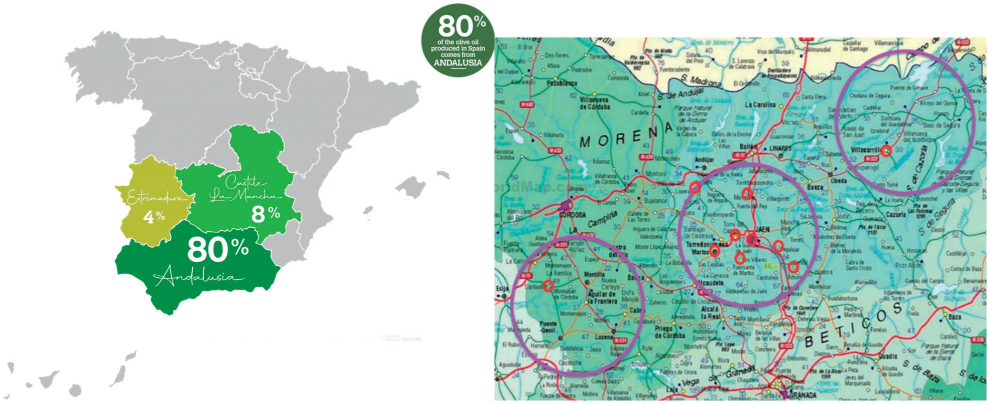


Figure 2.2: Regional olive oil production contribution percentage to national output (left) in Spain and the Region of consideration of biofuel value chain (right) (adapted from [30]. Red dots indicate the places where stakeholder interviews were conducted.

#### 2.6.1.2 *Design Space and Propositions*

This work is conducted in collaboration with the work of Veen *et al.* (2023) under the same project, CLEANSHIPPING [24]. A field visit is performed where various diverse stakeholders (such as farmers, farmer unions, technology developers, government officials, etc.) are engaged via participatory techniques (including 44 interviews and 1 multi-stakeholder workshop). These techniques led to the identification and validation of the ideal and suitable design characteristics of olive residue-based biohubs in the region, considering the prevailing context (such as existing biomass uses, cultural preferences, etc.). The questionnaire used during the stakeholder interviews and the format of the multi-stakeholder workshop conducted in Jaén are summarised in the Appendix 7.2.6. Design space is obtained by considering different biohub aspects such as biomass extraction, biorefinery, final products, and benefits generated. Design propositions are derived from the identified desired characteristics of the biohub, which were then translated into conceptual process scenario designs.

### 2.6.2 HTL and Upgrading Process

Based on the capacities of different (primary and secondary) olive oil mills, a hypothetical 588 dry biomass tons per day (DTPD) biofuel value chain was used as the base case scenario (which is the capacity of the largest secondary extraction mill in Jaén) for the techno-economic analysis. The capacity chosen was based on the feasibility of transforming the largest capacity secondary extraction mill in the region. The annual operating hours of the facility were assumed to be 8000 hours per year [17].

#### *2.6.2.1 Process description*

The HTL biofuel production system includes two parts, i.e., bio-crude production via thermochemical HTL process in a biorefinery and bio-crude upgrading in the oil refinery to marine biofuel by hydrotreating. The process design of biorefinery conversion and bio-crude upgrading is based on the literature [16], [17], [27]. Biorefinery conversion includes the following processes: HTL and a cogeneration (CHP) plant. Because the raw material is already a slurry-like material, no feedstock preparation step is necessary. Bio-crude upgrading includes bio-crude hydrotreating and a Pressure Swing Adsorption (PSA) unit for hydrogen recycling.

In the biorefinery, the incoming COP is stored in a closed environment. It is then mixed with hot water (fresh and recycled from HTL) to form a slurry with 15 wt.% solids content. Following, the prepared slurry is pressurised using a series of pumps and sent to the HTL reactor. HTL process occurs at 330°C and 150 bar and produces bio-crude, off-gases, post-HTL wastewater, and biochar. The non-condensable off-gases, consisting mainly of carbon dioxide and a small fraction of C1-C4 hydrocarbons, were burned in the cogeneration plant to produce process heat and electricity. Due to a lack of understanding of biochar properties for other applications, biochar was burned along with the off-gases for similar purposes to make the biorefinery self-sufficient for energy. The excess electricity was fed to the national grid. Based on the work of Zhu *et al.* (2021), the water stream from the HTL process was rich in nutrients and carbon from the feedstock; therefore, 75% of it was recycled back to the process to capture the atoms as well as to reduce the amount of freshwater consumed [31]. The remaining 25 % of purged wastewater was sent for treatment in a municipal wastewater treatment plant.

The HTL bio-crude was transported, in liquid tanker trucks, to the port of Gibraltar for bunkering in the scenario where the direct blending of HTL bio-crude with fossil marine fuel (VLSFO) was possible. Alternatively, an upgrading step was investigated.

The HTL bio-crude is a heavy organic liquid with a relatively high oxygen content that can be converted into conventional fuel via hydrotreatment. This process of treating the bio-crude with hydrogen occurs at 250- 450°C under a pressure of 0.75-30 MPa [32]. Andalusian regions foresee and are investing in a lot of green hydrogen projects, therefore, green hydrogen for the hydrotreater was assumed to be procured from external providers located in the region. Conventional NiMO/$Al_2O_3$ catalysts were assumed to be used, according to Tews *et al.* (2014), similar to the hydrotreatment of fossil crude. The required quantity of the catalysts was calculated, in a similar method reported by Tews *et al.* (2014), using the liquid hourly space velocity (LHSV) of the hydrotreater reactor[16]. The hydrotreating reactor effluent was further classified into upgraded oil, off-gases, and wastewater streams. Based on the requirement and scenario, the upgraded oil was further distilled into naphtha, jet, and diesel fractions. The off-gases with light hydrocarbons were sent to the PSA unit to recover hydrogen and are further flared.

In an integrated stand-alone HTL biohub configuration, the HTL process and hydrotreatment unit were present in the same facility. However, in a distributed HTL biohub configuration, bio-crude from various (small) HTL biorefineries was transported via liquid tanker trucks to a larger petroleum refinery with existing infrastructure to co-process the bio-crude along with the fossil crude. *Figure 2.3* shows the process flows for the integrated and distributed HTL biohub systems.

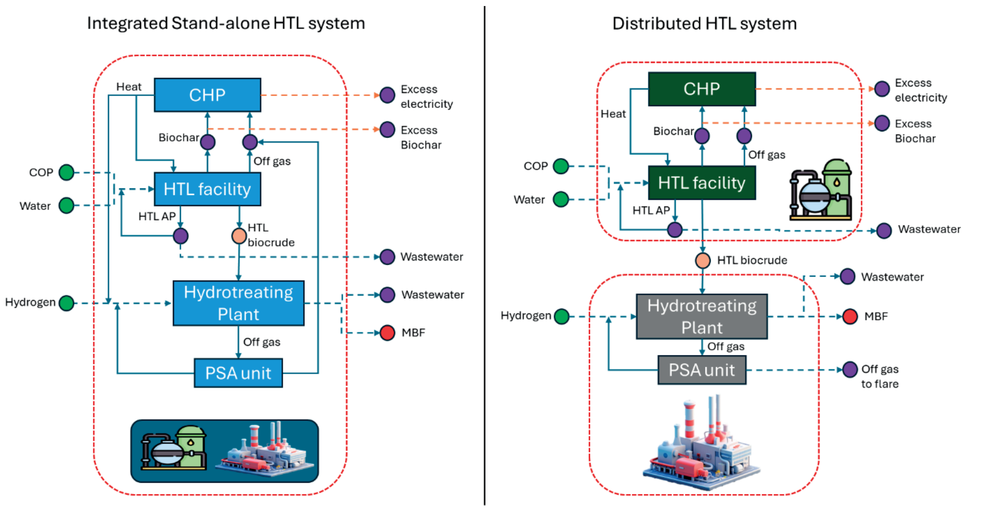


Figure 2.3: Process flow diagram of biomass to biofuels conversion stage for an integrated and distributed system, where green dots represent inputs, red dots indicate the final product, orange dots indicate intermediates, and purple dots indicate by-products. Internal stream flows are described using weighted lines, and blue dotted lines indicate external flows. System boundaries are visualised using brown dashed lines.

### *2.6.2.2 Modelling approach*

A robust modelling approach was performed for the HTL and the upgrading stage applicable to different feedstocks has been used for crude olive pomace in the context of Spain. The co-location assumption is independent of the methodologies used. The HTL methodology applies to various feedstocks; however, in this case is evaluated for crude olive pomace processing. Similarly, the approach used in the upgrading process of hydrotreatment is not influenced by co-location in a refinery.

#### *2.6.2.2.1 Process simulation*

Aspen Plus was used to perform process simulations to obtain mass and energy balances. For the developed design scenarios, the thermochemical reactor and its operating process conditions were considered to be the most relevant factors. The results reported in the work of Cutz *et al.* (2025), Evcil *et al.* (2021), and Filippis *et al.* (2016) were used as the basis for process conditions and yields [27], [33], [34]. A yield reactor was used to simulate the HTL unit, at a steady-state condition at a constant operating temperature and pressure. From the literature, it can be inferred that the operating conditions play a crucial role in determining the chemical composition of the biocrude, energy efficiency of the process, and mass distribution of the HTL output streams [34]. For instance, at a lower temperature range (250°C- 280°C), the biochar yield is higher than that of biocrude. Similarly, the use of a catalyst can contribute to an increase in the biocrude yields [34]. As the choice of thermodynamic property methods is crucial to achieving reliable modelling parameters, various models were considered. The Soave-Redlich-Kwong (SRK) method was chosen for all unit operations except for gas-liquid separators, for which the non-random two-liquid (NRTL) method was used due to the vapour-liquid equilibrium description [19], [20]. The operating conditions are reported in *Table 2.2*.

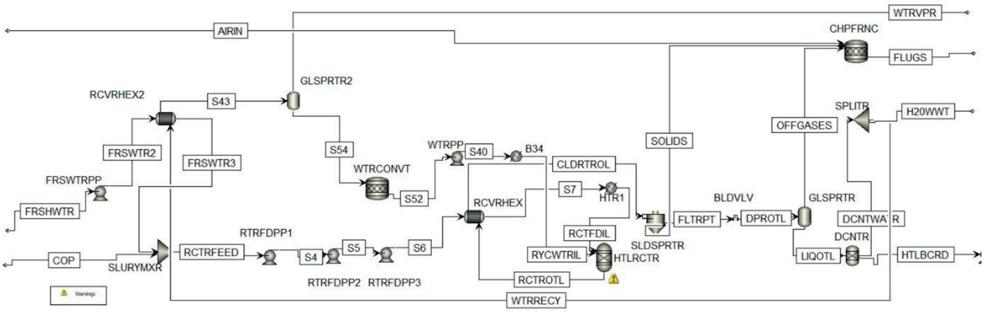


Figure 2.4: Aspen Plus process flowsheet of HTL system

The composition of the gas product was assumed to be like that reported by Tews *et al.* (2014) due to a lack of experimental data. Similarly, the organics in the aqueous stream were assumed to be 5% of the organic fraction. The composition of the bio-crude oil was modelled using the model compounds reported in the literature [27]. In the case of missing compounds in the Aspen database, a substance with a similar boiling point, molecular mass, and functional group was chosen. The composition of the bio-crude is reported in Appendix 7.2.4.17.2.4.

#### *2.6.2.2.2 HTL*

The PFD of the biomass conversion system is shown in *Figure 2.4*. The (slurry-like) crude olive pomace is mixed with the required amount of water to obtain the desired solid/liquid ratio. The feed slurry is then pumped to a preheating unit, which uses the reactor outlet for heat exchange, and then to the liquefaction reactor. After the required residence time, the reactor outlet is sent to a filter to remove solid residues, which are then combusted for heat generation. The furnace inlet airflow rate is determined by the oxygen excess specifications to obtain complete combustion, i.e., 5 wt.% Oxygen in excess. During startup or under capacity of residues, natural gas can be co-fed to the furnace to meet the threshold process heat. An adiabatic furnace is used for combustion, therefore assuming complete transfer of heat to the flue gas, which is then used to heat the HTL reactor. Surplus heat will be recovered as electricity before the flue gas is discharged at 150°C.

The hot HTL reactor effluent is passed through a recovery heat exchanger to heat the influent feed stream, enabling separation and reaction. The off gas, usually light gases, is separated using a flash drum at 50°C and 1 atm. This ensures a high separation efficiency of the light gas fraction. The recovered off-gas stream and solid residue are sent to the furnace as fuel for the combustion [20]. The oil-aqueous stream is then passed to a decanter where the aqueous phase is removed. The separated aqueous phase (consisting of 5 wt.% organics) is then recycled back with a 75% ratio to minimise the costs related to wastewater treatment. The most relevant data process inputs and assumptions for bio-crude production via HTL are listed in Table 2.2**.**

#### *2.6.2.2.3 Bio-crude-oil upgrading*

A single-stage hydrotreatment process is used in this study. The process flowsheet of the bio-crude upgrading system is shown in *Figure 2.5*. The reactor outlet is cooled down, depressurised, and the gas stream is separated. The separated gas stream still contains unreacted hydrogen, which will be recovered using a pressure swing adsorption unit and recycled back into the upgrading reactor to improve the hydrogen conversion efficiency. The upgrading conditions considered in *Table 2.2* are based on bio-crude components as listed in the Appendix 7.2.4. Moreover, excess hydrogen is provided, exceeding the required stoichiometric quantity, to ensure complete deoxygenation. The hydrogen stream is compressed using a multistage compressor with intermediate cooling stages to reduce the work done. As a precaution, the liquid stream is further sent to a decanter for aqueous phase removal. Literature suggests that a minimum of 25 wt.% of water is required to achieve an effective phase separation [20]. Since the water produced during the process does not meet the threshold, the liquid separation is performed more as an enhancement unit. Based on the requirement and quality of the upgraded bio-crude, the organic stream is further sent to a series of distillation units (designed as RadFrac units in Aspen Plus) to obtain naphtha, bio-jet, and diesel fractions. The recovered hydrogen stream is mixed with the incoming hydrogen stream prior to the compression stage.

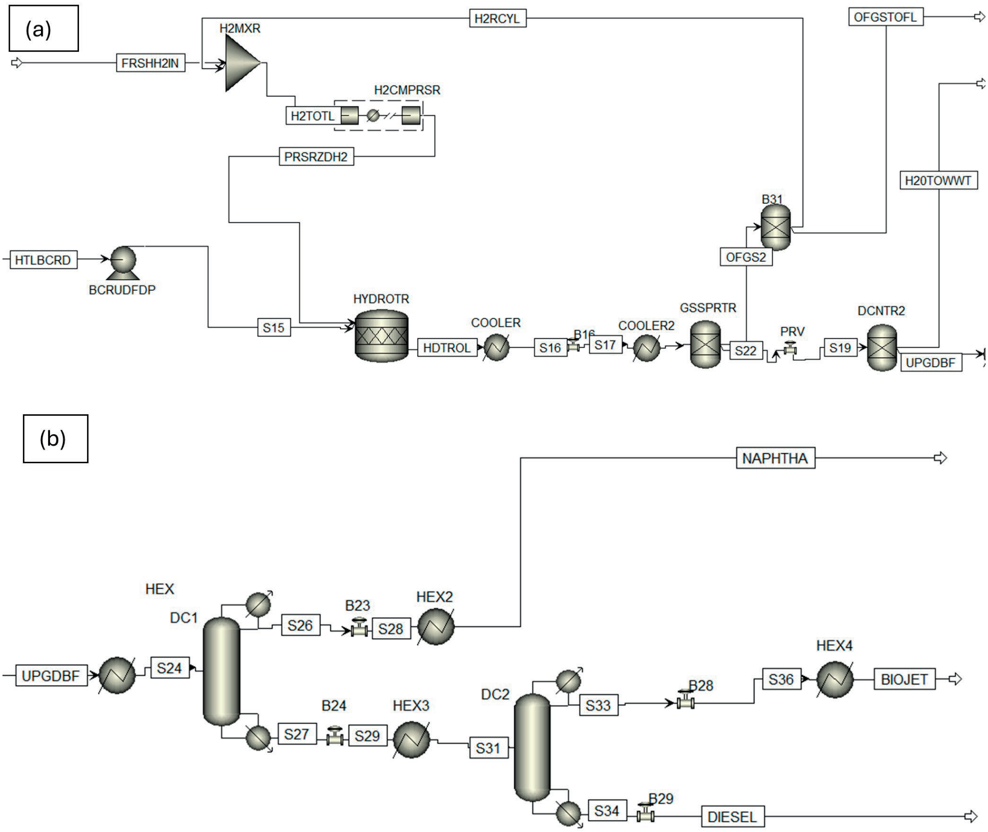


Figure 2.5: Aspen Plus process flowsheet of HTL bio-crude upgrading system. a) Hydrotreating section, b) Fractionation section

Table 2.2: Major modelling parameters for biomass to the biofuels conversion stage

| Parameters | Value and conditions | Data Source |
|---|---|---|
| **Biorefinery** | | |
| Capacity | 588 DTPD | |
| Total operating time | 8000 hours | |
| Hydrothermal Liquefaction | | |
| Material and Energy input | | |
| *Temperature* | 330°C | [35] |
| *Pressure* | 150 bars | [35] |
| *Catalyst* | - | |
| *Biomass/water ratio* | 0.15 | [35] |
| Output yields | | |
| *Biooil/Off gas/Aqueous stream/Biochar (in kg/kg DM biomass)* | 0.29/0.24/0.19/0.28 | [35] |
| *Energy content bio-oil/biochar (in MJ/Kg)* | 31.2/28.1 | [35] |
| **Oil refinery** | | [16], [32] |
| Hydrotreating | | |
| *LHSV, $h^{-1}$* | 0.22 | |
| Material and energy input | | |
| *Catalyst* | 0.41 kg catalyst/tonne bio-oil | |
| *Temperature* | 400°C | |
| *Pressure* | 106 bars | |

### 2.6.3 Economic analysis

The process modelling and simulation directly influence the economic model, which estimates the minimum fuel selling price (MFSP) or the break-even selling price for each biofuel. The methodology proposed by Sieder *et al.* (2017) is used to calculate the capital expenses and operating costs of a 588 DTPD greenfield biorefinery using olive residues [36]. The same has been tabulated in *Table 2.3* and *Table 2.4*, respectively. The rates are normalised to 2023 Euros using the Chemical Engineering Plant Cost Index (CEPCI), and the conversion rates are mentioned in the Appendix 7.2.8.

### 2.6.4 Capital investment

Based on Sieder *et al.* (2017), the CAPEX is calculated using the cost of equipment, using the estimation formula in *Table 2.3*. Equipment costs are calculated based on the mass balances obtained from process models to determine the size of the equipment. Total Purchased Equipment costs (TPEC) are scaled to the necessary capacities using suitable factors of 0.65-0.75, following Swanson *et al.* (2010) and Tews *et al.* (2014). The installation factor is assumed to be 2.5 on average [16], [37].

For easy and short-term to mid-term project implementation, the facility's operating capacity is matched with the raft capacity of the largest secondary extraction mill in Jaén, i.e., 588 DTPD [30]. The project's life span is assumed to be 15 years, as opposed to the conventional 30 years in the petrochemical sector [17]. Furthermore, due to the non-commercialisation of biorefineries and minimal construction experience, a 50% contingency factor is assumed, against a conventional 15-20%, for an $N^{th}$ kind of plant design [17].

Operational expenses are included within the working capital prior to sales revenue and were based on the prediction of sales revenue using market prices of marine gas oil (MGO) or very low sulphur fuel oil (VLSFO) and electricity. Finally, to make a relevant and realistic estimation, the location factor was considered to include the variations in costs reported in the literature and biorefinery sites.

Table 2.3: Methods for estimating the CAPEX of the investigated HTL biofuel production process [36].

| Symbol | Description | Formula or factor |
|---|---|---|
| **FCI** | **Fixed capital investments include** | **FCI = DC + IC + CF + CC** |
| DC | Direct capital costs include | DC = TPEC + INST |
| *TPEC* | *Total production equipment costs* | *Combination of scaled equipment costs* |
| *INST* | *Installation costs (labour and materials)* | *250% of TPEC* |
| IC | Indirect costs | 34% of DC |
| CF | Contractor's fee | 23% of TPEC |
| CC | Capital contingency | 50% of TPEC |
| **WC** | **Working capital** | **20% of sales revenue** |
| **SC** | **Startup costs** | **7% of FCI** |
| **LF** | **Location factor** | **0.9** [38] |
| **CAPEX** | **TOTAL CAPITAL INVESTMENT** | **CAPEX = LF*(FCI + WC + SC)** |

## 2.6.5 Operating costs

Operating costs or operating expenses (OPEX) are costs incurred during the facility's operation. It uses site-specific regional costs for feedstocks, water and electricity, taxes, human labour, insurance, and capital depreciation. A detailed split of operating costs is shown in the Appendix 7.2.8.3.2. To accommodate the learning curve of the technology, a contingency factor of 20% was accounted for on direct production costs for unforeseen expenses due to technology in the early stage of commercialisation. The contingency factor in OPEX is less than that of CAPEX as the operating know-how is certain and similar to that of the petrochemical sector, hence fewer uncertainties. The variable costs (such as feedstock costs, etc.) were calculated based on the scaled capacity of the facility.

Similar to that of da Silva (2016), for calculating human capital or labour costs, an assumption of three 8-hour shifts with 6 workers per shift was made [39]. The costs of chemicals, water, landfill, and natural gas were obtained from literature and stakeholders during field visits. Although according to PNNL, the HTL wastewater is more suitable for wastewater treatment, we assumed certain costs for its treatment and disposal. The raw material price used in this study includes the transport costs from mills to the HTL facility. *Table 2.4* shows the methodology for calculating operational expenses.

Table 2.4: Methods for estimating the OPEX of the investigated HTL biofuel production process [36].

| Symbol | Description | Factor or formula | References |
|---|---|---|---|
| **DPC** | **Direct Production Costs, including** | **DPC = VC + LC + M** | |
| VC | Variable costs, including | VC = f +t + c + u + wt | |
| f | feedstock[a] | Crude olive pomace = 25 EUR/ton | This study |
| u | Utilities | Natural Gas = 1389 EUR/ton Water = 0.08 EUR/ton<br>Electricity = 28.6 EUR/GJ | [39], [40], [41] |
| t | Transport | Truck Transport, fixed = 12 EUR/ton<br>Truck transport, variable = 0.27 EUR/ton-km | This study |
| wt | Waste treatment | waste processing: gas = 6.00 EUR/ton<br>waste processing: water, black = 0.60 EUR/ton<br>waste processing: solids = 135 EUR/ton | Based on [42] |
| LC | Labour costs, including | LC = dw + sv | |
| dw | Direct wage and benefits | 12 EUR/hr | This study |
| sv | Supervision and supplies | 50% dw | |
| **M** | **Maintenance of equipment** | **10% of FCI** | |
| **OC** | **Operating Contingency** | **20% of DPC** | |
| **PO** | **Plant Overhead** | **70% of LC** | |
| **FC** | **Fixed charges, including** | **FC = lt + i + d** | |
| lt | Local taxes | 1.5% of fixed capital costs | |
| i | Insurance | 1.0 % of sales revenue | |
| d | Linear depreciation | 14.0% of fixed capital costs | |
| **GE** | **Administrative overhead expenses** | **10% of sales revenue** | |
| **OPEX** | **Total Operating Expenses** | **OPEX = DPC + OC + PO + FC + GE** | |

[a]Feedstock prices are at gate value (including transport)

### 2.6.6 MFSP calculation

The minimum fuel selling price (MFSP) is one of the crucial indicators of economic performance. MFSP is defined as the price of a unit of marine biofuel when the total annual OPEX equals the total annual revenue, as shown in Equation 1. The surplus electricity produced in the CHP plant was sold to the national grid for 28.6 EUR/GJ in Spain [40]. In this work, MFSP represents the facility's break-even point and includes capital depreciation but not return on investment.

$$MFSP = \frac{Operating\ expenses - Sales\ Revenues\ from\ biochar,\ \ electricity,\ \ naphtha,\ \ and\ biojet}{Biofuel\ production\ capacity} \qquad Equation\ 1$$

The MFSP was standardised into a ratio with the national MGO or VLSFO price for better insights for comparison with conventional fuels. Prices from 2023 for the port of Gibraltar of MGO and VLSFO were used as 890 EUR/ton and 640 EUR/ton, respectively [43].

## 2.7 RESULTS

### 2.7.1 Design Propositions and Scenarios

*Table 2.5* highlights the design characteristics and choices preferred by the potential stakeholders of the new value chain.

Table 2.5: Design Proposition for olive residues-based biohubs in Andalusia

| Biohub elements | Design Variable | Desired Characteristics | Design Proposition |
|---|---|---|---|
| Biomass extraction | - Type of biomass<br>- Biomass transport<br>- Biomass storage | - Large availability, easy accessibility, good compatibility with technology, and less competition<br>- Existing knowledge and infrastructure of biomass, transport, and storage.<br>- Feedstock with less physical impurities (sand and stones) and with suitable elemental composition (less hetero atoms such as N, S, O, and inorganics) | - Use COP as the main feedstock.<br>- Use olive pruning biomass if the feedstock price can be greater than the current economic value (65 EUR/ton) |

Table 2.5: Design Proposition for olive residues-based biohubs in Andalusia (*continued*)

| **Biohub elements** | **Design Variable** | **Desired Characteristics** | **Design Proposition** |
|---|---|---|---|
| Biorefinery | - Technology<br>- Location<br>- Capacity | - Less dependent on natural gas imports<br>- Benefit from economies of scale<br>- Less stress on water resources | - Implement biomass conversion that can be managed by current mill operators.<br>- Use existing infrastructure for biomass handling and conversion.<br>- Biomass conversion to take place near plantations or mills.<br>- Technology with minimal water consumption<br>- Use byproducts for electricity/heat generation and as soil amendment. |
| Final Products | - Bulk chemicals<br>- Speciality chemicals<br>- Fine chemicals | - Products should be matched with feedstock quality and quantity.<br>- Product with access to an existing regional market | - COP and OMWW for bioenergy; OTPB, EOP, and OL for bio-based chemicals<br>- Value chains with multiple products with a (marketable) anchor product |
| Benefits | - Economic, environmental, and social | - All | - Any alternatives that can provide more economic benefits than the current system.<br>- With reduced environmental (less $CO_2$ emissions, reduced water consumption, etc.) footprint<br>- Byproducts valorisation for self-sufficient processes and the sustainable olive sector |
| End-user market segment | - Technical<br>- Economic<br>- Environmental<br>- Social | - New fuels should have similar physio-chemical properties in comparison to fossil fuels<br>- The price of the new alternative fuels should be less than twice that of conventional fuels.<br>- Feedstock should not compete with food crops.<br>- A secure and continuous feedstock supply guarantee is needed | - Drop-in biofuels are preferred<br>- The selling price ratio of HTL marine biofuels: fossils should be less than 2.<br>- Lignocellulosic non-edible feedstocks are preferred.<br>- Diverse feedstock providers (small-scale and large-scale)<br>- Combination of both processing and field residues. |

*Table 2.6* shows some examples of how the stakeholders' preferences in terms of design propositions were translated into technical design choices.

Table 2.6: Translation of design propositions into technical design choices

| Design Propositions | Design decisions |
|---|---|
| Technology with a lower water requirement. | Recycling 75% of the aqueous stream of HTL output to reduce freshwater consumption. |
| Feedstock with large availability, with fewer heteroatoms, and compatible with HTL. | COP, with high moisture content, will be the feedstock of interest, with 2 million tons of annual availability in the province of Jaén, with negligible nitrogen and sulphur content. |
| Implement biomass conversion that can be managed by the current mill operators and use existing infrastructures. | HTL process with no catalyst, optimal process conditions for the highest biofuel yield, and upgrading at the dedicated hydrotreating facility or petroleum refinery. |
| Use byproducts for electricity or heat generation and as soil amendment for non-renewable independence. | The biochar and off-gas will be burned in a combined heat and power (CHP) plant for process energy. Excess electricity will be sold to the grid. |
| Facilities should benefit from economies of scale and be situated near olive plantations. | HTL processing capacities to be considered: 60 DTPD (raft capacity of the smallest secondary mill), 588 DTPD (raft capacity of the largest secondary mill), and 1494 DTPD ( one million metric tons of COP on wet basis) of COP. |
| Multiple products with a specific marketable product. | Fractionation of upgraded HTL biocrude into naphtha, bio-jest, and diesel fractions. |

Based on the design propositions, four biohubs design scenarios have been created (SC1-4) with 21 variations as shown in *Table 2.7* and *Figure 2.6* respectively.

Table 2.7: Summary of the different possible HTL biohub scenarios in Jaén. [PM = primary mill, SM = secondary mill, Ub= Central HTL facility at Ubeda, VLSFO = very low sulphur fuel oil, () indicates possible variations within the scenarios]

| Scenario | Province of Jaén | CEPSA, San Roque | Gibraltar | Products | Reference |
|---|---|---|---|---|---|
| SC1 (3) | HTL (PM/SM/Ub) | | Direct blend | MBF | VLSFO |
| SC2 (6) | HTL (PM/SM/Ub) | (Upgrading / Co-upgrading) | | MBF | MGO |
| SC3 (6) | HTL (PM/SM/Ub) | (Upgrading / Co-upgrading) + Co-distillation | | MBF and SAF | MGO |
| SC4 (6) | HTL (PM/SM/Ub) + (Upgrading) + (distillation) | | | MBF | MGO |

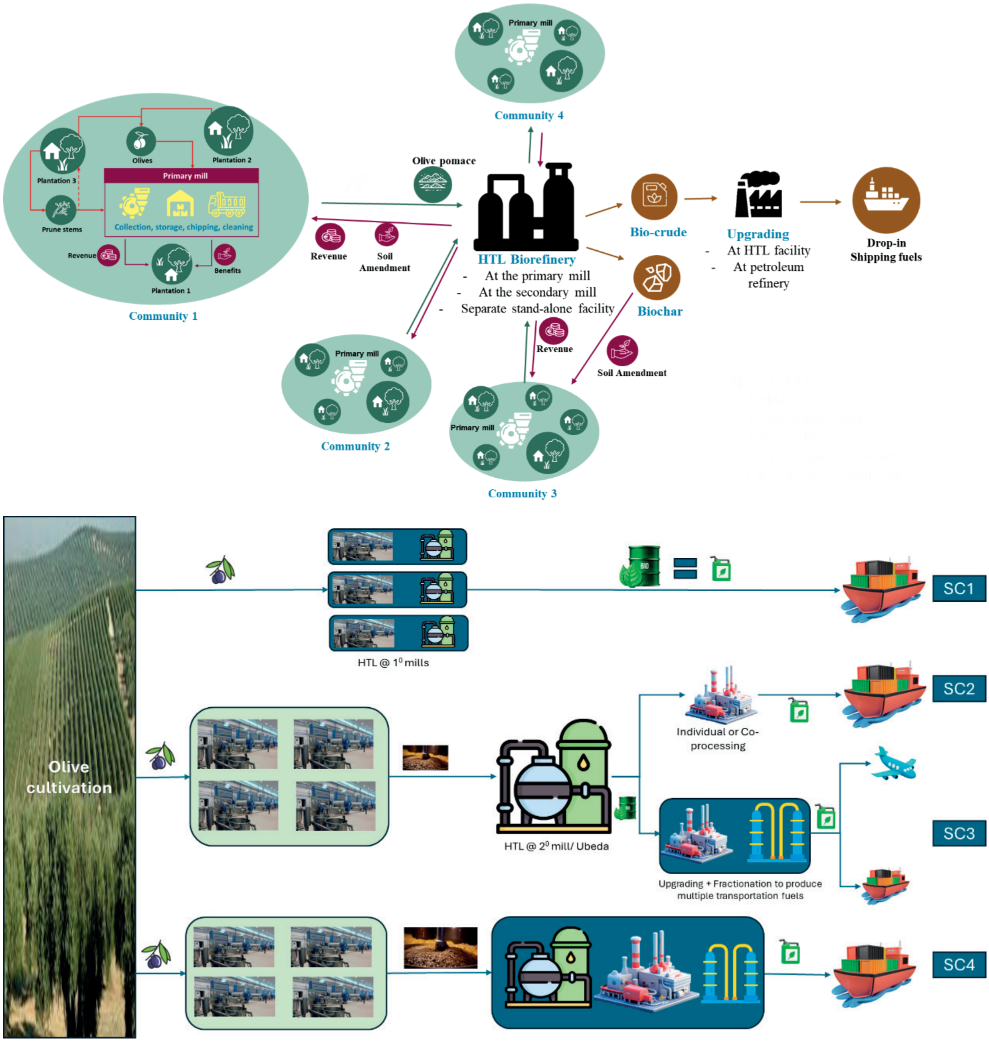


Figure 2.6: Possible biohub design based on crude olive pomace in Jaén (top) and biohubs scenario variations (bottom)

The major variations among the 4 scenarios are the biorefinery configurations (stand-alone HTL facility or integrated with CEPSA's San Roque refinery), the location of the HTL facility (centralised or decentralised at mills), and the products produced. In scenario 1 (represented as SC1), the HTL bio-crude from COP is assumed to be of high quality and can be directly blended with conventional marine fuels at the port of Gibraltar. For scenario 2 (SC2), the crude olive pomace is collected from primary mills and processed at the HTL facility located at secondary extraction mills or a centralised dedicated HTL facility at Ubeda, followed by (co-)upgrading at CEPSA. SC3 is very similar to SC2, however, the obtained upgraded bio-oil is further fractionated to get marine biofuel (MBF) and sustainable aviation fuel (SAF). The final scenario (SC4) is a standalone centralised HTL facility at Ubeda with in-house upgrading (and distillation). The COP is transported from primary mills to HTL facilities via road transport using Scania trucks implemented in the region's existing olive value chain. The distance from primary mills to secondary mills and the centralised location at Ubeda are assumed to be 30 km and 60 km, respectively. The HTL bio-crude from the HTL facilities will be transported to the CEPSA oil refinery in San Roque, located at an average of 380 km away, by road transport in liquid tanker trucks. At the CEPSA refinery, the HTL crude is further upgraded separately or by co-processing with fossil crude based on bio-crude properties. The biofuel obtained will be sent to final consumption with existing pipelines from the refinery to the port. Based on the residue availability and location of the mills, the processing capacity for HTL facilities at various locations is assumed to be 100 ktpa (or 60 DTPD), 500 ktpa (or 588 DTPD), and 1000 ktpa (or 1494 DTPD) of wet crude olive pomace (COP) for HTL at the primary mill, secondary mill, and standalone facility at Ubeda, respectively.

Prior to analysing the economic performance (i.e, MFSP) of the different scenarios, a further understanding of the technical aspects of the process is provided.

### 2.7.2 Technical performance

The Aspen Plus simulation model represents a steady-state processing condition with fixed operating parameters. *Table 2.8* indicates the key performance results for the 588 DTPD and 1494 DTPD HTL biofuel production systems, which include upgrading and fractionation. In both cases, it is assumed that the fractionation step resembles only distillation and not hydrocracking; therefore, it does not consume any electricity, energy, or hydrogen as it is performed by co-processing with fossils in the refinery [44]. The required inputs, if needed, can be obtained from the fossil hydrocarbon stream. Concerning inputs for the HTL stage, the process consumes 2.36 kg water/kg DM biomass and 0.043 kWh electricity/ kg DM biomass. The electricity consumption is lower than the reported values in the literature, as the feed does not require any pretreatment or processing before the HTL reactor, owing to its slurry-like nature [10], [16], [17]. The HTL bio-crude has been found to have superior qualities due to the very negligible inorganics (mainly N and S) and silica content in the feedstock. Therefore, this makes it a likely scenario for direct blending with marine fossil fuels up to 10 wt.% [45], [46]. However, more experimental validation is necessary by performing blending trials. Nonetheless, for the upgrading stage, the system requires 0.01 kg hydrogen/kg DM biomass and 0.057 kWh electricity/kg DM biomass. The hydrogen consumption is almost $1/4^{th}$ of the reported values, which can be attributed to the stoichiometric reactions of compounds present in HTL bio-crude obtained from olive residues [10], [14], [15], [17], [47], [48]. However, this value also includes the 100% excess supply for single-stage hydrotreater conversion. With these inputs, the process yields an output of 0.1, 0.04, and 0.13 kg/kg DM biomass of MBF, light naphtha, and jet fuel, respectively. Meanwhile, it also generates 1.31 kWh electricity/kg DM biomass after meeting the process requirements from biochar and off-gases combustion in the CHP plant. The effect of scaling up (60 DTPD, 588 DTPD, and 1494 DTPD COP processing capacity) on technical efficiency (such as by-product yields and energy efficiency) was also studied. It was found that, with increased scale, the by-product yields reduce and the energy efficiency increases as utility consumption per dry ton of feedstock processed reduces. This could be attributed to the equipment's efficiency and the desired product's large output. Uniquely, at 1494 DTPD COP scale, the internal energy demand is satisfied independently by off-gases, thereby generating 0.30 kg/kg DM biomass of biochar as a co-product. This effect is also noticed in the yields of off-gases, wastewater, and ash generation, with a reduction of 60-70%. The reduction in internal energy demand can also be attributed to the higher productivity of the system due to economies of scale. *Figure 2.7* shows the mass balances of a 588 DTPD plant in tons/hour.

It is crucial to highlight that the technical performance of the system varies, in terms of the mass balances, process yields, material and energy efficiency, along with the chemical composition of the products, with the changes in processing conditions (temperature, catalyst, and residence time), as can be inferred from the literature [34]. Therefore, a sensitivity analysis on one of the technical performance indicators is investigated later in the study.

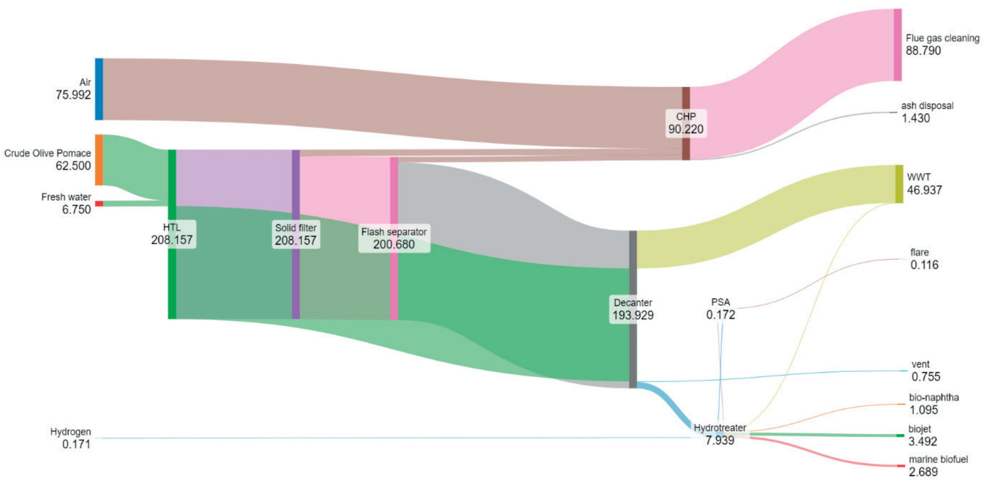


Figure 2.7: Stream mass balance (in tons per hour) in a 588DTPD HTL marine biofuel system.

Table 2.8: Key Performance results for the COP-based HTL and upgrading system.

| **Raw Materials and Utilities** | | |
|---|---|---|
| Crude olive pomace processing capacity (in DTPD) | 588 | 1494 |
| Water (kg/kg DM) | 2.36 | 1.53 |
| Natural gas (kg/kg DM) | 0 | 0 |
| Electricity (kWh/kg DM) | 0.043 (HTL)/ 0.057(Upgrading) | 0.034 (HTL)/ 0.055 (Upgrading) |
| Hydrogen (kg/kg DM) | 0.01 | 0.01 |
| | | |
| **Overall process yields** | | |
| Marine biofuel output (in ktpa) | 21.5 | 54.6 |
| Marine Biofuel yield (kg/kg DM) | 0.1 | 0.1 |
| Coproducts | | |
| *Electricity (kWh/kg DM)* | 1.31 | 0.03 |
| *Light Naphtha (kg/kg DM)* | 0.04 | 0.04 |
| *Biojet (kg/kg DM)* | 0.13 | 0.13 |
| *Biochar (kg/kg DM)* | - | 0.30 |
| Wastes | | |
| *Off-gas (kg/kg DM)* | 3.68 | 1.45 |
| *Liquids (wastewater) (kg/kg DM)* | 1.92 | 0.75 |
| *Solids (ash) (kg/kg DM)* | 0.06 | 0.02 |
| Internal energy use (MJ/MJ biofuel) | 0.16 | 0.04 |

### 2.7.3 Economical Performance

The economic performance of the 588 DTPD HTL biofuel system is shown in *Table 2.9*. The location-adjusted total capital investment (TCI) has a major contribution from the total installed costs (TIC), which accounts for 58-60% of all scenarios. In the case of the HTL process individually, the MFSP of the bio-crude is calculated to be 1342.7 EUR/ton.

In the HTL system, the major cost contributors are the CAPEX and the fixed operational costs (especially due to maintenance costs, assumed to be 10% of fixed capital investment), contributing to 35% and 36%, respectively. The high maintenance costs align with other typical factors implemented in the sector for processes like liquid-solid handling systems. Although biomass transportation costs are included in the feedstock gate price, the transport of bio-crude from the facility to the port has been assessed and estimated to be 8.5% of the total costs. The MBF: fossil (VLSFO) MFSP ratio is estimated to be 2.1, thereby indicating that the current alternative is more expensive than that of conventional fuels. As the MFSP of the HTL system is almost twice the conventional fossil (VLSFO) price, the bio-crude can be upgraded, via hydrotreatment, to improve the quality and economic performance. The MFSP of the HTL biocrude from crude olive pomace was found to be lower than that of the other biomass-based HTL biocrudes, indicating promising potential for implementation [17], [19].

Regarding the hydrotreated bio-crude, the results show that MFSP depends on CAPEX when green hydrogen is bought at a market price of 3.1 EUR/ton. Based on the calculation, the electricity consumption needed for hydrotreating is balanced by the generated energy in the CHP plant at the HTL facility. For the co-processing of HTL bio-crude, the electricity consumption and operating costs (like hydrogen and catalysts) are in addition to the integration facility. In these scenarios, the additional costs of upgrading were estimated to be 325.8 EUR/ton, resulting in an overall MFSP of 1688.5 EUR/ton. Although the MFSP increases by 24%, the ratio of MBF: fossil (MGO) reduces to 1.86 as the quality of bio-crude is improved by the removal of heteroatoms. Based on comparing the experimental properties results of COP-based HTL bio-crude and other biomass-derived HTL bio-crude, with proven blending capabilities, co-processing is potentially a favourable scenario [45]. If the properties of HTL bio-crude allow for co-processing with fossil fuels, the MFSP can still be reduced to 1204.9 EUR/ton. This is predominantly due to a decrease in TPEC by 16% due to integration. Further co-fractionation of this upgraded biofuel into naphtha, jet fuel, and diesel fuel improved the economic value (MFSP) of MBF to 1052.8 EUR/ton. This is largely due to increased revenue from sales of other hydrocarbons. Therefore, a trade-off between biofuel quantity and price must be made based on the market scenarios. We show that co-processing and fractionating in petroleum refineries drastically improve the economic performance of the system. The distribution of Total capital investment (TCI) and total operating costs (TOC) for different configurations is shown in *Figure 2.8***.**

Table 2.9: Estimated costs for the HTL biofuel system

| **Scenarios** | **BtL** | **Upgrading** | | **Fractionation** | |
|---|---|---|---|---|---|
| **Variations** | **HTL** | **HTL + Upgrading** | **HTL + Co upgrading** | **HTL + Upgrading+ Codistillation** | **HTL + Co-Upgrading+ Codistillation** |
| Marine biofuel output (in ktpa) | 61.7 | 59.1 | 59.1 | 21.5 | 21.5 |
| % of Spain's HFO demand | 1.07 | 1.03 | 1.03 | 0.04 | 0.04 |
| *Total Purchased equipment costs (TPEC) (in million Euros)* | | | | | |
| HTL reactor system | 38.0 | 38.0 | 38.0 | 38.0 | 38.0 |
| Upgrading | n/a | 8.6 | - | 8.6 | - |
| Fractionation | n/a | n/a | n/a | - | - |
| Cogeneration plant | 6.4 | 6.4 | 6.4 | 6.4 | 6.4 |

| | | | | | |
|---|---|---|---|---|---|
| Total Installed costs (TIC) *(in million Euros)* | 111.1 | 132.6 | 111.1 | 132.6 | 111.1 |
| Indirect costs *(in million Euros)* | 37.8 | 45.1 | 37.8 | 45.1 | 37.8 |
| Fixed capital investment (FCI) *(in million Euros)* | 181.4 | 216.4 | 181.4 | 216.4 | 181.4 |
| Total capital investment (TCI) *(in million Euros)* | 207.7 | 248.6 | 210.1 | 247.2 | 208.6 |
| Location-adjusted TCI *(in million Euros)* | 186.9 | 223.8 | 189.1 | 222.4 | 187.8 |
| | | | | | |
| *Operating costs* (in million Euros per year) | | | | | |
| Variable operating costs | | | | | |
| Feedstock | 11.4 | 11.4 | 11.4 | 11.4 | 11.4 |
| Water | 0 | 0 | 0 | 0 | 0 |
| Hydrogen | 0 | 0.004 | 0.004 | 0.004 | 0.004 |
| Catalysts | 0 | 2.32 | 2.32 | 2.32 | 2.32 |
| Wastewater treatment | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 |
| Gas cleaning | 4.3 | 4.3 | 4.3 | 4.3 | 4.3 |
| Ash disposal | 1.55 | 1.55 | 1.55 | 1.55 | 1.55 |
| (Bio-crude/ biofuel) Transportation | 7.55 | 7.23 | 7.305 | 6.995 | 7.305 |
| Capital depreciation | 25.8 | 30.9 | 26.1 | 30.7 | 25.9 |
| Total Operating Costs | 85.5 | 98.7 | 89.5 | 97.5 | 88.6 |
| | | | | | |
| Annual Sales Revenue (in million Euros per year) | 40.7 | 52.7 | 52.7 | 45.4* | 45.4* |
| MFSP of MBF (in Euro/ ton) | 1342.7 | 1668.5 | 1511.6 | 1204.9 | 1052.8 |
| MBF: fossil MFSP ratio | 2.097 | 1.864 | 1.689 | 1.346 | 1.176 |

* *With Naphtha price = 617.2 EUR/ton, jet fuel price = 743.4 EUR/ton*

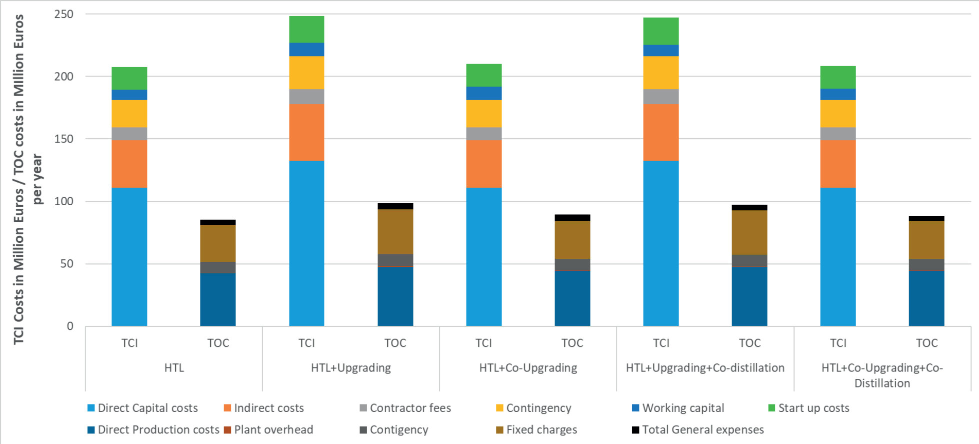


Figure 2.8: Detailed total capital investment (TCI) and total operating cost (TOC) of studied HTL biofuel scenarios.

The reported techno-economic performance is based on assumptions such as the plant capacity, scaling factors for capital and operational expenditures (like high contingency and installation factors), which involve a lot of uncertainties. Therefore, a sensitivity analysis is required to understand the effect of changes in these assumptions due to technological development and market changes.

## 2.7.4 Sensitivity analysis

### *2.7.4.1 Distributed HTL plant*

The economic analysis in the previous section indicates the effect of HTL bio-crude quality and the different choices in the level of integration with existing petroleum refineries on the MFSP of marine biofuel. However, the previous section provides an estimate for one biomass processing capacity, which was assumed to be the same as the raft capacity of the largest secondary mill in the region. Therefore, it effectively resembles a (standalone/integrated) centralised plant. However, the effect of processing capacity on the MFSP has to be understood to make an informed decision to place the HTL facilities, such as in primary mills, secondary mills, or dedicated centralised facilities at Ubeda. Compared to a centralised plant, a potentially distributed plant eliminates the need for COP storage and transport, providing a possibility for better economic returns and access to social benefits (such as excess biochar distribution to farmers). Therefore, to assess the possibility of developing distributed small and large-scale centralised standalone HTL facilities, the MBF: fossil MFSP ratio for different configurations was investigated. The results are shown in *Figure 2.9*. With COP biomass processing varying from 60 to 1494 DTPD, the MBF: fossil MFSP ratio ranged from 0.66 to 3.14.

For a stand-alone scenario with a fractionation step, the MFSP of a distributed HTL facility with a COP processing capacity of 1494 DTPD was 713.7 EUR/ton, which is almost 41% lower than the previously considered scenario, which was 1206.6 EUR/ton. This decrease originates due to economies of scale. A crucial element was also the effect of the large quantity of off-gas generated during the HTL process, which is processed in CHP for internal energy consumption. This not only eliminated the burning of biochar but also reduced the capital costs for cogeneration. However, the revenue from biochar is not accounted for in the MFSP calculation as its end-of-life is not considered due to its unknown chemical properties. The MFSP of base 1206.6 EUR/ton for the 588 DTPD plant further decreases by 51% to 588.1 EUR/ton due to a 20% reduction in equipment costs due to downstream integration. Considering the prices of VLSFO and MGO at Port of Gibraltar in 2023 and biofuel traders' preference for a desired ratio less than or equal to 2, the minimum processing capacity of the distributed HTL facility should not be less than 60 DTPD of COP at 25 EUR/ton.

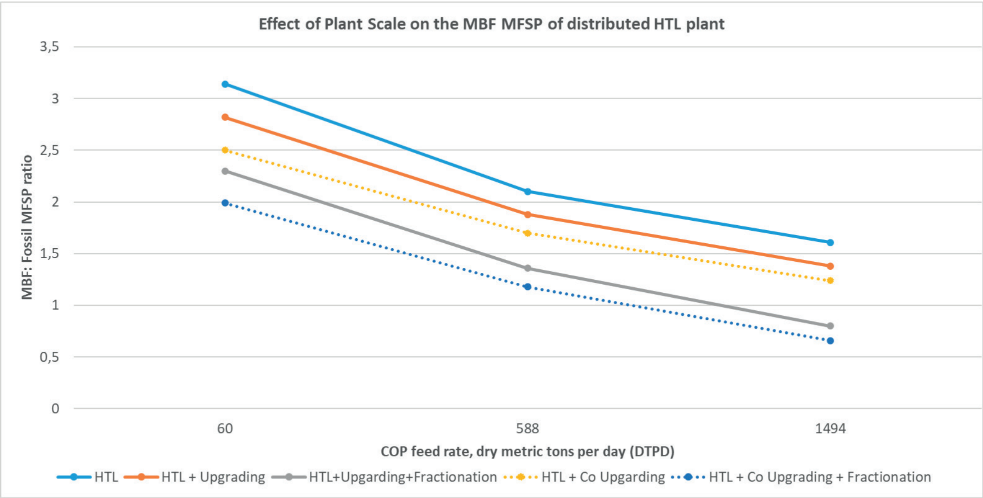


Figure 2.9: Effects of plant scale on the MBF: fossil MFSP ratio of the distributed HTL plant.

### 2.7.4.2 *Identification of key factors*

The MFSP of a product depends on several technical and economic parameters implemented in the biohub. Hence, a sensitivity analysis is necessary to understand their effects on the production cost. The sensitivity analysis for a 588 DTPD standalone centralised (with upgrading) system was performed, and the results are visualised in *Figure 2.10*. Technically, the variation in the final biofuel yield affected the MFSP with a 33% increase, leading to a 23% decrease in the MBF: MGO MFSP ratio. The assumption of increasing yield is based on the lack of use of catalysts in the current system, and the use of various catalysts is positive in the literature, generating yields up to 59% [34].

In terms of economic parameters in production, the effect of scaling factors ( for contingency and installation costs), HTL reactor equipment cost (Capital), and feedstock and transport costs (variable) were studied. The design parameters and basis of the HTL process are from the lab scale and literature information. Hence, the sensitivity to scaling factors is crucial to understand. A 40% decrease in the installation factor reduced the MBF: MGO ratio by 19%, indicating a larger sensitivity to the parameter. However, the MBF: MGO ratio only reduced by 5% when the contingency factor of 15% is implemented instead of 50%. In addition, in order to account for capital risks during scale-up as well as a reduction in material costs due to innovation, the reactor costs varied by 50% from the base case. This led to an almost 20% change in the value of MFSP in comparison with the fossils, mainly due to the proportionate change in the TCI. Similarly, as reported in various literature, the MFSP is sensitive to feedstock prices. An increase in the COP price by a factor of four increased the MFSP of biofuel by almost 41%. Finally, the 70% decrease in the contingency and 40% decrease in the installation costs scaling factors reduced the MBF: MGO MFSP ratio by 5% and 19%, respectively.

On the contrary, even though transportation costs contributed largely to the variable costs, the effect of variation in transport prices (both variable and fixed) was negligible (< 2%) in the MFSP ratio. This can be mainly attributed to the design configuration. The choice of locating the HTL facility near olive mills ensured the transport of energy-dense bio-crude, which is favourable.

Last but not least, the effect on the MBF: MGO MFSP ratio due to the market prices of MGO was assessed. The MGO prices affect the revenue generated, directly affecting biofuel's MFSP. However, this has an inverse effect on the perception of MBF as a viable alternative solution in the market. A 50% increase in MGO prices reduces the ratio by almost 30%. This is crucial and relevant for choosing end market location and market penetration.


Figure 2.10: Sensitivity analysis of the MBF: fossil MFSP ratio of HTL biofuels, Green (increase of parametric value from the base case), Orange (decrease of parametric value from the base case).

## 2.8 CONCLUSIONS

In this study, we present a methodology for developing a socially just and economically viable olive residue-based biohub utilising hydrothermal liquefaction (HTL) in the Spanish province of Jaén. With the approach of co-creation, various Capability Sensitive Designs (CSDs) are developed to produce marine biofuels from olive residues via HTL, which includes the choice of feedstock, scale, and location of the HTL facility, product portfolio, and configuration (stand-alone or integrated) of the facilities. This method ensures the incorporation and prioritisation of different stakeholders' (farmers, biofuel traders, technology providers, farmer unions, ministries, etc.) capabilities into technical choices of the value chain, thereby achieving a socially just design with relevance to the context of implementation. The techno-economic feasibility of the various biohub design scenarios, with a hypothetical 588 DTPD COP processing capacity HTL system in Jaén, showed promising results. The MFSP of HTL biofuels varies from 1053 EUR/ton to 1668 EUR/ton, which is almost 1.1 to 2.1 times the current price of the fossils, respectively. The COP processing capacity plays a crucial role in the MFSP of biofuels, with a variation of +100% leading to a decrease of 27% in MFSP for a stand-alone configuration. The capital expenditure, specifically the equipment costs, contributes 40-50% to the production costs. The ability to co-process the HTL bio-crude has a profound effect on the MFSP, with at least a 20% reduction in equipment costs. In terms of key performance indicators, the MFSP of MBF is sensitive to the reactor equipment costs, COP price, and HTL bio-crude yield. The study also infers that the minimum scale of the HTL facilities is to be between 588-882 DTPD COP processing capacity, as any lower will increase the MFSP beyond the threshold (MBF: fossil MFSP ratio ≤2) set by retailers, and any higher will require significant infrastructure developments (for COP storage and transport) with high investments.

Technically, future experimental studies are recommended, especially testing fuel quality, the properties of HTL bio-crude and hydrotreated fuels for their potential to be a "drop-in" as a marine residual, distillate, or sustainable aviation fuel in combustion engines. Co-processing of HTL bio-crudes has to be thoroughly investigated to validate the performance of some scenarios. This will make the biofuels more cost-competitive and provide opportunities for fossil refineries to make sustainable transitions. Although economically attractive, the environmental footprint of the design configuration is still to be evaluated for sustainability. Socially, the study leaves potential room for validation of the final design results through feedback analysis for optimisation (operational, tactical, and strategic decisions) and reiteration of the design choices. Moreover, the robustness of this approach can also be validated by replicating it in other olive-producing regions in Spain and in the Mediterranean region (such as Italy, Portugal, Greece, and Malta), where drop-in marine biofuels are expected to play a role with the increasing share of renewables. Overall, we conclude that HTL biofuel systems based on olive residues for marine biofuel production in the Mediterranean region can be a viable alternative pathway for handling the polluting residue streams for a sustainable future.

## 2.9 SUPPLEMENTARY DATA

Supplementary data for this study can be found in Appendix A (see section 7.2)

## 2.10 REFERENCES


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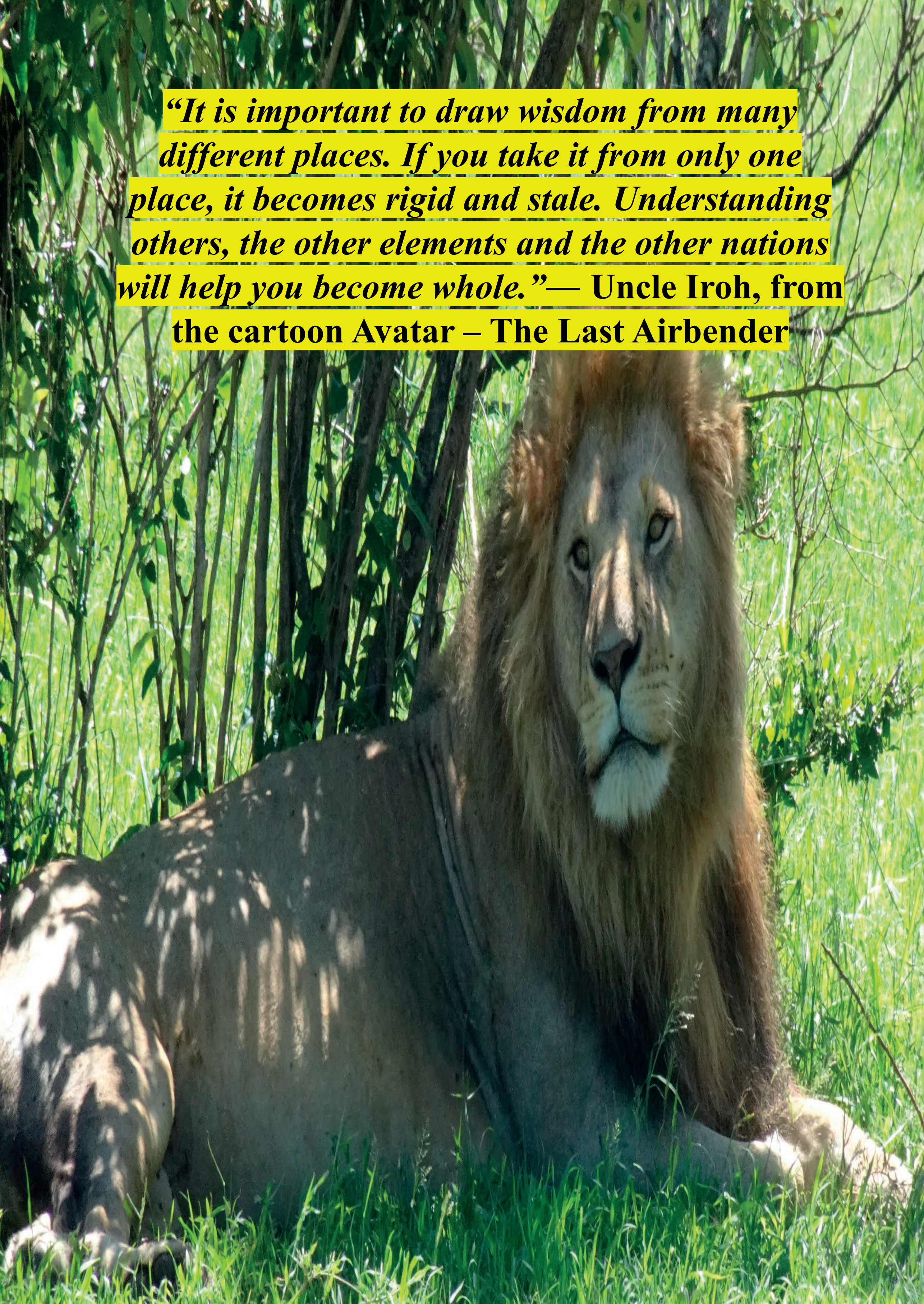
*"It is important to draw wisdom from many different places. If you take it from only one place, it becomes rigid and stale. Understanding others, the other elements and the other nations will help you become whole."* **— Uncle Iroh, from the cartoon Avatar – The Last Airbender**


3

# 3

# Agrarian Biohubs for drop-in marine biofuels: A Techno-economic and environmental assessment of inclusive, context-specific, and capability-sensitive Biohubs in Spain, Colombia, and Namibia using field residues

This Chapter is under review in the Chemical Engineering Journal

S. Chandrasekaran, P. Osseweijer, and J. Posada (under review), Agrarian Biohubs for drop-in marine biofuels: A Techno-economic and environmental assessment of inclusive, context-specific, and capability-sensitive Biohubs in Spain, Colombia, and Namibia using field residues.

# GLOSSARY

| | |
|---|---|
| 1,4-DCB | 1,4-dichlorobenzene |
| BBVC | Biobased value chain |
| CAPEX | Capital Expenses |
| CFC | chlorofluorocarbons |
| CHP | Combined Heat and Power |
| CO | Colombia |
| $CO_2$ eq | Carbon dioxide equivalent |
| Cu | Copper |
| DM | Dry metric ton |
| dt | Dry ton |
| DTPD | Dry tons per day |
| e-LCA | Environmental Life Cycle Analysis |
| eq | equivalents |
| ES | Spain |
| EUR | Euros |
| GHG | Greenhouse gas |
| GIS | Geographical Information System |
| $GWP_{100}$ | Global warming potential (100 years) |
| HFO | Heavy Fuel oil |
| HHV | Higher heating value |
| HTL | Hydrothermal Liquefaction |
| IEA | International Energy Agency |
| kg | kilogram |
| kWh | Kilo watt-hour |
| L | Litre |
| LHV | Lower heating value |
| m2a crop eq | Annual cropland |
| m3 | Cubic meter |
| MBF | Marine biofuel |
| MFSP | Minimum fuel selling price |
| MGO | Marine Gas oil |
| MJ | Megajoule |
| MW | Megawatt |
| NA | Namibia |
| NOx | Nitrogen oxides |
| OPEX | Operating Expenses |
| PM2.5 | Fine Particulate Matter with a diameter of less than 2.5 µm |
| SO2 | Sulphur dioxide |
| SSD | Slow-stroke diesel engine |
| USD | United States Dollars |

## 3.1 INTRODUCTION

Currently, biomass is the primary source of global renewable energy [1]. The wide range of global availability of biomass and local accessibility to affordable bioenergy will increase the above-mentioned share by a factor of 2 by 2030 [1]. The "hard-to-abate" shipping sector is one of the end-users that will be contributing to the increase in consumption of large-scale biofuels to meet the regulations [2]. Due to bunkering abilities and benefitting from existing infrastructure, "drop-in" biofuels are seen as short to mid-term solutions ahead of zero-carbon fuels. However, this growth and widespread global adoption of the biobased economy can only be achieved if the challenges in the commercial-scale deployment of (traditional) biobased value chains (BBVCs) are addressed. More specifically, the secure and sustainable mobilisation of field and processing residues must be ensured to de-risk commercialising lignocellulosic residue-based second-generation biorefineries.



Recently, according to the International Energy Agency (IEA), Biohubs have been identified as a potential way to successfully integrate biomass supply chains (especially for bioenergy), overcome the drawbacks of conventional BBVCs, and enable the commercial deployment of the bioeconomy globally [3]. Biohubs [or (community) hubs in general] act as an intermediary point where various activities such as collection, storage, pretreatment, and processing of biomass into intermediate products (such as pellets, briquettes, wood chips, bales, etc.) can be performed. By acting as processing points, biohubs will reduce the physical distance between the suppliers (biomass producers and growers) and end-users (biorefineries) and also enable them to robustly handle and process diverse biomass feedstocks in the region. However, predominantly, the literature focuses on valorising forestry residues in the global North from an economic feasibility perspective [4]. So far, the validation of this concept in global South countries with biomass feedstocks predominantly available as field residues, and where local social livelihood is interconnected, is yet to be investigated. This requires attention as the promise of biohubs can provide crucial input for global bioeconomy strategies.

Different researchers have studied the biohub concept in terms of economic performance. For example, Pradhan *et al.* (2022) investigated the economic feasibility of a "first of its kind" biohub in Canada with a 1500 DTPD plant to produce several bioproducts (firewood, bark, woodchips, regular pellets, torrefied pellets, biochar, and bio-oil) using various production pathways [5]. The cost of production of firewood, bark, wood chips, regular pellets, torrefied pellets, biochar, and bio-oil was reported to be 46 USD/dt, 13 USD/dt, 38 USD/dt, 118 USD/dt, 157 USD/dt, 87 USD/dt, and 0.49 USD/L, respectively [5]. However, the commercial perspective was not taken into consideration. In another study, Berry (2022) concludes that local biohubs had a preference while producing biochar, and (larger) regional biohubs in the case of pellets as products. This preference is mainly attributed to transportation costs for the former and operational efficiencies at a greater scale for the latter [6]. Lan *et al.* (2021) highlight that the minimum fuel selling price (MFSP) of the product is inversely related to the scale of the biorefinery and not necessarily to the capacity of the depots. The decentralised systems, although with higher MFSP based on their analysis, indicated other potential benefits such as supply chain risk mitigation and improved quality of processing feedstocks, which were not quantifiable in the study [7]. Thereby, emphasising the need for a much broader analysis of biohubs, with a focus on more than just economic and operational feasibility.

Very few works of literature have been reported to investigate the environmental or societal dimensions of sustainability for these biohubs. Rai *et al.* (2024) investigated and reported the potential of three (two forestry and one non-forestry residue-based) biohubs to reduce GHG emissions by up to 90% based on the system configuration of biofuel value chains to defossilise hard-to-abate sectors [8]. Lan *et al.* (2020) performed a cradle-to-gate attributional LCA to investigate the effect of a multi-feedstock depot-based biobased supply chain. The environmental hotspots were identified as occurring during the biorefinery processing and depot feedstock preprocessing stages. The environmental impacts were insensitive to the depot size, biorefinery scale, and transportation [9]. For the social dimension, although BBVCs are supposed to be socio-technical systems, only a handful of literature has been found addressing the social impacts. These are incorporated in assessing the macro-socioeconomic impact of the value chains through various multi-criteria decision-making analyses [10]. There is still a large gap in addressing the social capabilities of these systems in terms of qualitative social perspectives such as inclusion, benefit sharing, and access to participation. These gaps become crucial when feedstocks such as agricultural residues are valorised, but are more difficult to quantify and generalise as they merely relate to specific local and regional contexts. Moreover, the conceptual process designs of biohub lacks perspectives for potential environmental (such as mitigating soil, water, and air pollution) and social (such as inclusion and participation) benefits of valorising mismanaged or underutilised field residues beyond reduction in GHG emissions of bioproducts, especially in the upstream of the value chain, are currently lacking.

This investigation aims to address the above-mentioned knowledge gaps by integrating the technical (process and value chain design) aspects with non-technical (social values) elements. This study showcases an early-stage, context-specific, capability-sensitive, and stakeholder-inclusive approach to conceptual design of biohubs to answer the question *"How to design context-specific, and sustainable biohubs based on field residues with early-stage stakeholder inclusion?"* and assess their possible technical, economic, and environmental performance of an inclusive HTL-based biohub-implemented marine biofuel value chain in Spain, Colombia, and Namibia by addressing the problem statement *"What are the economic performance and environmental impacts of the co-designed inclusive field residue-based biohubs for marine biofuel production in Spain, Colombia, and Namibia?"*.

The inclusive design approach presented here and the biohubs systems investigated are designed through the Capability Sensitive Design (CSD) approach by setting a design space (DS) and by deriving design prepositions (DPs) from participatory techniques [11], [12], [13]. The novel bottom-up approach developed in this paper for co-designing biohubs makes the system design inherently inclusive. A bio-hub is defined as a circular system where private and public actors cooperate to 1) source bio-based streams and wastes, and transform them into marketable products, 2) improve the sustainability of local farming practices and traditional biomass use, 3) fulfil local needs, including energy and clean water, and 4) fairly distribute costs, benefits, risks and opportunities

3

The non-forestry biohubs in this study for marine biofuel production via HTL focus on valorising underutilised or mismanaged lignocellulosic non-edible field biomass residues. Firstly, the Spain case study implements the olive tree pruning biomass, which is currently burned as a quick method of disposal, causing significant emissions of particulate matter to the air [14]. Secondly, in Colombia, the aim is to utilise the coffee pulp residues from the coffee sector, where no value chain for residue valorisation exists [15]. Finally, in Namibia, the focus is on encroacher bush (mainly Acacia Mellifera), which is currently posing an ecological threat by causing rapid groundwater depletion, destruction of natural savannah habitat, and drastically reducing the grazing capacity of the land. There has been no prior reported investigation on using these geospatial residue streams for the production of alternative "drop-in" biofuels for the marine segment of transportation. The problem statement is addressed by the following objectives: a) development of inclusive design approach; b) identifying design propositions for the context-specific biohubs through multiactor approach and participatory techniques; c) codesigning inclusive biohubs; d) develop process models in Aspen Plus for mass and energy balances; e) estimation of capital (CAPEX) and operating (OPEX) expenses of biohubs in Spain, Colombia, and Namibia for producing HTL marine biofuels; f) estimation of the minimum fuel selling price (MFSP) of the HTL biofuels; g) comparison of the calculated MFSP with general values reported in the literature; h) determination of environmental impacts, especially the global warming potential ($GWP_{100}$) of HTL biofuels; and i) key parametric sensitivity analysis that influence the MFSP of HTL biofuels.

## 3.2 METHODOLOGY

### 3.2.1 Case Study Scenarios for Biohub Development

#### *3.2.1.1 Olive Tree Pruning in Spain*

Spain is the leading producer of olive oil in the world, accounting for 40% of the global annual production [16]. The autonomous region of Andalusia, in the south of Spain, accounts for 80% of the national production with almost 1.5 million hectares of olive cultivation farm area [17]. The province of Jaen is the leading region for olive production in Andalusia and practices the traditional method of cultivation, which is both labour and resource-intensive [18]. Every year, in EU-28, the olive oil production value chain generates 21.4 million tons of field and processing residues, which are predominantly either underutilised or mismanaged [19]. Between 2004 and 2016, the average annual production of olive tree pruning biomass in Spain was estimated to be approximately 3.9 million tons, owing to 1.5-3 tons of pruning biomass per hectare per year [20]. Furthermore, the burning of pruning residues leads to economic costs and associated environmental risks due to potential wildfires and GHG emissions, thereby making the current disposal method unsustainable. Therefore, valorising this renewable source of energy will benefit associated small-scale farmers both economically and environmentally [21]. In recent years, the number of scientific investigations for valorising olive tree pruning biomass for bioenergy and bioproducts in the Mediterranean regions has increased [22], [23], [24]. However, there are no commercial-scale value chains established for olive pruning residues. Predominantly, the above-mentioned investigations focused on either biochemical conversion techniques to produce biochemicals and bioproducts or heat via thermochemical pathways.

This case study focuses on the province of Jaen. The large availability (approx. 1 million tons per year on a wet basis) of pruning residues [22], the geographical proximity to the end market segment at Port of Algeciras or Port of Gibraltar, stimulating bioenergy policies, and opportunities for strengthening rural economies, make the spatial choice of Jaen a promising region. This case study aims to valorise underutilised olive pruning biomass to produce marine "drop-in" biofuels using hydrothermal liquefaction technology, while improving the socio-economic status of the small-scale farmers.

#### *3.2.1.2 Coffee sector in Colombia*

With an average annual production of 800 kilotons of coffee between 2019-2023, Colombia is the third largest coffee producer in the world [25]. The sector spans over 800,000 hectares (ha), involving about 550,000 families, with most (95%) of them cultivating less than 5 ha each [26]. More than 85% of the national coffee production happens in 10 departments with Huila leading the race with 18.37%, followed by Antioquia (15.81%), Tolima (13.29%), Cauca (10.46%), Caldas (7.78%), Risaralda (5.44%), Valle del Cauca (5.33%), Santander (5.21%), Nariño (4.32%), and Cundinamarca (2.77%) respectively [27] . With the suitable climate and soil conditions for coffee production, the coffee axis (locally known as the "*Eje Cafetero*") region in Colombia produces coffee in an agroforestry system along with other crops such as cacao, avocado, and banana. Unlike other coffee-producing countries, the Colombian coffee sector is very vertical, with only a few registered exporters authorised to export coffee beans [28]. Similarly, most Colombian coffee producers sell their coffee in a pre-processed state in comparison to unprocessed coffee cherries, such as in Costa Rica. This predominantly leads to wide variations in the quality, thereby affecting the uniformity of the final export product. The Colombian coffee sector also lacks the implementation of (cooperative-owned) mills with exporter access, thereby making the value chain longer and increasing the distance between the producers and the end consumer [28]. Therefore, new residue value chains with design strategies to enable centralised processing of coffee beans can address the above-mentioned drawbacks.

The wet processing method, such is commonly followed in the Colombian coffee sector, often generates large amounts of residues, posing health, environmental, and economic issues [29]. The supply chain accumulates about 900 g of residues per kg of harvested coffee cherries [30]. The main residues are pulp, mucilage, stems, husks, and coffee grinds. In Colombia, approximately 1.7 million tons of pulp, 0.6 million tons of mucilage, and 3.1 million tons of coffee cut stems are generated on an annual basis [15]. Currently, there are no commercial value chains for handling these residues except for occasional traditional uses such as firewood or compost, making them a promising source of renewable feedstock [31]. In this case study, we perform a first-of-a-kind investigation for developing a value chain to valorise coffee pulp residues for producing "drop-in" marine biofuels, with an additional focus on strengthening the existing coffee sector in the department of Risaralda in the *Eje Cafetero* region.

#### *3.2.1.3 Encroacher Bush in Namibia*

In Namibia, the encroacher bush is causing a severe ecological threat [32]. The threats include depletion of groundwater, reducing biodiversity, limiting the grazing capacity of the land, and transforming savannah ecosystems into bushland, impacting human and wildlife. Around 45 million hectares (about one-third of the country) is bush encroached, at the loss of grass vegetation in the Savannah ecosystem [32]. Compared to the natural perennial grasses, these indigenous bushes deplete the groundwater at a much faster rate, reduce the grazing capacity of the land, restrict the movement of wildlife, and reduce the biodiversity of the region [32]. Due to various anthropological activities such as excessive animal browsing, increased atmospheric $CO_2$ concentration, and suppression of veld fires, the current estimate of the bush is approximately 400 million tons with an estimated annual growth rate of 3-4%, or 14 million tons per year [33]. Geographically, these encroached lands are present in nine of the fourteen regions of the country, with the most densely affected areas in the regions of Otjozondjupa, Oshikoto, Kavango West, and Omaheke [34]. Most of the Namibian population depends on agriculture, directly or indirectly, for their livelihood, with the majority being cattle farmers [35]. Therefore, valorising these abundant lignocellulosic renewable feedstocks can bring more than just economic benefits to the region. Currently, in addition to traditional uses such as firewood, fences, animal feed, etc., these bushes are used for charcoal production [34]. Namibia is one of the leading exporters of high-quality charcoal, obtained from encroacher bush, with a market size of 250 kilotons per year [36]. However, this value chain hardly consumes 2% of the total biomass available [37]. Therefore, there is a need for new value chains that can offtake the huge quantity of sustainably harvested biomass from bush-thinning activities to restore the savannah ecosystem.

With the increasing investments for infrastructural development in the country due to the discovery of fossil sources and new renewable energy projects, access to the port for exports in Walvis Bay, and the need for energy security and independence, encroacher bush is expected to play a significant role in Namibia's sustainable energy transition and development [38]. Commercially, Namibia Power Corporation (NAMPOWER) is currently constructing a 40 MW biomass power plant, which uses approximately 250,000 tons per year, using encroacher bush as the feedstock [39]. Furthermore, the potential for bush-based biochar production for soil amendment, protein-rich animal fodder, sustainable construction materials, and food production is a new area being explored. [40]. To complement these efforts, this case study focuses on the potential to implement value chains for using these bush lignocellulosic materials for marine biofuel production.

#### *3.2.1.4 Design Space (DS) and Design Propositions (DP)*

This investigation was performed complementary to the work of Veen *et al.* (2024) within the project for developing sustainable and inclusive value chains for marine biofuels (CLEANSHIPPING) [13]. The interdisciplinary team visited the case study location for 5 weeks, during which diverse potential stakeholders were involved in the sectors of interest (such as producers, processors, farmer associations, unions, cooperatives, transport companies, technology developers, policymakers, etc.) via participatory techniques such as semi-structured interviews and multi-stakeholder design workshops.

The semi-structured open interviews and the multi-stakeholder workshops resulted in the identification and validation of stakeholder capabilities and perspectives through a multiactor approach. The capabilities and values were further used to derive the design propositions for biohubs using field residues in the regions, considering the existing local contextual preferences, such as traditional biomass uses, values, capabilities, and capacities. The format of the interviews and the multi-stakeholder workshops organised for the three case studies is summarised in Appendix 7.3.1. The outcomes of the multi-actor approach for co-creation of biohubs led to the framing of both the Design Space (DS) (i.e., design aspects such as biomass feedstock choice, harvesting and collecting techniques, biorefinery technology, scale, and location, preference of intermediate or end products, logistical arrangements, co-processing with petrochemical industries, etc.) and the Design Propositions (DPs) (i.e., choice of design variables for each design aspect) for the potential biohubs systems valorising the residues in the chosen region of interest.

3

### 3.2.2 System boundaries and process modelling

#### *3.2.2.1 Biohub system boundaries*

The Biohub system boundaries encompass a wide range of activities: a) collection of crop/residue at the farm level, b) transportation of crop to the regional mill for processing or residues to the preprocessing facility for biomass preparation, c) transportation of pretreated residues to the biorefinery facility, d) conversion of biomass to biocrude using HTL at the biorefinery, e) transportation of HTL biocrude to the nearby petrochemical refinery for coprocessing, f) co-processing of HTL biocrudes in hydrotreaters present in existing petrochemical refinery, g) transfer of end product (marine biofuel) to the port bunker facilities using existing infrastructure, h) supply of utility systems (for electricity and water), and i) processing of waste streams at a waste processing facility. The preferred choices of the above-mentioned design variables were elucidated during the early-stage co-design process via DS and DPs identified in the section 3.2.1.4.

Key features of the biohub systems are expected to be similar irrespective of the region of interest, such as the HTL process, the off-gas and biochar streams being sent to the onsite combined heat and power (CHP) plant, the (solid/liquid/gas) waste streams sent to a waste processing facility before disposal into the environment. The *Figure 3.1* indicates the biorefinery process model boundaries in Spain, Colombia, and Namibia.

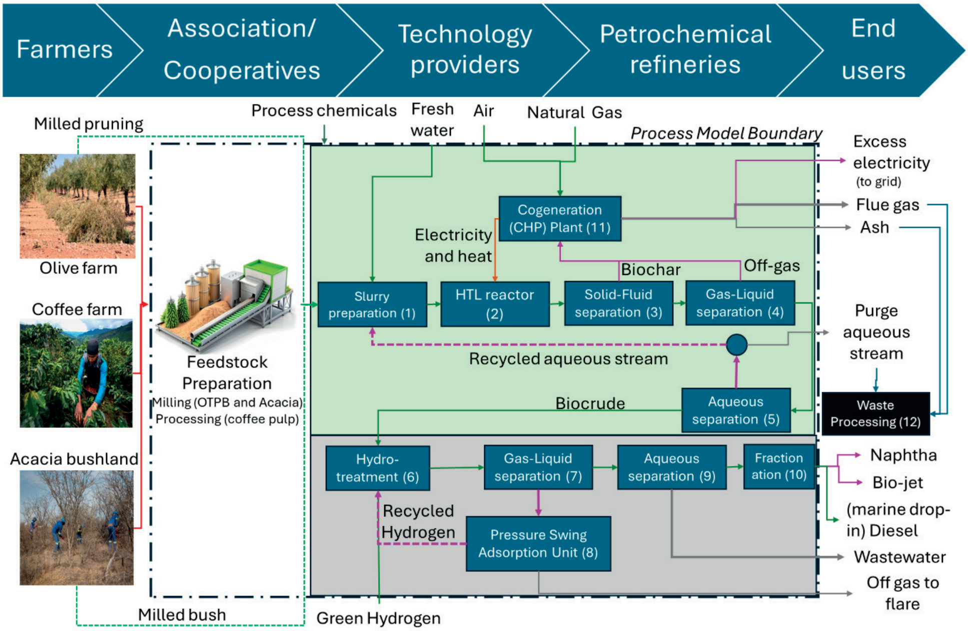


Figure 3.1: Marine biofuel value chain with process model boundaries (with unit numbers indicating unit process or unit operation) and stakeholder groups across the value chain. The green highlight indicates the HTL biorefinery facility, and the Grey highlight indicates the petrochemical facility.

### *3.2.2.2 Process model battery limits and description*

#### *3.2.2.2.1 Feedstock preparation*

The biomass feedstocks are cleaned, sorted, and chipped in regional mills or preprocessing facilities before the HTL conversion process. The electricity consumption for the feedstock pre-processing, if performed, is obtained from the literature [41].

#### *3.2.2.2.2 HTL biorefinery and Hydrotreatment upgrading*

The biomass-to-biofuel conversion pathway includes two stages: the HTL conversion (units 1,2,3,4,5) and the Hydrotreatment upgrading stage (units 6,7,8,9,10). In the HTL conversion process, the (pre-processed) prepared biomass is added to water (unit 1), and a slurry is formed. The slurry is pressurised (unit 2), up to 100 bar, through a series of pumps and further heated to around 300°C, thereby making the slurry react under subcritical conditions. Upon completion of the residence time (5-60 minutes), the biomass is deconstructed into bio-crude, an aqueous phase with dissolved organics, an off-gas stream, and biochar. *Table 3.1* shows the operating conditions, including the reactor temperature and pressure, along with the respective product yields. The experimental lab-scale data for the feedstock-conversion pathway are obtained from the literature [42], [43], [44]. The process performance of the experimental scale and the lab scale was assumed to be the same. Due to the lack of availability of HTL experimental data on olive pruning biomass, an assumption is made that olive pruning residues behave similarly to those of birchwood residues, owing to similar chemical composition in the feedstock [42]. The reactor output (unit 2à3) is fractionated using two solid-liquid-gas separating unit operations (units 3 and 4). Initially, the char is recovered using an ultrafilter. Due to a lack of evidence in the physiochemical properties of biochar and its unverified ability to act as a soil amendment, the biochar is sent to the cogeneration plant (unit 11) for producing process heat and electricity. Subsequently, upon depressurising, the off-gas stream containing some non-condensable gases is also sent to the cogeneration plant for valorisation. The liquid stream is subjected to a liquid-liquid separation (unit 5) where the aqueous phase with some dissolved organics is recovered. 75 wt.% of the recovered aqueous stream is recycled back into the slurry preparation phase, thereby reducing the necessity of fresh water. The remaining 25% is purged to wastewater treatment facilities for proper treatment before being disposed of into the environment. Based on Albrecht *et al.* (2018), the dissolved organics in the aqueous phase are assumed to be 5 wt.% of the total organic content in the reactor outlet [45]. The oil phase, commonly referred to as biocrude, is sent to upgrading (unit 6)for further treatment via hydrotreatment, where it is reacted with hydrogen to reduce the concentration of heteroatoms (such as N, S, and O). The HTL bio-crudes are reported to have superior quality compared to bio-oils obtained with other thermochemical conversion techniques [46]. Therefore, in this study, we consider the scenario where the HTL bio crudes are co-processed with fossil crudes in an existing oil refinery. Due to developments to establish green hydrogen production systems in the regions of investigation, it is assumed that green hydrogen will be procured for the hydrotreatment process [47]. Hydrotreating is one of the conventional processes used in the chemical industry to improve the quality of hydrocarbon streams, where hydrogen reacts with heteroatoms like Nitrogen, Sulfur, and Oxygen over a bed of nickel-based catalysts [48]. In this analysis, a single-stage hydrotreatment process (unit 6) is implemented, which is operated at 400°C and about 106 bar pressure [49]. The hydrogen is provided in twice more than the stoichiometric requirement (on a mass basis) to ensure complete hydrogenation of heteroatoms present in the biocrude [50]. The hydrotreater outlet is depressurised and cooled to ambient conditions and subjected to a gas-liquid separation (unit 7) to remove the gas stream. The separated gas stream still contains residual hydrogen, which is recovered in a pressure swing adsorption unit (unit 8) and further recycled back to the hydrotreater (unit 6). The liquid stream is subjected to an aqueous phase separation (unit 9) for the removal of residual water from the upgraded organic phase. The upgraded bio-oil is further fractionated (unit 10) in a series of distillation units to obtain naphtha, bio-jet, and diesel fractions based on the difference in boiling point. shows the HTL process model boundary of marine biofuel production.

*3.2.2.2.3 Process simulation*

This study focuses on the use of Hydrothermal Liquefaction (HTL) as the biomass conversion technology pathway. The biofuel production pathway, including the HTL and the hydrotreating processes, is simulated using Aspen Plus v12.0, based on the experimental lab-scale data, as mentioned in the section 3.2.2.2.2, at steady state conditions, on the chosen feedstocks (olive tree pruning [42], coffee pulp [44], and Acacia Mellifera [43]). The modelling approach implemented in this study is robust for both processes, as the method can be used for the different feedstocks in the selected countries, and therefore, the accuracy of the models is not affected by the choice of location. The hydrotreatment was performed by co-processing HTL biocrude in existing petroleum refineries along with fossil crude. The HTL reactor and hydrotreater were modelled as a yield and stoichiometric reactor, respectively. The Soave-Redlich-Kwong property estimation method is used for all unit operations, except for the gas-liquid separators, in which the Non-Random Two-Liquid (NRTL) property method is used, accounting for vapour-liquid equilibrium description. For the HTL process, a yield reactor is used, operating at steady-state conditions. The HTL off-gas composition is assumed to be similar to that reported by Tews *et al.* (2014) [49]. The composition of the HTL organic bio-crude is modelled using model compounds reported in the literature [42], [43], [44]. In the hydrotreatment process, a single-stage stoichiometric reactor is used to simulate the reactions used to remove the heteroatoms (N, S, and O) from the HTL biocrude, as indicated in the Appendix 7.3.5.1. The hydrotreatment output stream (unit 6 à7) is further processed through gas-liquid (unit 7) and liquid-liquid separators (unit 9) to obtain the upgraded bio-oil. The bio-oil is further sent through a series of distillation columns (unit 10) to obtain fractions of Naphtha, bio-jet kerosene, and (marine) diesel based on their boiling points. The overall process conditions of the HTL and hydrotreatment can be found in *Table 3.1*.

Table 3.1: Process parameters for the HTL conversion stage and the hydrotreatment upgrading stage

| | | | |
|---|---|---|---|
| **Biorefinery** | | | |
| Plant running time | 8000 hours | | |
| Plant lifetime | 15 years | | |
| **HTL** | | | |
| | **Spain** [42] | **Colombia** [44] | **Namibia** [43] |
| Mass and Energy input | | | |
| Temperature | 300°C | 320°C | 300°C |
| Pressure | 90 bars | 120 bar | 100 bar |
| Residence time | 30 minutes | 60 minutes | 30 minutes |
| Catalyst | KOH | - | $Na_2CO_3$ |
| Catalyst loading rate | 5 wt.% of biomass | - | 5 wt.% of biomass |
| Biomass/liquid ratio | 0.1 | 0.05 | 0.1 |
| Outlet yields | | | |
| Yields of Biocrude, off-gas, aqueous stream, and biochar (in kg/100 kg DM feed-stock) | 39.5, 0.3, 48.2, and 12.0 | 24.8, 8.6, 52.8, and 14.0 | 31.7, 16.1, 44.4, and 7.9 |
| Energy content of Bio-crude and Biochar (in MJ/kg) | 26.3 and 25.5 | 30.2 and 27.0 | 29.8 and 26.3 |
| **Hydrotreatment** [49] | | | |
| Stage | Single stage | | |
| Liquid hourly space velocity (LHSV), $h^{-1}$ | 0.22 | | |
| Catalyst (kg/tonne bio-crude) | 0.41 | | |
| Temperature | 400°C | | |
| Pressure | 106 bars | | |

#### *3.2.2.2.4 Utilities*

This subsection addresses the strategy implemented to meet the heat, energy, and water demands of the processes. The electricity demand was calculated for all the primary unit operations based on the Aspen Plus simulation (see Appendix 7.3.9) and literature data [51]. The heat demand was estimated using the energy balances (see Appendix 7.3.9 and 7.3.11) obtained from the process simulation based on the specific heat of substances and stream flow conditions. Heat integration techniques have been implemented in the simulation to address heat recovery, such as using a hot HTL reactor outlet stream to heat the inlet biomass slurry in a heat exchanger. The excess energy demand, not satisfied by the process integration for heat recovery, was met by an onsite combined heat and power (CHP) plant, also known as a cogeneration plant, which uses off-gases and biochar from biofuel production. This reduces the grid dependency of the process and maximises the energy recovery of the biomass products. In the CHP stage, the co-products (biochar and off-gas) were burned in excess of air, and the flue gas is passed through a turbine and a condensing boiler for heat and electricity production. An 80% efficiency is assumed for both the turbine and the condensing boiler [51]. Stoichiometric reactions were used to determine the combustion products and the amount of heat contained in the flue gas. The excess energy is sold as electricity to the national grid. The total water demand includes the water used in the process and for steam production in the heating system. The total water demand was calculated based on the assumption that demand for fresh water make-up and boiler blowdown was 22% and 3% of the steam demand, respectively [51].

### 3.2.3 Techno-Economic Assessment

In this section, the methodology for estimating the technical performance indicators, capital, and operating expenses of the value chain design in the three case study scenarios is described. The key technical indicators are the overall yield of the final liquid fuel ($Y_{MBF}$), the quality of the final liquid product (higher heating value and moisture content), and the energy efficiency ($EE_{Process}$) of the process. Similarly, the key economic indicator that is used in this study is the minimum fuel selling price (MFSP) to compare the economic performance of the alternative biofuels in the three case studies and also against their respective fossil counterparts in the regions of interest. The detailed capital and operating expenses estimation procedure can be found in the Appendix 7.3.6.

#### *3.2.3.1 Technical Performance Analysis*

The technical performance of the overall process can be defined using performance indicators. The process performance indicators estimated in this investigation are:

The **overall yield ($Y_{MBF}$)** of the marine "drop-in" biofuel is defined as the mass fraction of the amount of liquid marine biofuel produced per kilogram of dry biomass processed ($kg_{MBF}/kg_{drybiomass}$).

The **quality** of the marine "drop-in" biofuel is estimated by the higher heating value (HHV), which is associated with the energy content of the fuel and the moisture content. These are obtained through Aspen simulations.

**Energy efficiency ($EE_{process}$)**, which is defined as the percentage of useful energy output (biocrude, biochar, off-gas) obtained divided by the total energy supplied through biomass, natural gas, and electricity.

$$Energy\ efficiency:$$

$$\left(\frac{Total\ energy\ conetnt\ of\ output\ streams\ (Biocrude,\ Salable\ electricity,\ internal\ electricity\ and\ heat, aqeuous\ recyclate)}{Total\ energy\ content\ of\ input\ (biomass,\ natural\ gas)}\right)*100 \quad (1)$$

### *3.2.3.2 Capital Expenses (CAPEX)*

The economic estimation starts with calculating the capital expenses. The procedure, commonly known as the factor method, is used to determine the total purchased equipment costs (TPEC) of major equipment and process units based on the literature [49], [51]. The required equipment sizes were calculated using the stream flows from the process mass balances and are scaled to the respective needed capacities using the capacity–costs relation shown in Eq. (2).

$$Cnew = \left(\frac{Snew}{Sref}\right)^{z} *Cref \quad (2)$$

with $C_{ref}$ as the cost of equipment at the reference capacity ($S_{ref}$), and $C_{new}$ as the new equipment costs for the new needed capacity ($S_{new}$), with 'z' as the scaling cost factor for the respective equipment (ranging from 0.65-0.75) [51].

The project lifetime considered is 15 years with an average installation factor of 2.5 [51]. Due to the relatively novel application of the technology in the locations, a contingency factor of 0.5 is included, against the conventional factor of 0.2 for a commercial-scale facility [51]. The working capital (which includes the operational expenses before revenue generation) is calculated with sales revenue estimation using retail market prices of fossil fuels and electricity, as mentioned in the Appendix 7.3.6.3.3. The "drop-in" marine biofuels were compared against marine gas oil (MGO for both economic and environmental performance. The regional production cost differences between the literature data and the specific case study regions are eliminated by using location factors [52] (also in Table 3). The calculation scheme of capital expenses is shown in *Table 3.2*.

Table 3.2: Composition of Capital expenses (CAPEX) estimation based on Seider (2017) [53] and Tews et al. (2014) [49]

| Abbreviation | Definition | Factor/Formula |
|---|---|---|
| **FCI** | **Fixed capital investments include** | **FCI = dc + ic + cf + cc** |
| dc | Direct capital costs include | dc = TPEC + inst |
| *TPEC* | *Total production equipment costs* | *The sum of all scaled equipment costs* |
| *inst* | *Installation costs (labour and materials)* | *2.5*TPEC* |
| ic | Indirect costs | 0.34*dc |
| cf | Contractor's fee | 0.23*TPEC |
| cc | Capital contingency | 0.5*TPEC |
| **WC** | **Working capital** | 0.2*sales revenue |
| **SC** | **Startup costs** | 0.07*FCI |
| **LF** | **Location factor** | 0.9 (Spain), 0.8 (Colombia), 1.2 (Namibia) |
| **CAPEX** | **TOTAL CAPITAL INVESTMENT** | **CAPEX = LF*(FCI + WC + SC)** |

In this study, the HTL biocrude is assumed to be co-processed in petroleum refineries in the respective locations. Therefore, we do not consider the capital expenses associated with the upgrading and fractionation stage of the value chain based on the perspective of the transition of petrochemical refineries to renewable biofuels in the future.

#### *3.2.3.3 Operating Expenses (OPEX)*

*Table 3.3* indicates the calculation assumptions made for estimating the operational costs of the process and the biohubs. The operational costs consist of a fixed fraction and a variable fraction. The latter part includes country-specific expenses associated with feedstock procurement, catalysts and chemicals, utilities, waste processing, and transport. The feedstock procurement costs relate to the price of raw materials at the end gate of the pre-processing facility in the biohubs. The transport costs were calculated based on the fixed and variable transport costs incurred for transporting the raw materials and intermediates between processing facilities. The distance between these facilities is calculated using driving distances from online GIS tools such as Google Maps. The fixed variable expenses fractions consist of labour costs, taxes, insurance, maintenance, and plant overheads [41]. A contingency factor of 0.2 was used against the direct production costs to account for the unforeseen costs of a conversion technology at the lower Technology Readiness Level [51].

Labour costs are estimated based on a scenario with three 8-hour shifts, employing 6 workers per shift for the HTL conversion process [54]. The costs for chemicals, catalysts, and landfilling activities are obtained from the literature. The waste processing costs, which include wastewater treatment and off-gas cleaning treatment, were estimated based on methods reported in the literature. However, certain costs related to operating expenses, such as catalyst and electricity consumption costs, for the upgrading stage have been taken into consideration, as can be seen in the Appendix 7.3.6.3.3. The variable expenses due to fractionation are not considered in this study, as it is assumed to be cofractionated with the fossils.

Table 3.3: Composition of Operating expenses (OPEX) estimation methodology [53]

| Symbol | Description | Factor or formula | References |
|---|---|---|---|
| **DPC** | **Direct Production Costs, including** | **DPC = VC + LC + M** | |
| *VC* | Variable costs, including | VC = *F* + *T* + *U* + *Wt* | |
| *F* | feedstock[a] | Olive pruning residue = 100 EUR/ton<br>Coffee pulp residue = 48 EUR/ton<br>Acacia Wood chips = 68 EUR/ton[33]<br>Green Hydrogen, ES: 3.1 EUR/kg[55], CO: 3.1 EUR/kg[55], NA: 2.0 EUR/kg[56] | This study |
| *U* | Utilities | Natural Gas, ES: 1389 EUR/ton[54], CO: 641 EUR/ton[57], NA: 1389 EUR/ton[54]<br>Water, ES: 0.08 EUR/ton[58], CO: 0.08 EUR/ton[58], NA: 0.28 EUR/ton[59]<br>Electricity, ES: 28.6 EUR/GJ[60], CO: 36.1 EUR/GJ[61], NA: 29.7 EUR/GJ[62] | |
| *T* | Transport | Truck Transport, fixed = 12 EUR/ton (ES), 6 EUR/ton (CO), 12 EUR/ton (NA)<br>Truck transport, variable = 0.27 EUR/ton-km (ES), 0.16 EUR/ton-km (CO), 0.27 EUR/ton-km (NA) | This study |
| *Wt* | Waste treatment | waste processing: gas = 6.00 EUR/ton (ES), 6.00 EUR/ton (CO), 6.00 EUR/ton (NA)<br>waste processing: water, black = 0.60 EUR/ton (ES), 0.60 EUR/ton (CO), 0.60 EUR/ton (NA)<br>waste processing: solids = 135 EUR/ton (ES), 135 EUR/ton (CO), 135 EUR/ton (NA) | Based on [63] |
| *LC* | Labour costs, including | LC = *Dw* + *Sv* | |
| *Dw* | Direct wage and benefits | 12 EUR/hr (ES), 6 EUR/hr (CO), 12 EUR/hr (NA) | This study |
| *Sv* | Supervision and supplies | 50% *Dw* | |
| M | Maintenance of equipment | 10% of FCI | |
| **OC** | **Operating Contingency** | **20% of DPC** | |

Table 3.3: Composition of Operating expenses (OPEX) estimation methodology [53] (*continued*)

| Symbol | Description | Factor or formula | References |
|---|---|---|---|
| **PO** | **Plant Overhead** | **70% of *LC*** | |
| **FC** | **Fixed charges, including** | **FC = lt + i + d** | |
| lt | Local taxes | 1.5% (ES), 1.5% (CO), 1.5% (NA) of fixed capital costs | This study |
| i | Insurance | 1.0 % (ES), 1.0% (CO), 1.0% (NA) of sales revenue | This study |
| d | Linear depreciation | 14.0% (ES)[64], 28.0% (CO)[65], 25.0% (NA)[66] of fixed capital costs | |
| **GE** | **General administrative overhead expenses** | **10% of sales revenue** | |
| **OPEX** | **Total Operating Expenses** | **OPEX = DPC + OC + PO + FC + GE** | |

[a] *feedstock price includes the transportation costs from the farm to the pre-processing or the HTL facility*

### 3.2.3.4 *Minimum Fuel Selling Price (MFSP)*

Based on the capital and operational expenses, the minimum fuel selling price (MFSP) was estimated. Equation 2 presents the formula for calculating the MFSP, where it is the unit price of the final product is when the total annual sales revenue equals the total annual operating expenses.

$$MFSP = \frac{Operating\ expenses - byproduct\ sales\ revenue\ (such\ as\ electricty,\ \ biochar,\ \ naphtha,\ \ and\ biojet)}{Annual\ biofuel\ production\ capacity} \quad (3)$$

Due to unknown properties of biochar to be implemented for purposes such as soil amendment, in this study, the biochar produced is assumed to be burned in a cogeneration plant to produce electricity for the facilities. Excess electricity, if produced, is sold to the national grid at its wholesale retail market price (as shown in Table 4 for Spain, Colombia, and Namibia). The MFSP of HTL marine drop-in biofuels was compared against the MGO prices from 2023 at the Port of Gibraltar (for the Spain case study), Port of Buenaventura (Colombia), and Port of Walvis Bay (Namibia). The MGO prices in Gibraltar, Colombia, and Namibia are shown in the Appendix 7.3.6.3.3.

### 3.2.3.5 *Sensitivity analysis*

A sensitivity analysis was performed to understand the impact of four commonly reported factors due to their large variability and low resolution on the available data: a) feedstock price, b) HTL equipment costs, c) biocrude yield, and d) installation factor. These parameters were varied by ±50% to evaluate their impact on the overall process economics through the sensitivity on MFSP of marine "drop-in" biofuel.

### 3.2.4 Environmental Lifecycle Assessment (e-LCA)

#### *3.2.4.1 Goal and Scope*

To evaluate the environmental performance of the "drop-in" biofuels produced in the designed biohubs, an attributional life cycle assessment (a-LCA) is conducted to quantify the environmental footprint. The analysis is performed from a "Cradle-to-grave" approach following the international standard for e-LCA, ISO 14040, with the Functional Unit of 1 megajoule (MJ) of the drop-in marine biofuel [67], [68]. The environmental performance of the HTL "drop-in" biofuel is compared against the emissions from the life cycle of fossil-based marine gas oil (MGO) as a benchmark to contextualise the impact of the biofuels' environmental emissions.

3

The LCA inventory consists of and accounts for all stream emissions from each process and their respective upstream supply chain [67], [68]. This includes sourcing of feedstocks, production of biooil and fractionation, and consumption of biofuel fractions (incl. marine biofuel), from feedstock extraction up until final waste processing. However, the inventory does not include any emissions related to infrastructure development, construction, and equipment manufacturing, as these activities are proven to have minor contributions [41]. The foreground systems include biomass pre-treatment, biofuel production, upgrading, combustion, and transportation between these elements of the value chain. The background systems include biomass production and its upstream activities, such as cultivation.

As all of the feedstocks are either agricultural residues or have a short-term biomass cultivation period (≤ 5 years), the biogenic $CO_2$ during the biofuel combustion is considered to have a net-zero GWP. The emissions from each process stage are obtained using the characterisation factors. The mass flows and energy consumptions are obtained from the Aspen simulations (see Appendices 7.3.8, 7.3.9, and 7.3.11), which are then multiplied by their corresponding emission characterisation factors obtained from the ecoinvent database from SimaPro software, as mentioned in the Appendix 7.3.7. *Figure 3.2* illustrates the system boundaries for the marine biofuel production.

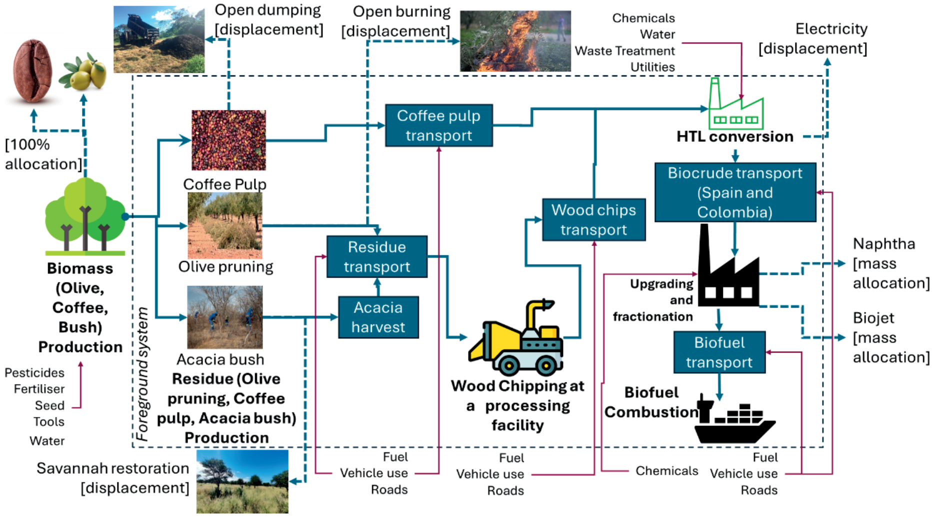


Figure 3.2: System boundaries of marine biofuel environmental life cycle assessment. Weighted blue line: Main product, Dashed blue line: Co-product [allocation method], and purple weighted line: inputs from background system

### *3.2.4.2 Inventory*

The life cycle stages of biohubs are biomass production, biomass transport, biomass pretreatment, pretreated residue transportation, HTL conversion, biocrude transport, hydrotreatment, upgraded biofuel transport, and biofuel combustion. The life cycle stages are described below, and the inventory results are available in the Appendix 7.3.7.

**Residue production,** as can be seen in *Figure 3.2***,** includes the crop cultivation phase, harvest, and residue generation activities. The data for the activities were obtained from the ecoinvent database and literature reports. The environmental burdens associated with the generation of agricultural residues are assumed to be zero in all the scenarios due to their low (<10%) economic value in comparison with the main (cash) crop [69]. However, emissions related to biomass extraction (such as harvesting of the Acacia bush) and biomass pretreatment (such as chipping) are considered in this study. We also assume no soil carbon change due to the sustainable harvest of Acacia and Olive tree pruning residues [38], [70]. Avoided emissions due to the current utilisation of olive pruning burning, coffee pulp disposal in open fields, and regrowth of savannah grasses after acacia harvest have been taken into consideration via system expansion (refer to Appendix 7.3.7).

**Transport emissions** are estimated using the emissions factors data, as mentioned in the Appendix 7.3.7, obtained from the literature reports and the ecoinvent data. In case of non-availability of country-specific data (such as in Namibia), alternative data from neighbouring countries or the continent was used, as can be seen in the Appendix 7.3.7. The emissions are associated with residue transport from the farm to the pretreatment facility and subsequently to the HTL facility in trucks (except for Namibia, where they would be transported by Rail). The HTL biocrudes are considered to be transported either through liquid tanker trucks (Spain) or pipelines (Namibia and Colombia). The transport of the final "drop-in" biofuel is performed using the existing infrastructures of the petrochemical refineries via pipelines.

3

The **biofuel production stage** includes pretreated biomass conversion via HTL and biocrude upgrading via hydrotreatment in an existing petrochemical refinery. The emissions related to foreground processes are estimated from the simulated process models (*i.e.,* the mass and energy balances in Appendices 7.3.8, 7.3.9, and 7.3.11), and the background data includes upstream emissions of utilities, water, and waste disposal (see Appendix 7.3.7). According to the ISO methodology, system expansion, also known as allocation by displacement, is implemented to allocate emissions amongst the biocrude and electricity sold to the grid from the CHP plant. The electricity from the biorefinery is assumed to replace the electricity produced from existing conventional sources, and therefore, the allocated impacts of biofuel are determined by deducting the impacts of displaced electricity, as shown in the Appendix 7.3.7. Due to similarity in mass and energy distribution among the fractionated products, the multifunctionality while allocating environmental emissions has been addressed by mass allocation.

The emissions related to **fuel combustion** in an internal combustion engine are very limited for lignocellulosic-based HTL drop-in biofuels, and therefore, it is assumed to be the same across all the case studies, based on experimental measurements, as mentioned in the Appendix 7.3.7. For the reference material, as a conventional shipping fuel, MGO is chosen in this investigation. Due to a lack of data for MGO, the data is obtained from the ecoinvent database for heavy fuel oil (HFO) and modified based on higher heating values for the two fuels according to Comer and Osipova (2021) [71].

#### *3.2.4.3 Impact Categories*

Given that the scope of the study is to evaluate the environmental footprint of marine biofuel from the perspective of the IMO 2020 regulation [72], the life cycle impacts are evaluated through the ReCiPe 2016 Midpoint (Hierarchist) method, with its 18 impact categories, listed as follows: Climate change (in kg $CO_2$ eq to air), Ozone depletion (in kg CFC-11 to air), Ionizing radiation (in kBq Co-60 to air), Fine particulate matter formation (in kg PM2.5 to air), Photochemical oxidant formation: ecosystem quality (in kg $NO_x$ to air), Photochemical oxidant formation: human health (in kg $NO_x$ to air), Terrestrial acidification (in kg $SO_2$ to air), Freshwater eutrophication (in kg P to freshwater), Human toxicity: cancer (in kg 1,4- DCB to urban air), Human toxicity:

non-cancer (in kg 1,4- DCB to urban air), Terrestrial ecotoxicity (in kg 1,4- DCB to industrial soil), Freshwater ecotoxicity (in kg 1,4- DCB to fresh), Marine ecotoxicity (in kg 1,4- DCB to marine water), Land use (in $m^2$*yr annual crop land ), Water use (in $m^3$ water consumed), Mineral resource scarcity (in kg Cu), Fossil resource scarcity (in kg oil), and Marine eutrophication (in kg N eq).

## 3.3 RESULTS AND DISCUSSIONS

In this section, the approach to context-specific, inclusive, capability-sensitive conceptual design of biohubs in the case study locations is discussed in section 3.3.1 using design propositions. The techno-economic and environmental performance of the developed biohub designs has been evaluated in Section 3.3.2 and section 3.3.3, respectively. Finally, a sensitivity analysis of the MFSP of the biofuels on some of the key performance indicators has been discussed in the section 3.3.4.

### 3.3.1 Design Space and Design Propositions

During the stakeholder interviews and multistakeholder workshop, the preferences for biohub design have been identified. The Design Space was classified and discussed through various design elements. For instance, the design aspect of feedstock included elements such as the choice of feedstocks, processing, and logistics. The design characteristics were elucidated based on stakeholders' perspectives and common agreement about the current needs that are to be addressed, as well as motivating features for biohub implementation in the future. Finally, design propositions were elucidated based on the norms of the capability approach [13] and design choices made by stakeholders. More detailed aspects of the translation of design propositions to technical design choices are reported in our previous work [73]**.** The *Table 3.4* shows the identified and local stakeholders' validated biohubs design characteristics and propositions within the Design Space for design elements in the new biobased value chains.

Table 3.4: Design Space, Design elements, Design Characteristics, and Design Propositions for biohubs in Spain, Colombia, and Namibia.

| Design Space | Design Elements | Desired characteristics | Design Propositions |
|---|---|---|---|
| **Spain** [73] | | | |
| Feedstock | *Choice of biomass* | - Can process all residues, allowing sustainable expansion of the primary olive sector<br>- Should bring more economic and environmental benefits than the current uses | - Use Crude olive pomace as the primary feedstock<br>- Olive tree pruning biomass, Olive leaves, and Exhausted olive pomace can be utilised as feedstocks if they can bring more economic revenue than existing uses. |
| | *Processing and Logistics* | - Combination of a central facility for chipping and the ability to process farmers' chipped biomass<br>- Farmers prefer to do the labour on their farms | - Central wood chipping facility at cooperative-owned primary mills<br>- Farmers can bring either pruned or chipped biomass<br>- Potential to use third parties for pruning, chipping, and transportation for farms with ageing owners. |
| Biorefinery | *Technology* | - Biochemical or Thermo-chemical conversion techniques<br>- Should match the technical skill set of existing stakeholders<br>- Fossil-free technology | - Centralised HTL facility<br>- Upgrading at San Roque refinery<br>- Off gas and biochar valorisation for energy requirements through a cogeneration plant. |
| | *Location* | - Accessible to all farmers<br>- Access to good transport infrastructures<br>- The facility should have access to the population with the technical skills | - Ubeda is preferred over Jaen due to the proximity to farms. |
| | *Products* | - Bulk/Fine/Speciality chemicals | - Transportation fuels<br>- Oleochemicals |
| Benefits | *Economic, Environmental, Social* | - Reduce air pollution mainly due to Particulate matter emissions from pruning biomass burning.<br>- Farmers need to get rid of pruning biomass before May every year, according to the Common Agricultural Policy<br>- Improvement of soil health | - At least 75% of the pruning biomass is available<br>- 100% of the pruning biomass is available when farmers are enabled to grow other cover crops (such as grasses)<br>- Valorisation of Crude olive pomace in large quantities can reduce soil and air pollution due to surface run-offs and open-pond storage |
| | | - Any valorisation which can bring additional revenue to farmers is encouraged | - Minimum selling price of olive tree pruning should be 70 Euros/ton |

Table 3.4: Design Space, Design elements, Design Characteristics, and Design Propositions for biohubs in Spain, Colombia, and Namibia. (*continued*)

| Design Space | Design Elements | Desired characteristics | Design Propositions |
|---|---|---|---|
| **Colombia** | | | |
| Feedstock | *Choice of biomass* | - Large availability, no/minimal competing uses<br>- Existing logistical and organisational infrastructure to build new value chains | - Valorisation of residues from the coffee sector is an example for other sectors, such as cacao.<br>- The coffee sector is well structured and organised for collective sectoral impact in the country |
| | *Processing and Logistics* | - New value chains can strengthen coffee and cacao bean quality uniformity for better economic revenue.<br>- Value addition should be close to the farm<br>- Residues should be transformed quickly to prevent biodegradation.<br>- Farmers should be able to process beans from their farms. | - Centralised facility to process cash crops (such as coffee, cacao) for uniformity in the processing of beans and can act as a logistical point for residue collection<br>- Located one per region in the department and owned by an association/cooperative/federation<br>- Farmers are willing to bring residues to the processing facility free of cost. |
| Biorefinery | *Products produced* | - Products that can be produced by consuming large quantities of residues<br>- Can be used within the region of the biorefinery<br>- Has market demand | - Biofuels<br>- Food and pharmaceutical products<br>- Bio-degradable plastics |
| | *Technology* | - Should not compete with water consumption in the primary sector<br>- Higher TRL or ability to scale up easily<br>- Process all residues from the agroforestry system, namely, coffee, cacao, banana, and avocado | - A technology with existing "proof of concept"<br>- Water recycling and off-gas valorisation techniques to be implemented.<br>- Biochemical transformation is preferred due to existing knowledge and expertise<br>- Promising Thermochemical technologies can be considered.<br>- Technologies can be integrated with the Sebastopol refinery |
| | *Location* | - In a special economic zone to benefit from foreign direct investment<br>- In the capital city of a Department, such as Pereira, to benefit from the workforce and infrastructure | - HTL facility in Pereira<br>- Upgrading at the Sebastopol refinery |

Table 3.4: Design Space, Design elements, Design Characteristics, and Design Propositions for biohubs in Spain, Colombia, and Namibia. (*continued*)

| Design Space | Design Elements | Desired characteristics | Design Propositions |
|---|---|---|---|
| Benefits | *Economic, Environmental, Social* | - Reduce soil and water pollution<br>- Reduce the import of organic fertilisers | - Any resource recovery strategy from residues is beneficial<br>- By-product valorisation to make the system "fossil-free" and enhance primary agriculture is encouraged. |
| | | - Broaden the income revenues of small-scale farmers suffering due to climate change<br>- Better revenues from primary crops | - Implement replicable and scalable solutions.<br>- Associations/cooperatives owned common processing facilities for better control of processing |
| **Namibia** | | | |
| Feedstock | *Choice of biomass* | - Ability to process all problematic species | - Acacia Mellifera, as it is one of the most abundant |
| | *Feedstock providers* | - Ideally, all three groups of farmers (Commercial, communal, and resettled) should be able to participate | - Commercial farmers providing 70-80% feedstock demand with 20-30% ad-hoc supply from communal farmers |
| | *Harvesting methods* | - Should be chosen based on equipment availability, accessibility, and species diversity.<br>- All modes (manual, semi-mechanised, and fully mechanised) should be practised<br>- Sustainable harvesting should be practised | - Choice to be made based on the region of interest and farmers' capabilities.<br>- Forest Stewardship Council (FSC) -certified feedstocks as proof of sustainable feedstock extraction<br>- The harvest should be done after obtaining a harvest permit and performing an impact assessment.<br>- Communal farmers should have community forest management practices in place |
| | *Feedstock handling (logistics, processing, and contracts)* | - A centralised processing facility, as many farmers cannot afford the equipment<br>- Constant off-take agreement will enable continuous supply.<br>- Processing facilities should cater to multiple supply chains, such as charcoal, fodder, fences, etc.<br>- Mode of transport (Rail/Road)<br>- Use the existing knowledge of the Biomass Industrial Park, but with modifications to make it successful. | - Wood chips will be the nature of the feedstock<br>- Biomass park concept for wood processing facility<br>- Common wood-chipping facilities will be placed near the biomass site, and with high population density<br>- Road or Rail transport for feedstock transportation from the Biomass park to the HTL facility |

Table 3.4: Design Space, Design elements, Design Characteristics, and Design Propositions for biohubs in Spain, Colombia, and Namibia. (*continued*)

| Design Space | Design Elements | Desired characteristics | Design Propositions |
|---|---|---|---|
| Biorefinery | *Products produced* | - Speciality/Fine/Bulk chemicals<br>- Should have a marketable anchor product<br>- Has both national and international markets<br>- Can uptake a large quantity of available bush biomass | - Biofuels<br>- Green hydrogen |
| | *Technology* | - Technologies that can process dry feedstocks<br>- Less water consumption<br>- Can be operated in a decentralised mode with current technical know-how of people<br>- Integrate or complement with existing value chains of bush valorisation | - Wood chips as the chosen nature of feedstock, as they can also be used for wood pellets and animal fodder<br>- Wood chipping at regional, decentralised locations<br>- HTL with water recycling methods.<br>- Ability to integrate with existing value chains and future projects. |
| | *Choice of location* | - Near the regions with high bush density<br>- Near the regions with high population density<br>- Skilled labourers are not available throughout the country. | - Biomass parks in the regions of Otjiwarongo, Tsumeb, Okhakarara, Grootfontein<br>- HTL facility at Walvis Bay |
| Benefits | *Economic, Environmental, Social* | - All | - Additional income, especially during drought seasons<br>- Almost all families can benefit from the sustainable bush valorisation<br>- Reclamation of Savannah lands, especially for game movement and livestock farming<br>- Improved soil inorganic and organic health<br>- Increased groundwater availability<br>- Inclusive and equal participation of different biomass providers in a commercial value chain<br>- By-products to be valorised as per the needs of local contexts, such as soil amendment, energy production, or water purification |

Based on the derived Design Propositions, the *Figure 3.3* shows the biohubs configurations here derived for each case study to produce marine biofuel from olive tree pruning, coffee pulp, and Acacia, in Spain, Colombia, and Namibia, respectively. More details regarding the biohub configurations are summarised in the Table *3.5*.

For Spain, the feedstock availability is conservatively assumed to be 50% (or 450,000 tons per annum) of the produced pruning biomass in the province of Jaen, accounting for cover crop application. In the department of Risaralda in Colombia, 100 % (or 83,000 tons per annum) feedstock availability is assumed due to the absence of any utilisation practices. Finally, in Namibia, a mobilisation of 250,000 tons per annum (2.5% of the total availability) of acacia wood is considered as a feedstock supply capacity. Additionally, for the "first-of-its-kind" biohub concepts considered in this investigation, the scales of the HTL facilities resulting from the biomass availability stated above for the three locations are therefore 1265 DTPD, 211 DTPD, and 692 DTPD of biomass feedstock in Spain, Colombia, and Namibia, respectively.

Table 3.5: Biohub design configuration details at different stages of biohub in Spain, Colombia, and Namibia

| | Case-study locations | | |
|---|---|---|---|
| **Biohub stages** | **Spain** | **Colombia** | **Namibia** |
| **Feedstock** | Olive tree pruning | Coffee Pulp | Acacia Mellifera |
| **Harvesting and transport from the farm to the pre-processing facility** | Farmers bring pruned biomass to their associated primary mills using their existing infrastructure and get paid at the gate. | Farmers bring coffee cherries to a centralised processing facility (possibly owned by a cooperative or association) | Farmers use suitable and dedicated harvesting techniques. Trailers and Trucks are used to transport the raw feedstock. |
| **Pre-processing facility location** | Primary mills will act as a processing facility, within a 10-km distance from olive farms | Coffee pulp will be generated in a new centralised coffee processing facility. One per region in the Department. | One new pre-processing facility in major cities with considerable population density, within a 100-km radius. |
| **Transport from the pre-processing facility to the HTL Facility** | Wood chips are transported in 16-32-ton trucks with an average distance of 45 km. | Coffee pulp is transported in 7.5-16 ton trucks with a refrigeration system, with an average distance of 75 km. | Wood chips are transported in a freight train over a distance of 450 km. |
| **HTL Location** | Ubeda | Pereira | At the refinery site in Walvis Bay |
| **HTL biocrude transportation to an upgrading facility** | Biocrude is transported via Liquid tanker trucks over a distance of 320 km. | Biocrude is transported via Liquid tanker trucks over a distance of 380 km. | HTL and Upgrading at the same site |

Table 3.5: Biohub design configuration details at different stages of biohub in Spain, Colombia, and Namibia (*continued*)

| | Case-study locations | | |
|---|---|---|---|
| **Upgrading Location** | Compañía Española de Petróleos, Sociedad Anónima (CEPSA) San Roque refinery | Sebastopol refinery | Joedilla Refinery |
| **Marine biofuel (MBF) transport** | MBF is transported via an existing pipeline over a distance of 15 km. | MBF is transported via a yet-to-be-constructed pipeline over a distance of 100 km. | MBF is transported via a yet-to-be-constructed pipeline over a distance of 20 km. |
| **End-use Location** | Port of Gibraltar | Puerto Berrío | Port of Walvis Bay |

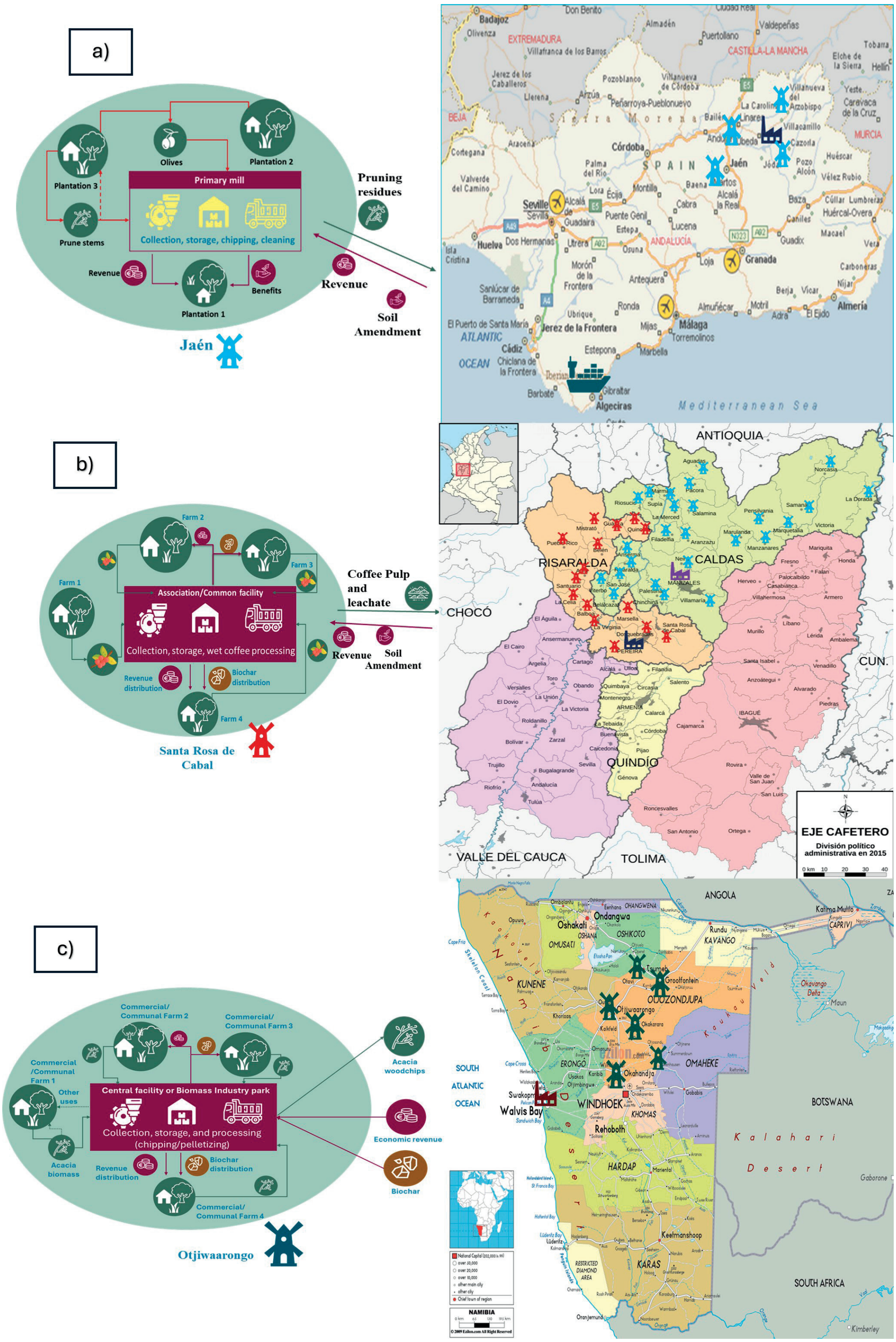


Figure 3.3: Biohub configuration for a) Spain, b) Colombia, and c) Namibia (from top to bottom)

## 3.3.2 Techno-economic performance of "drop-in" marine biofuel production from biomass

*Table 3.6* summarises the key technical performance indicators resulting from the process model as described in Sections 3.2.2.2.2 and 3.2.2.2.3, in combination with the Biohubs' characteristics identified and described in Section 3.3.1 (like capacity, conversion yields, and product distribution).

Initially, technical performance is investigated based on the mass and energy balances obtained from the process simulations. In the HTL conversion stage, the processes implementing catalysts (*i.e.*, KOH for olive pruning in Spain and $Na_2CO_3$ for acacia bush in Namibia) produce a higher yield of biocrude. The biomass to biocrude yield obtained from Aspen modelling is found to be slightly higher than that of experimental values, owing to the recovery of organics present in the aqueous recyclate. The quality of biocrude, especially the energy content of biocrude (HHV), obtained via modelling (40-44 MJ/kg), was found to be higher than that reported in the literature (30-36 MJ/kg)[42], [43], [44], owing to the higher efficiency of aqueous phase separation from HTL biocrude. The average electricity consumption ($kW/kg_{feed}$) for the HTL processes is found to be at least 45% lower than that reported in the literature, owing primarily to the reduced working volumes due to recycling of the output HTL-aqueous streams [41], [74], [75]. In terms of energy efficiency, all the HTL processes are self-sufficient (not fossil-dependent, no natural gas consumption as can be seen in *Table 3.6*), when the off-gas and biochar produced are fully used in the cogeneration plant. The heat from the cogeneration plant was utilised to satisfy the process's internal heat demand. Excess electricity from the cogeneration plant is sold to the national grid to displace fossil-based electricity. The major sinks for heat loss are found to be the flue gas and wastewater streams. This could be inferred from the reduced overall process energy efficiency for the coffee-residue-based case study, with only 68% compared to the other two case studies, as seen in the Appendix 7.3.11. The large differences in waste streams (in *Table 3.6*) generated and excess electricity produced are owed to the differences in quantity (Appendix 7.3.9) and energy content of the by-products (see *Table 3.1*).

In the hydrotreatment stage, based on the stoichiometric, complete hydrogenation of identified HTL biocrude components is assumed. To ensure complete hydrogenation, hydrogen is supplied in excess (200 wt.%) of the stoichiometric quantity. The hydrogen consumption in this study was found to be at least 50% less than that of the assumed values in the literature [51], [76]. The reduced hydrogen consumption could be attributed to the presence of lower moisture content in modelled biocrude from the HTL conversion stage. The upgraded oil yield obtained from the respective HTL biocrude is found to be dependent on the percentage of impurities (hetero atoms) present in the biocrude, indicated with the lowest biocrude to bio-oil yield for coffee residues

(81%) and highest for olive tree pruning biomass (94%). In the process simulation, due to the stream composition and thermodynamic behaviour of stream components, upon distillation, the upgraded oil from olive pruning and coffee pulp yields a larger fraction of diesel in comparison to that of acacia-based bio-oil, as represented by the yield of naphtha, biojet, and "drop-in" marine biofuel in *Table 3.6* . The difference in fractionation yield is attributed to the presence of a high amount of lower-boiling-point components in the bio-oil, which end up in the naphtha fraction.

Table 3.6: Technical performance indicators for the "drop-in" marine biofuel production

| | Case-study location | | |
|---|---|---|---|
| **Technical Parameters (unit)** | **Spain** | **Colombia** | **Namibia** |
| **Overall biofuel production Process** | | | |
| Feedstock processing capacity (in DTPD) | 1265 | 211 | 692 |
| % of total regional feedstock processed in a year | 50% | 100% | 2.5% |
| Drop-in marine biofuel output (in ktpa) | 58.11 | 5.58 | 17.06 |
| **HTL conversion** | | | |
| Liquefaction catalyst | KOH | - | $Na_2CO_3$ |
| Biomass to biocrude yield (kg/kg DM) | 0.38 | 0.27 | 0.33 |
| Biocrude quality | | | |
| *HHV (in MJ/kg)* | 43.05 | 41.32 | 39.45 |
| *LHV (in MJ/kg)* | 39.81 | 38.08 | 36.43 |
| *Water content (in wt.%)* | 2.5 | 3.4 | 2.6 |
| Natural gas consumption (kg/kg DM) | 0 | 0 | 0 |
| Water consumption (kg/kg DM) | 3.09 | 8.29 | 3.09 |
| Electricity utilisation (kWh/kg DM) | 0.06 (HTL)/ 0.09 (Upgrading) | 0.14 (HTL)/ 0.11 (Upgrading) | 0.06 (HTL)/ 0.09 (Upgrading) |
| Excess Electricity (kWh/kg DM) | 0.04 | 0.23 | 0.20 |
| Waste streams | | | |
| *Off-gas (kg/kg DM)* | 1.52 | 2.87 | 1.31 |
| *Liquids (wastewater) (kg/kg DM)* | 2.66 | 6.11 | 2.62 |
| *Solids (ash) (kg/kg DM)* | 0.00 | 0.1 | 0.04 |
| Internal Heat Use (MJ/MJ biofuel) | 0.02 | 0.99 | 0.26 |
| Process energy efficiency (in %) | 77 | 68 | 77 |
| **Hydrotreatment** | | | |
| Green Hydrogen demand (kg/kg DM) | 0.02 | 0.01 | 0.01 |
| Biocrude to upgraded bio-oil yield | 0.94 | 0.81 | 0.91 |

Table 3.6: Technical performance indicators for the "drop-in" marine biofuel production (*continued*)

| | Case-study location | | |
|---|---|---|---|
| **Fractionation** | | | |
| upgraded bio-oil to "Drop-in" marine biofuel yield | 0.36 | 0.37 | 0.25 |
| "Drop-in" marine biofuel to biomass yield (kg/kg DM) | 0.14 | 0.08 | 0.07 |
| Light Naphtha to biomass yield (kg/kg DM) | 0.06 | 0.03 | 0.11 |
| Biojet to biomass yield (kg/kg DM) | 0.14 | 0.10 | 0.10 |
| Drop-in marine biofuel quality | | | |
| *HHV (in MJ/kg)* | 43.03 | 43.05 | 37.68 |
| *LHV (in MJ/kg)* | 39.66 | 39.9 | 34.96 |
| *Water content (in wt.%)* | 1.9% | 0 | 0 |

The economic performance of the biohubs is specified in *Table 3.7*. The total production costs of biocrude are found to be largely influenced by the scale, biocrude yield, and capital costs. Due to the large scale, the MFSP of biofuel in the Spanish case study is significantly lower due to economies of scale. Due to lower yields of bio-oil from coffee pulp, more feedstock is needed, thereby increasing the capital costs and negatively influencing the MFSP of biofuel obtained.

The HTL reactor is the major contributor to the total equipment costs, followed by the pre-treatment facility (if present) and cogeneration plant. The biocrude production costs are estimated in the range of 1260.2-3911.3 EUR/$ton_{biocrude}$ in comparison to 0.6 EUR/$kg_{Brent\ crude}$ [77]. Overall, for the three case studies, the capital depreciation (24-58%), maintenance costs (12-19%), feedstock price (5-20%), and catalysts (4-10%) contribute majorly to the production costs, as can be seen in Appendix 7.3.10. With co-processing, the upgrading production costs are in the range of 125-921 EUR/$t_{bio\text{-}oil}$, with biocrude transportation contributing a significant proportion in Spain (65%) and Colombia (68%), as can be inferred from the table in Appendix 7.3.10. The upgrading costs compare well with the reported values of 0.5-0.97 EUR/$L_{bio\text{-}oil}$ in the literature [74], [75]. Moreover, the production costs of final "drop-in" marine biofuel, on an energy content (HHV) basis, are found to be (32.19-112.24 EUR/GJ) and are higher than marine gas oil (19.38 EUR/GJ, in 2024 at Port of Gibraltar). However, except for coffee pulp owing to its small scale, these values are lower or within the range (17-50 EUR/GJ) of drop-in marine biofuels obtained from other thermochemical conversion pathways [51], [78], [79], [80], [81], [82]. Finally, the ratio of the minimum fuel selling price of "drop-in" marine biofuel to that of its fossil equivalent (marine gas oil, MGO) is found to be in the range of 1.05-5.54. This value is highly sensitive to the changes in the (regional) market price of MGO. The cost incurred due to the avoided emission of fossil $CO_2$ is not considered in this investigation, which, in addition, might lead to more cost-competitive cases for alternative biofuels.

Table 3.7: Economic performance of the marine biofuel production in the case study locations

| | Case-study locations | | |
|---|---|---|---|
| **Economic Parameter** | **Spain** | **Colombia** | **Namibia** |
| **Capital costs** | | | |
| ***Total Purchased equipment costs (TPEC) (in million Euros), includes (contribution%)*** | 93.0 | 42.5 | 59.5 |
| Feedstock pretreatment | 5.9 (6.3%) | 0 | 3.5 (5.9%) |
| HTL reactor system | 82.1 (88.3%) | 39.3 (92.5%) | 52.1 (87.6%) |
| Cogeneration plant | 5.0 (5.4%) | 3.2 (7.5%) | 3.9 (6.6%) |
| ***Total Installed costs (TIC) (in million Euros)*** | 139.5 | 63.8 | 89.3 |
| ***Indirect costs (in million Euros)*** | 79.1 | 36.1 | 50.6 |
| ***Fixed capital investment (FCI) (in million Euros)*** | 379.6 | 173.5 | 243.0 |
| ***Total capital investment (TCI) (in million Euros)*** | 442.2 | 192.9 | 275.8 |
| ***Location-adjusted TCI (in million Euros)*** | 398.0 | 154.3 | 331.0 |
| **Operating costs (in million Euros per year) include** | | | |
| ***Variable operating costs (in million Euros per year)*** | 71.2 | 7.2 | 26.3 |
| Of which, Feedstock | 45.1 | 3.6 | 16.3 |
| Of which, Water | 0.1 | 0.05 | 0.2 |
| Of which, Hydrogen | 0.03 | 0.003 | 0.005 |
| Of which, Liquefaction Catalyst | 14.9 | - | 3.61 |
| Of which, Hydrotreatment Catalyst | 6.4 | 0.7 | 2.85 |
| Of which, Wastewater treatment | 0.7 | 0.3 | 0.2 |
| Of which, Gas cleaning | 3.8 | 1.2 | 1.8 |
| Of which, Ash disposal | 0.13 | 0.98 | 1.35 |
| Of which, Biocrude Transportation | 16.87 | 0.34 | 0 |
| ***Capital depreciation*** | 55.0 | 42.6 | 82.1 |
| ***Total Annual Operating Costs (in million Euros per year)*** | 224.1 | 73.5 | 162.7 |
| ***Biocrude Production costs, EUR/$t_{biocrude}$*** | 1260.2 | 3911.3 | 2136.4 |
| ***Upgrading costs of biocrude to biooil, EUR/$t_{biooil}$*** | 125.0 | 920.8 | 225 |

Table 3.7: Economic performance of the marine biofuel production in the case study locations (*continued*)

| | Case-study locations | | |
|---|---|---|---|
| ***Total production costs of upgraded biooil, EUR/t$_{product\ mix}$*** | 1385.2 | 4832.1 | 2361.4 |
| ***Annual Sales Revenue (in million Euros per year)*** | 123.7 | 10.3 | 43.0 |
| Of which, marine biofuel | 51.7 | 4.5 | 13.6 |
| Of which, biochar | 0 | 0 | 0 |
| Of which, electricity | 0 | 0.01 | 0.01 |
| Of which, naphtha | 15.8 | 1.06 | 14.68 |
| Of which, biojet | 56.1 | 4.79 | 14.6 |
| ***MFSP of MBF (in Euro/ton)*** | 940.4 | 4447.1 | 1935.9 |
| ***MBF MFSP : MGO ratio*** | 1.05 | 5.54 | 2.4 |

### 3.3.3 Environmental performance of "drop-in" marine biofuel production from biomass

The allocated environmental impacts of the "drop-in" marine biofuel production (in a well-wake approach) are shown in *Table 3.8*. The GWP for the investigated scenario is estimated to be 10.9, -43.37, and -7.24 g-$CO_2$ eq/MJ $_{\text{"drop-in" marine biofuel}}$ for Spanish, Colombian, and Namibian scenarios, respectively. This translates to a reduction of 89.6%, 141.3%, and 106.9% in GHG emissions in comparison with fossil MGO. These values are within the range reported in the literature [50], [69], [83]. In other impact categories, all three alternative renewable fuels performed lesser than their fossil counterparts for Ozone formation (terrestrial ecosystem), Marine eutrophication, Land use, and water consumption. This could be attributed to the emissions due to biomass growth, which are absent in fossil production. The Spanish and Namibian biofuels also performed relatively poorly in the impact category of mineral resource scarcity and ecotoxicity (freshwater and marine) due to the consumption of inorganic catalysts during the HTL phase. Finally, the Spanish scenario also causes freshwater eco-toxicity that can be attributed to the additional fertiliser consumption due to the utilisation of pruning biomass, which would otherwise generate ash on burning, which acts as organic fertiliser.

Table 3.8: Environmental impacts of "drop-in" marine biofuels

| | | Spain | Colombia | Namibia | Fossil MGO |
|---|---|---|---|---|---|
| **Impact category** | **Unit** | **per MJ** | **per MJ** | **per MJ** | **Per MJ** |
| Global warming | kg CO2 eq | 1,09E-02 | -4,34E-02 | -7,24E-03 | 1,05E-01 |
| Stratospheric ozone depletion | kg CFC11 eq | 7,37E-09 | 1,12E-08 | 5,57E-09 | 4,38E-08 |
| Ionizing radiation | kBq Co-60 eq | 1,35E-03 | 3,49E-05 | -3,36E-05 | 1,59E-03 |
| Ozone formation, Human health | kg NOx eq | -3,01E-04 | 3,52E-05 | 5,14E-05 | 2,47E-04 |
| Fine particulate matter formation | kg PM2.5 eq | -1,06E-05 | 2,99E-05 | 1,04E-05 | 3,82E-04 |
| Ozone formation, Terrestrial ecosystems | kg NOx eq | 1,44E-03 | 6,10E-04 | 1,81E-03 | 2,54E-04 |
| Terrestrial acidification | kg SO2 eq | -3,78E-05 | 3,04E-05 | -1,53E-05 | 1,15E-03 |
| Freshwater eutrophication | kg P eq | 4,70E-06 | 2,97E-07 | -7,05E-06 | 1,78E-06 |
| Marine eutrophication | kg N eq | 2,57E-06 | 2,07E-06 | 2,05E-06 | 1,43E-07 |
| Terrestrial ecotoxicity | kg 1,4-DCB | 6,47E-02 | 4,71E-02 | 1,21E-01 | 4,52E-01 |
| Freshwater ecotoxicity | kg 1,4-DCB | 7,83E-04 | 1,66E-04 | 9,00E-04 | 2,72E-04 |
| Marine ecotoxicity | kg 1,4-DCB | 1,00E-03 | 2,35E-04 | 1,16E-03 | 7,01E-04 |
| Human carcinogenic toxicity | kg 1,4-DCB | 3,32E-04 | 1,05E-04 | -4,35E-04 | 6,82E-04 |
| Human non-carcinogenic toxicity | kg 1,4-DCB | -5,25E-01 | 8,95E-03 | 1,39E-02 | 1,51E-02 |
| Land use | m2a crop eq | 3,39E-03 | 4,43E-04 | 2,42E-02 | 2,35E-04 |
| Mineral resource scarcity | kg Cu eq | 9,42E-05 | 2,71E-05 | 1,94E-04 | 4,14E-05 |
| Fossil resource scarcity | kg oil eq | 2,37E-03 | 9,63E-05 | -2,40E-03 | 5,86E-02 |
| Water consumption | m3 | 1,36E-03 | 6,59E-04 | 1,26E-03 | 1,07E-05 |

The stagewise GWP or GHG emissions contribution towards the final product is shown in *Figure 3.4*. For the Spanish scenario, HTL catalysts (KOH) consumption contributes majorly to GHG emissions, accounting for 50%. In the Colombian context, with -130 g-$CO_2$ eq/ $MJ_{\text{drop-in biofuel}}$, the avoided emissions due to open-field conventional disposal of coffee pulp significantly reduced the overall GWP of the coffee-pulp-based HTL biofuel. Finally, in Namibia, based on system expansion, the increased $CO_2$ uptake due to the restoration of savannah grasses and the excess electricity from biochar valorisation, sold to the grid, reduced the GHG environmental footprint of acacia-based HTL marine biofuel with an impact of -69.55 g-$CO_2$ eq/ $MJ_{\text{drop-in biofuel}}$.

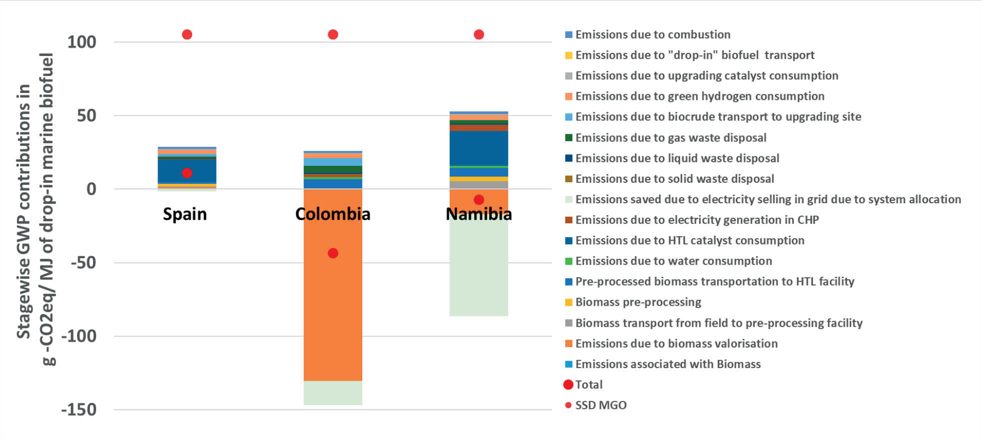


Figure 3.4: Stagewise GWP contributions in g-CO2 eq/MJ of drop-in marine biofuel

### 3.3.4 Sensitivity Analysis

A sensitivity analysis is performed to understand the effect of some key parametric indicators on the MFSP of marine biofuel, as mentioned in section 3.2.3.5. As illustrated in *Figure 3.5*, the MFSP is more sensitive to changes in equipment costs than to feedstock price. Thus, a 50% change in HTL equipment costs has a proportionate effect of 29%, 43%, and 40% in the Spain, Colombia, and Namibia scenarios, respectively. Similar changes in feedstock price led to a direct change of only 18%, 3%, and 5% for olive pruning-based, coffee pulp-based, and acacia-based biohubs. With an increase in scale, the sensitivity of MFSP toward equipment and feedstock costs is found to narrow down, but the former predominantly dominates at smaller scales. This could be attributed to the need for a high-pressure reactor system and a low TRL level of HTL, impacting the capital costs at smaller scales. This trend also indicates the potential for the reduction in MFSP when the facilities are scaled up to a commercial scale (with a processing capacity of 2000 DTPD). At the designed capacities, except for the Spanish scenario, with a 50% reduction in HTL equipment costs, the MFSP of marine biofuel is still significantly higher than that of its fossil counterpart. In terms of biocrude yield, if it can be increased by +50% due to process improvements such as catalysts or process optimisation, the MFSP of biofuels in all the case studies can be reduced by 33%. Likewise, the reduction in the installation factor by +50%, to account for uncertainty, led to a reduction of MFSP of the marine biofuels by 16%, 22%, and 22% in Spain, Colombia, and Namibia, respectively.

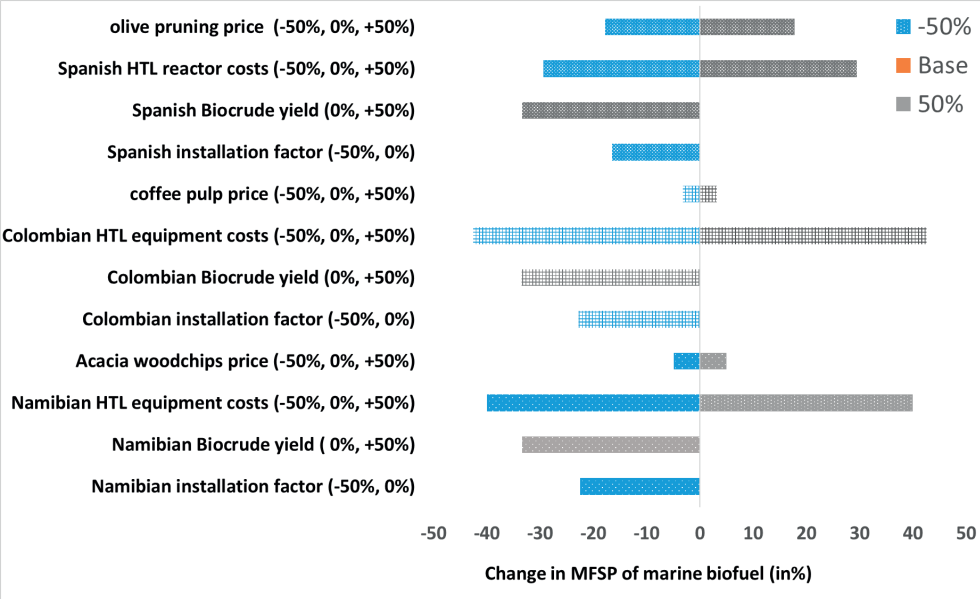


Figure 3.5: Sensitivity analysis of the MFSP of HTL "drop-in" biofuels. Grey (increase of parametric value from the base case by 50%), Blue (decrease of parametric value from the base case by 50%).

## 3.4 CONCLUSION AND RECOMMENDATIONS

This "first-of-a-kind" study conceptually co-designed agrarian biohubs for HTL-based "drop-in" marine biofuel production utilising field biomass residues in the form of olive pruning, coffee pulp, and encroacher bush in Spain, Colombia, and Namibia, respectively, using capability-sensitive design. The early-stage inclusion of potential stakeholders and a novel bottom-up co-design approach identified opportunities and showstoppers for implementing bio-based value chains during the conceptual phase. However, stakeholders' perspective on the final results for validation has not been carried out, and it is highly recommended in the future. The detailed process simulation indicated that the choice of biomass feedstock directly impacts the final biofuel distribution (Naphtha/bio-jet/bio-diesel) of the product mix obtained through the HTL process. For the designed scenarios, without consideration of carbon credits, the alternative marine biofuels were expensive (1.05-5.5x) than their fossil counterparts. Therefore, a more detailed investigation on the impact of carbon credits on the economic performance of the biohubs is recommended in the future. The biofuels had significant positive environmental GWP impacts, with a potential reduction of at least 89% of GHG emissions in comparison to fossils. The MFSP of the biofuels was found to be more sensitive to the HTL stage equipment costs, thereby indicating the potential for improvement in economic performance upon scale-up and technological advances due to process optimisation or mass/heat integration. Overall, early stage consideration of the stakeholder perspectives and contextual knowledge during the conceptual process design highlights the interconnectedness of technical and nontechnical aspects of value chain development. For instance, in Spain although the scale of the HTL biorefinery aids the economic performance of HTL marine biofuels, the social arrangements of co-operative owned mills enables proper organisation and mobilisation of feedstock, i.e, pruning biomass. On the contrary, in Colombia, although the biohub design was co-created responsibly with the local stakeholders, the scale of biorefinery due to limited feedstock supply makes the value chain cost-intensive. Therefore, a trade-off between nontechnical and technical aspects should be attained and thoroughly discussed amongst the stakeholders for informed and better decision-making.

Future research should focus on the technical viability of the HTL process to valorise multiple diverse feedstocks simultaneously to benefit from economies of scale in the region with high biomass availability, with varied nature of feedstocks, such as in an agroforestry system. The proposed biohubs should also be investigated using other biochemical conversion techniques for producing fine or speciality chemicals, which could improve the feasibility in regions like Colombia. The current investigation should further be supported with a macro-socioeconomic assessment and a multi-criteria decision analysis based on the context-specific selection and weightage of performance indicators to evaluate the trade-offs of the decision-making process during the design phase. Based on environmental performance, the impact of carbon credits, the incorporation of renewable energy systems such as solar or wind-based electricity, and the technical viability of biochar as a soil amendment need to be further explored to improve the sustainability of the biohubs. If proven, the use of biochar for soil amendment can bring local social benefits and improve soil health, thereby more detailed analysis on the best use of HTL byproducts is recommended for improving the socio-economic footprint of biohubs. Overall, sustainably and inclusively designed biohubs have the potential to offer opportunities beyond climate change mitigation by improving the existing agro-systems and strengthening the rural economies.

## 3.5 SUPPLEMENTARY DATA

Supplementary data for this study can be found in Appendix B (section 7.3).

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*“Our lives are defined by opportunities,*
*even the ones we miss.”* **– Benjamin Button,**
**from the movie, The Curious Case of Benjamin**
**Button**


4

# 4

# Biohubs for the emerging bioeconomy: Factualisation of early-stage inclusion of stakeholders to conceptual design through empirical studies in Spain, Colombia, and Namibia

This Chapter has been submitted as:

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## GLOSSARY

| | |
|---|---|
| BBVCs | Biobased value chains |
| CA | Capability Approach |
| CAP | Common Agricultural Policy |
| COP | Crude olive pomace |
| EU | European Union |
| GHG | Greenhouse gas |
| HFO | Heavy Fuel Oil |
| HTL | Hydrothermal Liquefaction |
| IEA | International Energy Agency |
| IMO | International Maritime Organization |
| IRENA | International Renewable Energy Agency |
| MAA | Multi-Actor Approach |
| MBF | Drop-in Marine Biofuel |
| SAF | Sustainable Aviation Fuel |
| SDG | Sustainable Development Goal |
| SWOT | Strengths, Weaknesses, Opportunities, Threats |
| TRL | Technology Readiness Level |
| VSD | Value Sensitive Design |

## 4.1 INTRODUCTION

The bioeconomy is commonly viewed as a promising pathway for addressing the current global challenges of climate change, energy security, poverty alleviation, migration, and food security [1]. This is mainly attributed to its unique ability to valorise biomass that is intrinsically connected to producers' social livelihood, enabling the manufacture of potentially marketable end-products. These products are often considered fossil alternatives with a better environmental footprint, due to their biogenic carbon emissions and short time for carbon recycling, thereby enabling socio-economic development. However, biomass mobilisation (choice and access to biomass) remains the key limiting factor for large-scale global commercial deployment of bio-based value chains to promote the bioeconomy [2]. This is evident through the outcomes of various bio-based projects and a significant difference between theoretical, practical, and sustainable global biomass availability [3]. The key factors contributing to these differences are technological constraints, geographical distribution, infrastructure development, stakeholder capacity, and institutional frameworks. To address this limitation, the International Energy Agency (IEA) highlights the concept of bio-hubs, an intermediary location which connects biomass suppliers with end users such as biorefineries, where farmers and growers can deliver by-products for processing into value-added commodities which are crucial for bio-based projects, as key to the successful integration of biomass supply into the bioeconomy by ensuring a secure supply of high-quality feedstocks to biorefineries [4].



From the end user and product-segment perspective, to ensure sustainability, various techno-economic and environmental studies have been performed, indicating the feasibility and potential of bioproducts from various biomass sources for a climate-friendly future [5], [6]. Similar to the other conventional bio-based value chain development, the IEA biohubs' current scope for sustainability is limited to the technical aspects of biomass supply and its conversion into intermediate products and storage [7], [8]. However, there is a significant challenge in realising these potential sustainable value chains. This indicates the presence of a blind spot in the conventional "feedstock to market" approach, which focuses on the maximum valorisation of feedstocks through various (cascading) pathways. The performance of the same has been traditionally evaluated predominantly from an economic and environmental aspect, overlooking the social aspect of sustainability, especially at the early stages [9]. The current approach to bioeconomy overlooks the circular dependencies and upstream biomass-related aspects in such sustainable value chains, which are predominantly context-related, such as soil maintenance, water restrictions, food, and other biomass requirements. This has to be addressed immediately to promote the global deployment of sustainable, inclusive, and circular biobased economies. This is crucial, as the vast majority of global biomass is located in the Global South, primarily in the form of agricultural (or other non-forestry) residues, where the biomass value chains are intricately interlinked with the social context of the production site.

The development of any biomass value chain involves hierarchical decision-making at various levels, such as strategic, tactical, and operational, each made at different nodes across the value chain, by multiple stakeholders with diverse knowledge and expertise [10]. The complexity of these decisions is strongly dependent on the nature of feedstock, the conversion technology, the targeted end-user segment, and the local prevailing context at the biomass production site, such as cultural values, capacity available, and institutional framework. Various literature studies have investigated the decision-making process and optimised the same predominantly for different forest-based biomass value chains [11], [12]. This includes the selection and estimation of quantitative sustainability (technical, environmental, and social) performance indicators through various assessment techniques [13]. The designed value chains are also optimised for their performance using robust simulation and modelling techniques such as multi-criteria decision analysis and Geographical Information Systems aided mixed integer linear programming [14]. These tools are also used to identify the uncertainties and hotspots associated with the developed design configuration, mostly based on quantitative technical aspects. Value chain integration is identified as one of the crucial aspects to overcome these uncertainties and risks of secure supply of feedstocks and a strategy to benefit from the economies of scale [15]. Furthermore, consideration of non-technical aspects during the design stages is recommended to understand the nuances of implementation [16]. Also, a rigorous exercise of bio-based value chain development is lacking for agricultural-based field residues in the Global South countries. Therefore, an approach that integrates social and technical experts along with potential value chain actors is needed.

The multi-actor approach is seen as a promising pathway for stakeholder and value chain integration [17]. This approach also has the potential to promote circularity, sustainability, and inclusiveness of the design. Cerca *et al.* (2022) recommend including multi-disciplinary perspectives and multi-stakeholder groups, along with early-stage consideration of local contextual knowledge during the strategic planning process [9]. They highlighted that incorporating social sustainability upfront led to identifying bottlenecks that affect the successful development of a circular bioeconomy. Palmeros Parada *et al.* (2021) presented the Open Sustainability-in-Design (OSiD) framework to integrate context-sensitive ex-ante sustainability analysis in the conceptual design of biobased processes [18]. This is done by considering the stakeholders' perspective and identifying the tensions between different sustainability aspects. From an inclusion perspective, Asveld *et al.* (2023) and Robaey *et al.* (2022) investigated three case studies using agri-residues and discerned three strategies to include practices and design context-sensitive biorefineries that are truly inclusive to the local stakeholders using the capability approach [19], [20]. However, an empirical investigation by designers and a parallel analysis of context-sensitive design for circularity, sustainability, and inclusiveness is lacking, as these three aspects are highly intertwined in multiple aspects of reality [21]. There is a need for a trans-disciplinary approach to effectively combine and utilise the scientific knowledge generated by academic researchers and the practical experience of real-world designers or stakeholders for sustainable and inclusive value chain development.

Here, we investigate and present the effectiveness of a novel integrated and trans-disciplinary approach for addressing the research question "What are the outcomes of operationalising early-stage regional multi-stakeholder inclusion on the conceptual design of bio-based value chains?". In this investigation, we analyse three empirical case studies focusing on valorising underutilised or mismanaged lignocellulosic residues from a) the olive sector in the Andalusian region of Spain, b) the coffee and cacao sector in the Coffee Axis in Colombia, and c) the encroacher bush sector in the region of Otjiwarongo in Namibia for potential biohubs. Marine biofuel obtained via the hydrothermal liquefaction route is chosen as the product of interest, due to an expected increase in the global demand, and due to the regulations [22], [23], [24]. The specific objectives of this research are i) to perform a comparative analysis and identify common desired biohub characteristics, ii) to identify enablers of biohub implementation using a SWOT analysis, iii) to find the context-specific purposes (or end-goals) of biohubs, and iv) to identify the conflicts and trade-offs resulting from early-stage stakeholder inclusion in the conceptual design process. The novelty of this work also lies in the chosen case study locations for value chain development, as there are neither commercial value chains established for residue valorisation nor any scientific investigations for marine biofuels as end products. The novelty extends into the analysis of the sector in the current scenario, focusing on the existing dynamics between its value chain actors and the different roles of the biohubs in generating context-specific impulses for regional sustainable development.

## 4.2 MATERIALS AND METHODS

The methodology implemented in this study combines methodologies reported in the literature on biorefinery design, value-sensitive design (VSD), multi-actor approach (MAA), and the capability approach (CA) for generating context-specific capability-sensitive biohub design alternatives [19], [20], [25]. This includes a combination of the three aspects of investigation under the VSD framework, namely conceptual, empirical, and technical. During the conceptual phase, the problem definition was defined, and a case study selection was performed based on the criteria mentioned by consortium partners and experts of the bio-based economy. The empirical case studies in the selected region, which include a 5-6 week-long field visit, were conducted by a multi-disciplinary team with a designer (with expertise in bio-chemical engineering) and a VSD researcher (with expertise in cultural anthropology and sustainable development). The field visit included semi-structured interviews of potential direct and indirect stakeholders to identify their needs, capabilities, capacities, skillsets, etc. and a multi-stakeholder workshop to create an ideal biohub scenario with a potential roadmap for implementation. The investigation and analysis were performed from the designer's perspective. *Figure 4.1* shows the methodological approach followed in this study.

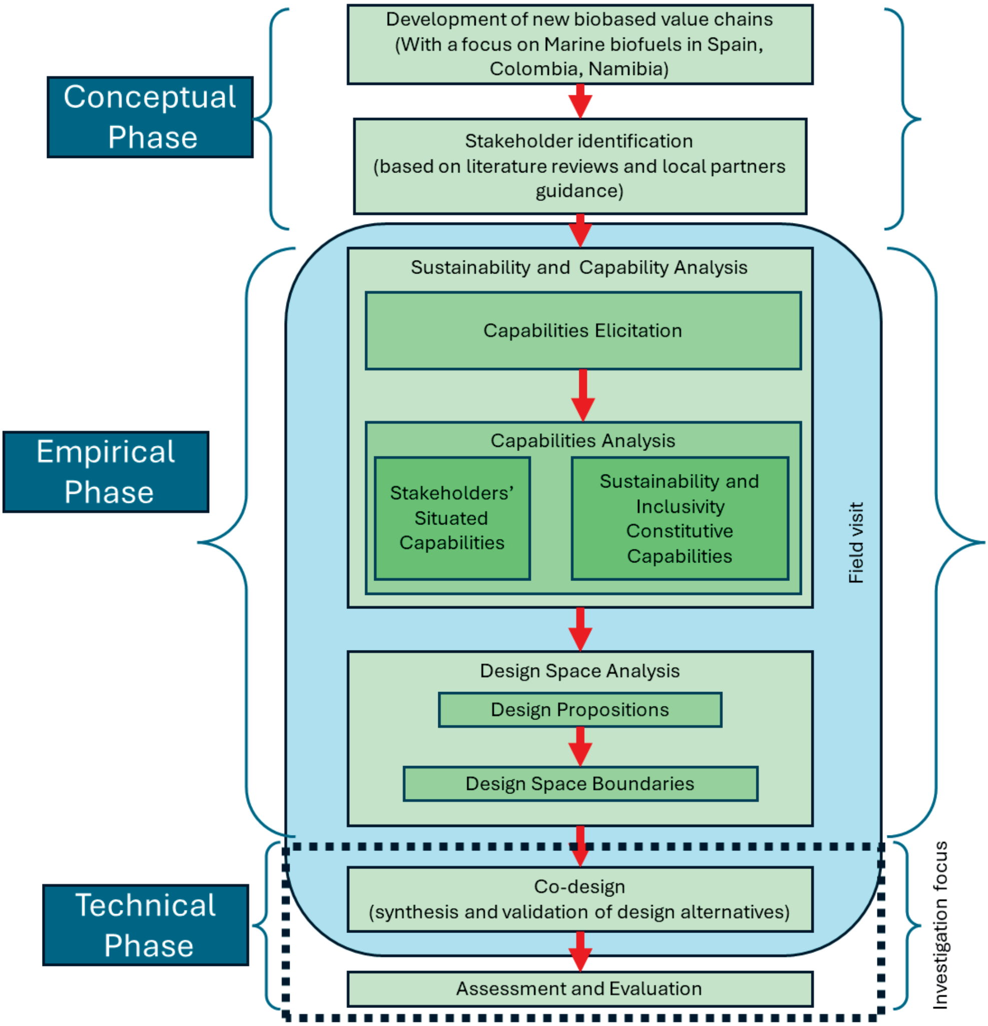


Figure 4.1: Visual representation of the performed trans-disciplinary approach in the context of biohub development

### 4.2.1 Case studies – Biobased value chains and Drop-in marine biofuel (MBF) in Spain, Colombia, and Namibia

Since the International Maritime Organisation (IMO) implemented the IMO 2020 mandate, the global shipping sector has been actively looking for various renewable alternatives to substitute the emission-intensive fossil-based heavy fuel oil (HFO) [23]. Drop-in marine biofuel (MBF) is seen as a potential alternative for HFO and has recently gained immense attention from both academia and industry alike [24]. However, a large-scale biomass mobilisation is required to establish MBF production on a commercial scale. While the possibility of (partly) fulfilling such large demands with high feedstock security is highly questioned [26], we chose to analyse the opportunities to develop such a substantial and secure value chain in regions where local communities could benefit from such production. This provided the basis for case study selection, such as underutilised biomass availability, opportunity to gain additional income and business, security of supply and quality of product. This resulted in three case studies of the olive sector in Spain, the coffee sector in Colombia, and the encroacher bush in Namibia. The present investigation was conducted under a project, CLEANSHIPPING, aimed at developing sustainable and inclusive value chains for marine biofuel production from valorising lignocellulosic residues through hydrothermal liquefaction technology. Although the end goal was focused on the production of MBF, the conceptual design phase of bio-based value chains (BBVCs) was primarily aimed at developing configurations for piloting and commercial implementation in the regions of interest. Therefore, the investigation was an early-stage study offering diverse decision-making space for the stakeholders. The primary design variables for the project were the choice of biomass, technology, by-product valorisation, and value chain.

In the European Union, the olive sector is the leading agricultural sector and holds a historical connection with the society of the Mediterranean region, spanning over the countries of Spain, Portugal, Italy, and Greece, in terms of socio-economic aspects. Spain, a leading olive oil-producing country in the world, generates a huge amount of residues of diverse nature along its production chain [27], [28]. The Andalusian region of Spain, which had a perfect blend of diverse cultivation practices, well-structured and organised production chains, and stimulating policies, was chosen as the region of interest [29]. With the proximity to existing petrochemical infrastructure and various air- and sea-ports, including the port of Gibraltar, developing new bio-based (marine biofuels) value chains based on olive residues can bring significant benefits to the region. This case study represents a region and sector with an established primary agricultural sector with developed infrastructure, organised farmer associations, logistical expertise to handle residues, and traditional residue valorisation techniques.

In South America, Colombia is the second-largest producer of coffee. With its tropical climate and fertile soil, the "Eje Cafetero" region is one of the largest coffee-producing regions in Colombia. Following the wet coffee processing method, Colombia is faced with the challenges of handling large quantities of residues generated annually [30]. Currently, these residues are left on the field or (rarely) turned into compost. There are no commercial value chains developed to handle these residues. The coffee sector in Colombia is hierarchical, and most of its cultivators are small-scale producers (with < 5ha). Unlike other South American coffee-producing nations, historically, Colombian farmers are not organised in associations and are individual coffee bean producers, leading to diverse quality coffee beans for export. However, in the past decade, this has been addressed by the formation of new associations and organised cooperatives via the federation of coffee. But still, the post-harvesting process is done individually at the farm level. This case study represents an archetype of a recognised primary agricultural sector with relatively no current commercial residue valorisation expertise, with minimal infrastructure for logistics due to geographical conditions. However, the agroforestry systems with diverse residues, along with access to the ports and new potential petrochemical infrastructure, make bio-based (marine biofuels) value chains in the Department of Risaralda a promising pathway for ensuring sustainable development.

Finally, in the Sub-Saharan region, Namibia faces a unique challenge of bush encroachment. The native bush species encroached on almost 45 million hectares of land (equalling 400 million tons of biomass spread over one-third of the country), transforming historical savannah ecosystems into bushlands [31]. This phenomenon is accelerated due to anthropogenic activities such as over-grazing, suppressing veld fires, and increased concentration of carbon dioxide in the atmosphere. These bushes deplete the groundwater at a much faster rate than savannah grasses, reduce the grazing capacity of the land, and restrict the natural movement of wildlife, thereby posing an ecological threat. Currently, these bushes are harvested for bush-thinning activities and valorised for local traditional purposes such as firewood and fence poles. Commercially, these bushes are used for manual labour-intensive charcoal production, with a market capacity of 250,000 tons of annual production. New value chains for bush to electricity, animal fodder, and construction materials are currently being investigated. Socially, the bush is owned by different types of farmers with varied capabilities. Firstly, the large commercial cattle farmers who own, on average, 7000 ha. Secondly, communal farmers, who use the land that belongs to the government and share the resources within the community. Finally, the resettlement farmers, who were previously disadvantaged farmers who are placed on land sold by commercial farmers. Namibia currently does not have any petrochemical refineries and thereby imports all of its fossil products, including transportation fuels. This case study represents the archetype of a region with abundant biomass, no national petrochemical infrastructure, with well-established value chain actors with a high interest in valorising the biomass. Therefore, developing new commercial-scale bush biomass, with annual regrowth of 3-4% of total availability, based value chains for new fossil alternative products can bring both ecological and socio-economic benefits to the country.

### 4.2.2 Stakeholder identification

Stakeholders of a bio-based value chain, especially marine biofuel production, are diverse and global. *Figure 4.2* indicates the various direct and indirect stakeholder groups involved across the bio-based value chain from the biomass production stage until the end use of the product. The current and potential stakeholders in the biomass-producing region for a bio-based value chain were identified using literature reviews and with the help of a collaborating local institute with expertise in the sector of focus. The missing stakeholder groups' aspects were obtained from an expert or the CLEAN-SHIPPING project consortium partners, who represented different stakeholder groups.

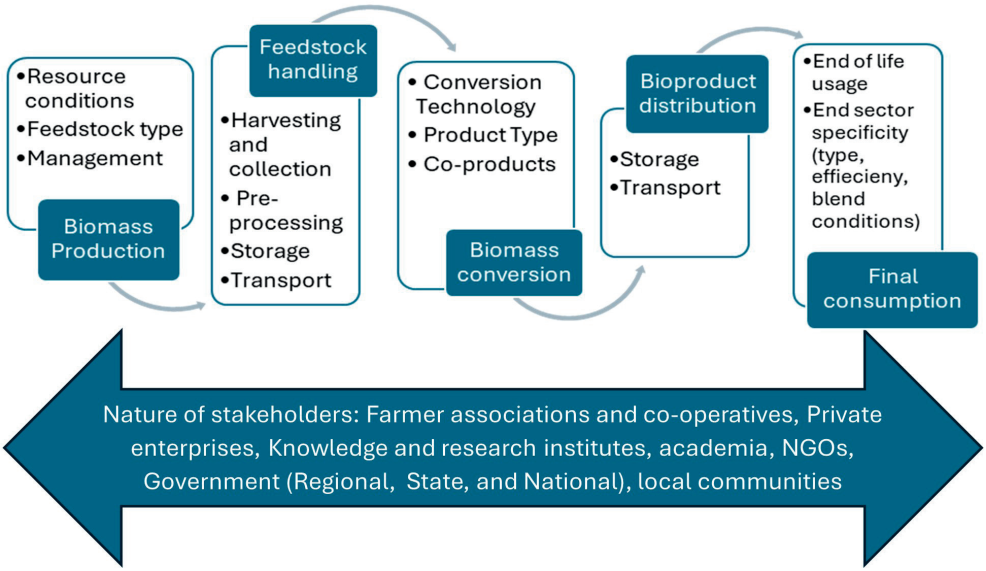


Figure 4.2: Generic scheme of a biobased value chain with the nature of direct and indirect stakeholders

## 4.2.3 Sustainability and Capability Analysis

### *4.2.3.1 Capabilities Elicitation*

Initially, in the conceptual phase, a literature review was performed, followed by interviews of the CLEANSHIPPING consortium partners and experts in bio-based economies, representing the diverse stakeholder groups, to identify the potential criteria for go or no-go's while developing a bio-based (marine biofuel) value chain, such as certifications, biomass quantity and quality, infrastructure available and biomass competing uses.

Secondly, context-specific capabilities elicitation was performed via empirical investigation during field visits by a multidisciplinary team to the three countries (Spain: 18$^{th}$ Oct 2021 – 27$^{th}$ Nov 2021; Colombia: 20$^{th}$ June 2022 – 29$^{th}$ July 2022; Namibia: 16$^{th}$ January 2023 – 17$^{th}$ February 2023). Various participatory techniques, such as semi-structured interviews with the potential stakeholders, observation, and a multi-stakeholder workshop, were used as stakeholder engagement tools for capturing technical and non-technical aspects. The questions and activities were aimed at understanding and eliciting stakeholders' values, skillsets, necessities, needs, capabilities, capacities, and co-design desired biohubs' characteristics. The semi-structured interviews were conducted with the identified stakeholders about the prevailing regional and sectoral context, barriers, foreseen potential role, opportunities, threats, hurdles, and position on the power-interest grid. Language barriers were overcome using language translators or using representations through associations or unions. Thirdly, a multistakeholder workshop was organised (Spain: 25th April 2022; Colombia 28th July 2022; Namibia: 16th February 2023) to identify the ideal design characteristics and co-design potential biohubs by discussing various design variables (technical, social, policies) at different (strategic, operational, and tactical) levels of decision-making. At the end of the workshop, participants were involved in co-formulating a roadmap to identify concrete actions to be achieved to attain the preferred scenario within a time frame of 20 years.

4

Finally, in technical investigation, knowledge from the conceptual and empirical phases was translated into design propositions to develop context-specific biohub design alternatives. *Table 4.1* indicates the stakeholder groups and the number of participants involved during the field visit.

Table 4.1: List of stakeholder groups engaged during participatory activities

| **Stakeholder Group** | **Spain** | | **Colombia** | | **Namibia** | |
|---|---|---|---|---|---|---|
| | Interviews | Workshop | Interviews | Workshop | Interviews | Workshop |
| Biomass suppliers | 27 | 2 | 24 | - | 8 | - |
| Farmer cooperative/ association | 8 | 8 | 8 | 4 | 1 | 3 |
| (Field) workers | - | - | 4 | - | 8 | - |
| Farmer Union/federation | 2 | 1 | 5 | 2 | 3 | 2 |
| (Secondary) industry/processors | 1 | 1 | 1 | 1 | 3 | 1 |
| Business Entrepreneurs | - | - | 2 | 1 | 1 | 1 |
| Logistics and Transport companies | 1 | - | 3 | 3 | 1 | - |
| Government representatives | 1 | 4 | 4 | 3 | 5 | 5 |
| Technology developers | 2 | 2 | - | - | - | - |
| Academic/knowledge Institutions | 3 | 3 | 10 | 7 | 2 | 1 |

Table 4.1: List of stakeholder groups engaged during participatory activities (*continued*)

| Stakeholder Group | Spain | | Colombia | | Namibia | |
|---|---|---|---|---|---|---|
| Non-governmental organisations (NGOs) | - | - | 2 | 1 | 3 | 3 |
| Bioenergy associations | 1 | 4 | - | - | 1 | 4 |
| **Total** | **44** | **25** | **63** | **21** | **36** | **20** |

#### *4.2.3.2 Capability analysis*

This work was done in complement to the work of Veen et al (2024) [32]. The capability approach was used to elucidate the stakeholders' capabilities, especially those of biomass producers, to derive design propositions. The capability approach (CA) is a useful (open) framework that can be implemented in the context of social justice and value chain design. The CA allows us to identify capabilities; however, it does not answer questions regarding which capabilities matter more or what constitutes an equal distribution of capabilities. The CA accounts for diversity in what we value and in our ability to fulfil those meaningful activities. Conversion factors, a measure of this diversity, are internal or external to a person and determine whether a person can transform resources into capabilities. The data obtained from the field visit via participatory techniques (interviews and multi-stakeholder workshops) were coded and analysed to identify emerging values and capabilities. The discussions were recorded with participants' consent, transcribed verbatim, and coded using MAXQDA 2012 software. This investigation performed qualitative analysis to gain in-depth insights into prevailing real-time contexts and intricate dynamics of stakeholders in the sector. To overcome the subjective limitations of the data input, the information was triangulated using in-depth interview documents, semi-structured interviews, observation, and a multi-stakeholder workshop. Prolonged stakeholder engagement with stakeholders and the research context was obtained due to 5-6 weeks of field visits. The research findings (interview and overall project results) were discussed and validated with local collaborating partners and other expert regional organisations. The multi-stakeholder workshop was used to validate the interview findings. The detailed case study research protocols and transcripts can be made available upon request.

#### *4.2.3.3 Design Space Analysis*

The identified capabilities during the observation and semi-structured interviews, along with conversion factors, were used to frame design propositions [32]. Initially, preliminary biohubs designs were created based on the contextual understanding of the investigator. These design alternatives were designed using these propositions to incorporate the identified social values and stakeholder capabilities. The design alternatives were then analysed and discussed, co-designed if needed, based on the four design aspects, namely biomass, biorefinery, institutional framework, and impulse for regional development. The 4 design aspects were discussed in detail using 12 design variables, namely, choice of feedstock, feedstock pre-processing method, feedstock transportation, feedstock procurement, biomass conversion technology, biohub products, biorefinery ownership, biorefinery location, configuration of biorefinery, policies, Sustainable Development Goals (SDGs) to be addressed, and potential contribution of biohub to local development needs. Considering the obtained ideal biohub design to be commercially implemented in the region within a 20-year time frame, a roadmap was created with dedicated goals to be achieved in a 5-year and a 10-year timeframe. The road map was categorised with specific action points in aspects of biomass, biorefinery, and institutional framework, along with their impacts, roles, and responsibilities. However, in this investigation, the designer's perspective was limited to the scope of analysis for the first two aspects of the roadmap.

### 4.2.4 Design Alternatives

The biohub designs created for the three case studies during multi-stakeholder workshops are illustrated in the *Figure 4.3* below

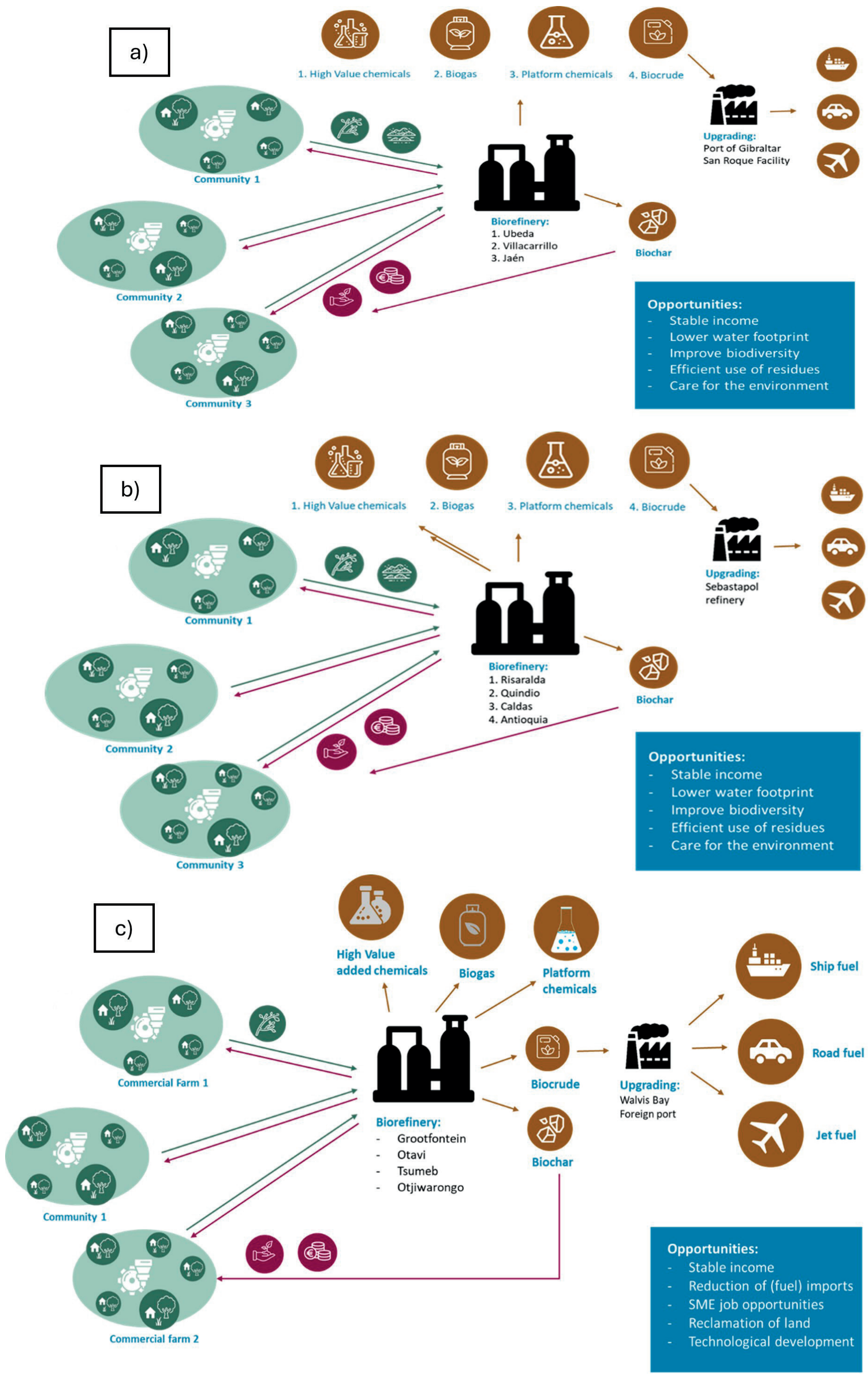


Figure 4.3: Co-designed biohub scenario in Spain (a), Colombia (b), and Namibia (c)

## 4.3 RESULTS AND DISCUSSIONS

### 4.3.1 Biohub Characteristics

In this subsection, we compare the co-designed biohub design alternatives to desired characteristics from the perspective of end-users and general sustainability criteria and investigate sensitivities and design boundaries. These outcomes are qualitatively analysed to derive criteria for the 'best practices' design of biohubs. These are qualitatively investigated based on the design decisions and flexible design space boundaries for some common biohubs' ideal or desired characteristics.

#### *4.3.1.1 Feedstock*

The **selection of feedstock** is the primary design variable to be addressed in any BBVC development. The criteria for the choice of biomass vary between stakeholders of the same value chain. On the one hand, the upstream biomass producers, also farmers, are very much interested and willing to valorise all types of residues, irrespective of quantity or quality, to gain maximum socio-economic development [32]. On the other hand, the end-users are very selective about the choices of feedstocks with criteria such as quantity, chemical composition, and sustainable practices during cultivation. For example, in Chapter 2, the stakeholder representing the shipping sector as an end user of marine biofuels preferred large quantities of biomass with negligible sulfur and Nitrogen content due to IMO standards. Likewise, end-users preferred to stay away from feedstocks involving controversial global sustainability views, such as 1$^{st}$ generation feedstocks or residues from the Palm oil industry, adhering to the (modified) Renewable Energy Directive. Similarly, the experts representing technology providers opted to utilise certain types of feedstocks that are easily compatible with the conversion technology to minimise production costs [33]. To further enhance the selection choices, the stakeholders were restricted to the focused case of developing a marine biofuel production chain using hydrothermal liquefaction. This enabled the stakeholders to make choices quickly and further discuss the potential for implementation. Therefore, from a designer's perspective, the selection of the end product- technology- feedstock pathway is crucial and recommended at the early stage of the value chain design. This allows for the advancement of technological developments required for targeted routes. Furthermore, biomass resource allocation per sector, for example, cleaner (with less physical and chemical impurities) feedstocks, such as sugarcane bagasse and micro-algae, for producing high-value products such as sustainable aviation fuels or alternative proteins, and low-quality feedstocks, such as municipal solid wastes or sewage sludge, for bulk chemicals such as marine biofuels, is recommended.

For **feedstock pre-processing**, the technical necessity, severity, and location are highly dependent on the nature of the feedstock, chosen biomass conversion technology, and prevailing context and capabilities of the upstream stakeholders. For feedstocks such as crude olive pomace and coffee pulp, which are wet slurry-like processing residues, no pre-processing steps are required if the chosen technology of conversion is HTL or anaerobic digestion. However, for field-residue feedstocks such as olive tree pruning, coffee-cut stems, or acacia bush, the long branches should be treated for physical impurities such as sand and stones, and further, be converted into either wood chips or pellets before the biomass conversion stage. In Spain, a farmer said: *"What I can I do, I do myself. Because the people, we like to do it our way. So if you have time, you do it yourself, and if you don't, you try to find people who can do it."* (S-F3). This indicates a strong preference to prune their farms or allow only trusted members to perform the activity on their behalf. On the contrary, a Namibian commercial bush farmer said, *"A lot of people employed Oshiwambo and then there are a lot of illegally employed people also working in the rural areas here who are coming from Angola who don't have a Namibian citizenship, but they are motivated enough to do a hard physical job like Bush chopping"* (N-F2). This was validated by other stakeholders, with the reason being a lack of trust and motivation in fellow Namibian citizens, despite high unemployment rates. Irrespective of the farmers' preferred values, in all cases, small-scale farmers do not have the capabilities to perform pre-processing such as wood chipping or pelletising by themselves due to the high equipment costs. Therefore, the pre-processing techniques of field residues should be performed either in a collective facility, such as association-owned mills or through leasing equipment to provide access to all farmers. This was also validated by stakeholders (N-U1, N-CF1) in Namibia, who were involved in a pilot study of pelletising bush feed in communal lands. Therefore, as indicated in Chapters 2 and 3, olive tree pruning is designed to be chipped in the HTL facility at Ubeda, and Acacia pellets are to be the end product of the Namibian biohubs.

**Feedstock transportation** is the third design variable to be addressed predominantly from a tactical or operational level of management. Feedstock transportation is identified as one of the crucial choices by many stakeholders, as it has multiple impacts on the economics and supply security of the feedstocks to the biorefineries. On a strategic level, the transportation choice will also impact the overall environmental footprint of the biohubs. Except for Namibia, there are no dedicated stakeholders or organisations in the case study regions, representative of the global south scenario, for handling and transporting residues. In Spain, the crude olive pomace is currently transported by trucks that are owned by primary mills. For pruning, one small-scale dedicated stakeholder (S-L1) was identified and interviewed. They identified and indicated their potential role by stating, *"You cannot transport the pruning rests directly from the field to the factory; there needs to be a step in the middle. You need to treat it, but this system of recuperation is not viable. You need an intermediate to treat it first, like us*". Both in Spain and Colombia, the farmers indicated their willingness to bring field residues from their farms to the potential processing location in their existing method of transportation. In Colombia, during the interviews, a logistics stakeholder (C-L2), who has expertise in transporting fruits and flowers, stated, *"Obviously yes, we are not working on that kind of product currently, but we can structure a project and organise a group of little trucks to pick up from the farm to the hub. From the hub to the port. We have no expertise in liquids, but it can be done"*, and indicated the opportunities and challenges for their business to include residue transportation. Due to their biodegradable nature, over long distances, certain feedstocks, such as coffee pulp, may need transportation infrastructures similar to those of handling fruits and vegetables for quality preservation. Therefore, longer distances of transportation are not recommended from a technical and economic perspective. Finally, in Namibia, a logistical stakeholder (N-T1) who already performs the transportation of bush to the local cement industry for bioenergy purposes, shared their potential perspective for scaling up. Hence, prevailing local contextual knowledge on available infrastructure and feedstock nature is key to selecting appropriate transportation methods.

**Feedstock procurement** is the final design variable on feedstock aspects in the biohubs. This variable discusses the preferred nature of contractual agreements to be made between biomass producers and biorefineries. This variable can act as a mode of inclusion of underprivileged biomass producers [20]. This variable is highly dependent on the socio-economic conditions of biomass producers as well as the seasonality of the crops. In Spain, the primary mills, on an annual basis, sell COP to secondary mills by using a formula that includes the moisture content, residual olive oil content, price of pomace olive oil, and exhausted olive pomace to estimate the price of COP. Currently, the primary mill pays 6-8 EUR/ton COP and bears the transportation costs. Therefore, a new value chain with long-term offtake (with short-term payment structure) contracts and improved COP selling price is seen as a potential improvement. In Namibia, currently, the communal farmers are not allowed to participate in bush valorisation without the establishment of a communal forest management council to monitor sustainable harvesting. Therefore, based on their existing capacities, they can be considered for ad-hoc suppliers of bush to the primary supplier of feedstock, such as commercial farms. In all three case studies, the biomass procurement needs to be tailor-made to enable the participation of diverse producers for inclusion. The stakeholders representing the biorefinery owners opted for a long-term contract to secure feedstock supply for at least the project's lifetime. However, biomass producers prefer to get paid on a seasonal basis according to the harvest calendar. Biohubs should therefore have the capacity to play a crucial role in managing and monitoring fair price distribution by acting as a market with biomass residues as commodities.

#### *4.3.1.2 Biorefinery*

**Bioconversion technology** is one of the important decision variables for establishing a biobased economy. Currently, there are various thermochemical and biochemical pathways for transforming biomass into various bioproducts [34]. In Spain, currently, the (nascent) industrial expertise is aligned with thermochemical routes of direct burning or gasification [35]. However, the biochemical valorisation of olive residues to produce high-value-added nutraceuticals and fine chemicals is thoroughly investigated by academic experts [36], [37], [38]. For the same reason, biochemical routes are preferred despite requiring high initial investments. In Colombia, the stakeholders preferred technologies with commercial status, or TRL 9, for easy implementation [32]. This is predominantly justified due to the lack of indigenous technology developers and providers for developing novel technologies. In Namibia, the stakeholders who participated in interviews and multi-stakeholder workshops were not technical experts; no conclusion about the choice of technology was made. However, the Namibian academic system currently aims at developing technical expertise for both thermochemical and biochemical routes and thereby relies on international partnerships and expertise in technology selection. But, currently, there are projects, such as Steambio Africa and PyroNam, aimed at the thermochemical conversion of encroacher bush using torrefaction and pyrolysis, respectively. The Spanish and Namibian stakeholders opted for technologies with no or minimal water consumption, due to the prevailing water-stress environment in the regions [32]. The stakeholders' choice of conversion technology was therefore found to be dependent on the existing available infrastructures and local technical expertise for development. Therefore, technologies producing intermediates that can be combined with existing petrochemical infrastructures could be a potential design option.

**Biorefinery product** choices predominantly depend on the local needs of the region, with the availability of bioresources. In Namibia, due to the absence of any petroleum refineries, the country imports almost 60% of its energy consumption from international markets. With the large biomass availability, the stakeholders opted for all products that can satisfy the local demand, but that can also be exported. Products that promote the integration of other renewable projects, such as biomass-based methanol or sustainable aviation fuel (SAF) that consumes green hydrogen, are supported. The Colombian and Spanish stakeholders, with their affinity to the food crops, are more inclined to produce high-value-added products such as cosmetics from olive residues, novel food products such as cacao pulp-based liquor, and artisanal coffee pulp-based desserts to promote small-scale entrepreneurial businesses at the farm level. Bioplastics have been identified as one of the key desired products for Colombia due to their fossil counterpart's widespread usage. Products aimed at improving soil health, such as biochar, are preferred across all the case studies. Therefore, the choice of end products should be considered for their ability to address local demands, share in the international market, and promote entrepreneurial activities.

In all three case studies, **biorefinery ownership** is perceived to be feasible either through a public-private partnership or an entirely foreign-based private entity. This is primarily due to a lack of trust and the presence of corruption in the existing government and institutional framework, which led to this choice from stakeholders. The lack of existing high-level technical and market expertise in the country also played a significant role in arriving at this decision. Some stakeholders also highlighted the prevailing favourable social perception of supporting foreign interests in establishing a value chain over the national initiative. For example, Pereira in the Department of Risaralda, similar to some other Global South cities, has a special economic trade zone to attract foreign investments.

4

**Biorefinery location** and **Biorefinery configuration** are two design variables that are highly intertwined with each other. The stakeholders located upstream of biorefineries opted for a near-biomass production site to receive maximum benefits of value addition. Although this aligns with the literature reported from other case studies, the stakeholders also acknowledged the difficulties in technical feasibility due to the availability of the necessary technical skill force and infrastructure to host and sustain complex biorefinery technologies in the region [39]. On the other hand, the end-users are more inclined to a location in the vicinity that promotes market penetration, usually located in the coastal region. Brownfield field biorefineries that can benefit and integrate with the existing infrastructures are preferred over greenfield biorefineries mainly due to the reduced threshold of capital investments. A trade-off should be made based on sustainability assessments for finalising biorefinery configuration as a modular and decentralised configuration is beneficial for the inclusion of remotely located farming communities; however does not benefit from economies of scale. In Colombia, special economic zones are created to attract foreign investments, and projects that can benefit from significant tax reduction and ease of bureaucratic procedures, making them attractive to be ideal sites for biorefineries. The decisions made should be further validated through various sustainability assessments to understand the economic, environmental, and social impacts of selecting various biorefinery sites and configurations on the performance of the value chains.

Overall, although there are some comparative identities (such as farmers' inclination to use all types of biomass, technology with minimal environmental footprint, etc.), amongst the three case study locations, the biohub characteristics are found to be highly dependent and sensitive to the local prevailing context of biomass production, stakeholders' capabilities, and the chosen end sector. Therefore, a transdisciplinary approach is needed for developing the bioeconomy transition involving Global North-Global South partnerships.

### 4.3.2 SWOT analysis of the current scenario for regional biohubs development

To implement the biohubs with identified desired characteristics, it is imperative to look at the status quo of the case study locations. Therefore, in this sub-section, *Table 4.2* shows the strengths, weaknesses, opportunities, and threats (SWOT) of the current sector to support a bio-based value chain development. The SWOT analysis helps designers, decision-makers, and investors identify the potential opportunities and challenges of developing a new BBVC with the focus areas for improvement.

Table 4.2: SWOT analysis of the status quo of the sector to support biohub development

| | Spain | Colombia | Namibia |
|---|---|---|---|
| **Strengths** | • Farmers are well organised in associations and cooperatives<br>• Spain is the leader in olive cultivation and olive oil production, with immense experience<br>• Large amount of residues<br>• Well-established and functioning infrastructure | • Farmers grow cash crops predominantly in an agroforestry system<br>• Ideal climatic conditions for crop cultivation, requiring fewer chemical inputs<br>• Presence of Federation and National Centres for managing the sector, especially in Coffee and Cacao | • The stakeholders in the sector are well-organised and structured<br>• Unified national interest to valorise the bush biomass<br>• Large quantity of biomass with a high annual regrowth<br>• Regional stakeholders' expertise and experiences in the bush valorisation |
| **Weaknesses** | • The olive oil market is a niche with a high rate of volatility in terms of prices<br>• Current practices do not manage the water resources for its sector's consumption<br>• Some farms are difficult to access due to steep terrain<br>• Current residue valorisation methods are not efficient and not inclusive<br>• Current residue handling methods cause environmental concerns due to air pollution, soil contamination, and unpleasant odour | • Farmers have volatile earnings based on the market price and yield of the cash crops<br>• Lack of capacity<br>• Lack of transparency across the value chain actors<br>• Geographical terrain makes farms and biomass less accessible<br>• Current practices for residue valorisation are inefficient and environmentally hazardous<br>• Low volumes of residues with high diversity within the region (coffee, cacao, avocado, banana, etc.) due to agroforestry systems | • Bush harvesting techniques are very diverse, with each method requiring a unique capacity<br>• The current charcoal value chain primarily focuses on international markets<br>• Communal farmers are prohibited from participating in commercial value chains for fear of unsustainable harvesting.<br>• Infrastructure is available only for implementing small-scale value chains<br>• Road infrastructure is poor in some bushlands |

Table 4.2: SWOT analysis of the status quo of the sector to support biohub development (*continued*)

| | Spain | Colombia | Namibia |
|---|---|---|---|
| **Opportunities** | • Olive farmers can benefit from additional income when olive prices are low<br>• Residue management promoting a better water footprint<br>• Practices to promote biodiversity and adhere to the new CAP policy<br>• Residue valorisation will immensely improve care for the environment | • Farmers can benefit from a stable income<br>• Effective use of residues as a renewable feedstock<br>• Avoiding environmental damage and thereby promoting care for the environment, especially for soil health<br>• Infrastructure development<br>• Ability to valorise diverse seasonal feedstocks available throughout the year | • Bush valorisation will provide a stable income to the local community, especially during the drought seasons<br>• Potential reduction of imports leading to energy and resource independence due to bioproducts<br>• Reclamation and restoration of savannah ecosystems<br>• Technical infrastructural development<br>• Development of new small-to-medium-sized enterprises<br>• New greenfield biorefineries with no competition from the fossil industry |
| **Threats** | • Current stakeholders practice generational farming culture; therefore, they might be reluctant to change<br>• Most farmers are small-scale holders owning 5-10 ha<br>• 60% of the olive farms are rain-fed.<br>• Traditional cultivation technique has less productivity compared to intensive or super-intensive techniques<br>• Need for investments to initiate new residual value chains | • Value chain actors' reluctance to change from current practices<br>• Most farmers are small-scale holders owning <5 ha<br>• Fear of and lack of trust due to Corruption<br>• Demand for high initial investment costs<br>• Species diversity leading to heterogeneity in the residue chemical composition | • Requires large external financial aid<br>• Namibian inhabitants are laid-back<br>• Lack of skilled labour<br>• Lack of trust in farmworkers<br>• Lack of resources for monitoring and organising management practices |

### 4.3.3 Enablers of Biohub implementation

In this section, the created roadmaps (in the Appendix 7.4.1) were analysed to identify the key enablers for the commercial implementation of the desired biohubs. Based on the derived biohubs' characteristics and SWOT analysis of the current sector, the enablers that can promote inclusion and social sustainability for a smooth transition from idea conception (TRL 1) to commercial implementation (TRL 9) of a biorefinery technology are discussed below.

Primarily, the biohubs should have the maximum possible *value addition (VA) at or near the biomass production site*. This is foreseen to enable the technological, economic, and social development of the region. For example, instead of international or intercontinental transport of raw biomass residues, the biomass could be initially converted into intermediate products (such as wood chips, pellets, platform chemicals, and bio-crude) in the country of origin before exporting. Technically, this provides an opportunity to retain maximum nutrient content within the region of production and will ensure the efficient transportation of high-energy-dense intermediates by reducing GHG emissions. Regional value addition also provides opportunities for the local community to develop their technological skill sets and experiences, along with being a stimulus for technical infrastructural development. In Colombia (C-F9CF), a young generational farmer prefers to stay on the farm only if it is challenging enough where he can apply his innovative skill sets or if the revenue is high. The innovative advances in technical aspects (such as the use of drones for seeding and fertilisation, Artificial Intelligence for weather prediction, roasting coffee beans, and sustainable farming practices to promote soil health) will create and attract new opportunities for entrepreneurship. VA is one of the key enablers in preventing urban migration and strengthening the rural economy, which is crucial for any (local/global) bio-based economy.

Secondly, the stakeholders perceive that the commercial success of the biohubs is primarily dependent on the economic feasibility of the value chain. Contrary to the scientific approach of maximum valorisation of biomass through cascading pathways and multi-product biorefineries, the stakeholders emphasise having a focus on a *marketable anchor product (MAP)*. A Namibian stakeholder (N-GIZ1) refers to the example of the investigation of the Biomass Industry Park as an example, where a detailed analysis of a multi-product biorefinery from encroacher bush using cascading pathways failed to attract investment due to a lack of a product having commercial market demand. A targeted end-user segment enables the development of biohubs tailored to the necessities of the consumer sector and streamlines the regional efforts to increase capacity building where and when required. A product, for example, “drop-in” fuels, with a global market, is preferred to prevent the vulnerability of the market demand due to policy changes and geopolitical tensions [40].

Thirdly, the biohubs should benefit from *integration with other (existing/new) upstream and downstream systems (INS)*. This creates synergistic effects between different sectors and provides benefits in terms of economic, environmental, and social aspects. As indicated in Chapters 2 and 3, economically, INS leads to lower selling prices of end-products due to reduced capital investments by infrastructure sharing. Environmentally, there is reduced demand for additional construction materials or land-use transformations. Socially, with INS, the stakeholders are provided an opportunity with a pathway requiring fewer modifications from their current practices (such as using primary mills for feedstock storage), which also enables trust-building due to familiarisation. Synergistically, biohubs can simultaneously promote new projects (such as green hydrogen, CCUS, or renewable electricity) by acting as a consumer while providing alternatives for existing petrochemical sectors (in terms of bio-based intermediates) that can be co-processed in the refineries. For example, the marine biofuel production value chain based on direct liquefaction techniques (such as pyrolysis or hydrothermal liquefaction) creates a demand for green hydrogen for its biocrude upgrading, which can be co-processed in the FCC unit or hydrotreater in an existing petrochemical sector [41]. Although the biomass conversion stage can be developed as a stand-alone configuration for autonomy over roles and responsibilities, INS brings an opportunity to promote brownfield biorefineries for realisable, holistic, sustainable, and inclusive development by reducing the threshold for huge investments, streamlining intersectoral development, and improving reliability.

Fourthly, to supplement the previous enablers, *technology and knowledge transfer (TKT)* at the national, regional, and farm levels are required. In all three case study regions, there is either no residue valorisation (such as coffee residues in Colombia) or only traditional methods of valorising residues that include burning on the field or for small-scale heating purposes. In certain regions of Spain and Namibia, the biomass is valorised for industrial heating or charcoal production, respectively. The upstream stakeholders of the agricultural sector, who currently have the roles and responsibilities of handling biomass residues, are most often unaware of the advanced technical conversion pathways for valorising residues. In Spain and Colombia, the farmers are unaware of the fate or value added to the crop by downstream activities before transforming it into the final product. This ignorance blinds them from potential negotiation power for better and fair prices or incentives, which are currently benefited by middlemen in the supply chain. The knowledge institutions (such as universities and centres for agricultural productivity) present in these regions perform various scientific investigations through thermochemical and biochemical conversion pathways to produce bioproducts [30], [31], [42]. However, the lack of commercial or demonstration-scale facilities indicates a stark presence of the academia-industry gap in these regions. On the other hand, the technology providers' perspective, who are often situated in the global north, is focused on achieving TRL 9 in a risk-free region with well-established infrastructure, an incentives scheme, and market reach for commercial success [43]. Therefore, there is a significant need for activities and projects enabling knowledge sharing and technology transfers to the regions of biomass production [44]. This enables inclusion and informed decision-making during supply chain management, improved and secure supply of feedstocks in large quantities, and better quality feedstocks for smooth biomass transformation.

To complement TKT, *Capacity building (CB) is required* for different stakeholder groups for the development and sustained operation of commercial-scale BBVCs. The need and nature of capacity building are highly dependent on the prevailing context in the biomass region. In Spain, the stakeholders of the olive sector are well connected and established, requiring minimal need for capacity building in the upstream of the BBVCs. In Colombia, the small-scale coffee and cacao producers are sparingly organised through associations or co-operatives. The Colombian farmers practice traditional practices for cultivating and processing coffee and cacao beans, which are most often not resource-efficient or vulnerable to losses. Therefore, capacity building in terms of producer organisation and process mechanisation for homogenous, high-quality beans and residue is needed in the Eje Cafetro region. Finally, in Namibia, although there is enough biomass available, the capacity to perform and closely monitor sustainable harvesting is lacking. Although the presence of a functioning forest management council enables communal farmers to participate in bush valorisation value chains, less than 10% of the communal regions have an established communal forest management council. Also, the skilled labour for operating biorefineries and their related activities is still lacking in the regions closer to biomass production, which limits the level of value addition that can be performed near the farms or bushlands.

Finally, to support the above-mentioned enablers, the local stakeholders recognise the need for *global north-global south and Public-private partnership* as a key factor in the global deployment of the bioeconomy, and in unlocking the maximum potential of biomass valorisation for sustainable and inclusive socio-economic development [45]. For example, initiatives like CBE JU have been initiated by the EU Commission to address the gap in technology development, and the mandatory inclusion of social sciences and humanities in the Horizon Europe 2020 calls enables multi-stakeholder networking and engagement [17]. The private sector can provide contributions to improving technical skills, organisational capabilities, marketing expertise, and capital investments. The public sector can play a crucial role in the development and enforcement of regulatory frameworks, planning public investments, and capacity building by including and educating stakeholders.

### 4.3.4 Context-specific purposes of Biohub designs

Although the enablers can ease the implementation of biohub designs, the context-specific purpose of the biohub has to be determined to address the existing, relevant challenges and necessities of the stakeholders. The conventional approach for developing biobased value chains, using novel technological pathways, is hinged on the main purpose of sustainable (especially economically profitable with low GHG emissions impacts) biomass conversion into fossil alternatives. However, this investigation elucidated other significant, context-specific purposes that are equally important for the real-life implementation of biohubs (or any BBVCs).

Initially, the biohubs should be designed to *complement and strengthen the existing (non) agricultural sector* in terms of its technical, economic, environmental, and social dimensions. In the Spanish olive sector, the capacity of secondary mills (that currently valorise crude olive pomace from virgin olive oil production) is one of the limiting factors for the increasing olive oil production capacity. Furthermore, being the only pathway for handling the large quantity of residues, the privately owned secondary mills gain an unfair advantage in determining the price of crude olive pomace (COP) to the cooperative-owned primary mills. Likewise, the current CAP policy restricts farmers from burning the pruning residues if they are entitled to an incentive scheme; however, it does not provide any alternatives for pruning valorisation. Therefore, biohubs based on innovative technologies to valorise (unpopular) COP and pruning biomass as feedstock will strengthen the socio-economic development of the Spanish olive sector. In Colombia, coffee and cocoa farmers predominantly have agroforestry systems and process their beans on their farms on a small scale in an uncontrolled traditional method. This leads to large variations in subpar-quality beans, which reduces their commercial value, thereby making it difficult for exporters (occasionally the farmer associations) to adhere to uniform standards for international markets. Also, in the current practice, the residues are generated and managed at the farm level, with very rudimentary and unsustainable forms of disposal. Therefore, the new biohubs promoting centralised bean processing facilities in locations near the farm will provide opportunities for farmers who are interested in availing of the technology. This will streamline the quality of beans due to monitored processing conditions, as well as concentrate the availability of field residues into processing residues for logistical collection. Finally, in Namibia, the bush sector is looking for new value chains that can consume biomass at the rate of annual regrowth capacity. The current harvesting techniques and monitoring capacity allow only commercial farmers to benefit from bush valorisation. Thereby making it socially exclusive for communal farmers. Therefore, the new biohubs should have operational decisions that provide an ecosystem for access to harvesting tools for all the farmers (such as by leasing equipment, increasing the capacity for manufacturing indigenous harvesting tools), etc. By opting for wood chips as the product of biohubs, various pathways such as biomass to energy, biomass to feed, or biomass to electricity can be developed further. This will primarily strengthen the necessary technical skills and infrastructural developments to mobilise large-scale encroacher bushes for bulk chemicals production.

With the prevailing geo-political tensions, biohubs are seen as a potential key for attaining a future with *fossil independence and energy and resource security* with Indigenous bioresources by the stakeholders. For biohubs designed based on agri-residues, such as in Spain or Colombia, it is preferred to have technologies producing by-products (such as biochar) that can be used as a soil amendment to reduce the dependency on expensive chemical fertilisers. Although using biomass as a direct fuel source is not an efficient pathway, it is needed to eliminate the non-renewable energy usage of biohubs. With millions of people still waiting for grid connection, especially in the Global South, biomass power plants are crucial for the decentralisation of biohubs. For example, valorising municipal organic wastes and other lignocellulosic materials in communal or small-scale biodigesters can provide biogas for clean cooking and heating purposes. For countries like Namibia, which do not have an existing petroleum refinery or a petrochemical cluster, biorefineries and biohubs can be influential in attaining resource independence by reducing imports (such as transportation fuels) by valorising their native available bioresources [3], [46]. The potential biohubs should be designed with marketable anchor products that satisfy local needs, along with opportunities for exports, strategies for maximum nutrient retention, and consumption of renewable sources of energy.

Thirdly, bioeconomy and bio-based value chains are widely known for their positive potential to contribute to global sustainable development by promoting socio-economic conditions and offering environmentally friendly products. The Sustainable Development Goals (SDGs) are the global action calls that were initiated to ensure peace and a prosperous life for all by 2030. However, contrary to the conventional approach of developing biohubs and assessing their sustainability impact, the stakeholders highlighted that biohubs should be designed to *enable, address, and contribute to the context-prevailing SDGs in the biomass-producing regions*. For example, in Spain and Namibia, restoring biodiversity (for SDG 15) is a crucial aspect of regional development due to prevailing monoculture crop cultivation and loss of savannah ecosystems due to bush encroachment, respectively [31], [47]. Therefore, strategic-level decisions while developing biohubs should include ways to either promote or influence this SDG goal [48]. For example, using biochar for soil amendment will improve soil health in Spain, and sustainable bush harvesting practices that include suitable and mandatory post-harvest aftercare monitoring services can contribute to biodiversity. In Colombia, the stakeholders identified that biohubs should focus on contributing to the following SDGs: 1,7,9,12,13,15, and 17. Due to the unique cultivation conditions (altitude, temperature, and humidity) required for coffee and cacao plantations, they are facing incredible challenges in achieving good yields due to global warming. Therefore, SDG 13 is given priority for biohubs development, followed by SDG 17, which ensures global partnerships to strengthen their global coffee value chains, as well as for regional technological development. Finally, in Namibia, the stakeholders associated the direct and indirect contribution of potential bush-based biohubs to SDG 1, SDG 6, SDG

7, SDG 8, SDG 9, and SDG 15. The bush valorisation activities can provide a stable source of income and bush feed for diverse farmers, especially in terms of droughts that are expected to become more severe with climate change. Sustainable bush harvesting will lead to many positive ecological impacts, such as the regrowth of perennial grasses, restoration of open savannah ecosystems, and recharge of groundwater levels, thereby enhancing water availability (SDG 6) and life on land. Bush-based bioenergy (such as solid, liquid, or gaseous biofuels) can also contribute to energy access in remote areas and provide employment opportunities in rural areas by combating unemployment. Namibian biohubs will act as a stimulus for industry, innovation, and infrastructural development.

Finally, the biohubs should *act as flexible sector couplers*. The concept of sector coupling (SC) is commonly investigated and used in the field of renewable energies for sustainable transitions of industries, transport, and residential sectors [49]. According to the International Renewable Energy Agency (IRENA), sector coupling covers broad topics of cogeneration, combined use, transformation, and replacement of various energy sources and demand forms, such as electricity, heat, and fuels [50]. However, its implementation for a biobased economy is almost non-existent. One of the crucial aspects impacting the real-life implementation of biohubs is the differentiation of roles and responsibilities based on the capacity of stakeholders. Based on the interviews from both upstream and end-user sectors, it was deduced that the biorefineries, specifically biomass conversion pathways, are commonly perceived as "out of the core area of business or knowledge expertise" for the sectors. The agriculture sector is primarily focused on improving the efficiency and productivity of crop production and its sustainability through residue valorisation. The upstream stakeholders predominantly perceive their roles to be limited to the supply of the residues and no further, due to the lack of technical expertise or knowledge. On the other hand, the end users prefer to play their roles only in handling the intermediate or end product that can be incorporated into their facilities for final conversion or direct use in the market, respectively. Therefore, biohubs or biorefineries are positioned in a grey zone of ownership and stakeholder responsibilities. This has to be addressed urgently to attract investments and ensure proper management of the biohubs. Therefore, the biohubs should be positioned independently of the upstream and downstream sectors, to be a link or coupler of the former sectors. Thereby, biohubs become a market for procuring and selling biomass as commodities. For example, a biohub in Namibia can act as a market where the farmers can sell their bush thinning for a fixed price. Biohub can further transform this unprocessed biomass into various intermediary products such as woodchips, pellets, briquettes, biocrude, or electricity, that can be sold to end users such as the residential sector, cement kilns, or petrochemical refineries. Furthermore, biohubs can also be connected with other regional renewable energy sectors, such as green hydrogen in Namibia or solar farms in Spain. This enables framing for smooth operational management decisions, for example, an end-user can arrange a contract agreement with one biohub for a secure and sustainable supply of feedstocks instead of numerous small-scale farmers. Biohubs should therefore act as couplers of stakeholders who are geographically, technically, and sectorally diverse. This also aligns with the findings from the study of Lange *et al.* (2021) [51].

### 4.3.5 Biohub design approach conflicts and trade-offs

Sustainability tensions and trade-offs are inherent during a multi-objective optimisation of bio-based value chains over the three facets of sustainability, namely, economic, environmental, and social aspects. From a designer's perspective, the trans-disciplinary approach highlighted the following conflicts and trade-offs that have to be carefully addressed while developing biohubs for emerging bioeconomies. *Figure 4.4* illustrates the identified conflicts and opportunities.

| Scope | Sustainability Conflicts | | | Opportunities |
|---|---|---|---|---|
| Technical | Economies of Scale | ⟷ | Economies of Scope and Economies of Numbers | Decoupling upstream and downstream sectors of biorefineries through intermediate products production |
| Technical | Effectiveness of the design | ⟷ | Robustness of the design | Marketable anchor products that are platform chemicals or drop-ins |
| Implementation | Preserving cultural values | ⟷ | Enabling commercial development | Early stage multistakeholder engagement to promote knowledge exchange and make informed decisions |
| Implementation | Efficiency | ⟷ | Inclusivity | Cross sector partnerships can find the balance between paradoxical tension |
| Implementation | Global Partnership | ⟷ | Energy Independence and resource security | New market creation |
| Sustainability | Global Sustainability | ⟷ | Local Sustainability | Achieving global sustainability by addressing local SDGs |

Figure 4.4: Summary of identified sustainability conflicts and opportunities during biohub development using a transdisciplinary approach. The aspects of Sustainability on either side of the arrow conflict with each other. The scope of conflicts is indicated using coloured columns, namely, Beige for technical aspects, green for biohub implementation, and dark yellow for sustainability aspects.

**Technical alternatives: Decoupling through intermediate products.** In any technology-driven conceptual process design, especially in a fossil-based system, the principle of the economy of scale is one of the most crucial and guiding principles. However, in the case of a circular or sustainable bio-based economy, the economy of scale is challenged by both the economy of numbers and the economy of scope. On one hand, specifically from a technical point of view, any bioconversion technology stage is a (bio-)chemical process that benefits from the economy of scale, proportionately affecting its energy and material efficiency. However, its upstream stage involves the procurement of biomass from various producers, expecting local rural benefits, to ensure a secure and constant supply of feedstock. The economy of numbers governs the inclusion of upstream stakeholders for maximum sustainable social benefits. On the other hand, the product portfolio is governed by the theory of the economy of scope, where various products are produced efficiently. From a cascading point of view, maximum biomass valorisation can be achieved through the economy of scope. The latter is, however, challenged by the limitations of the technical skillsets and infrastructure available at the biomass production sites. Therefore, from a designer's perspective, it is prudent to use the production of intermediate products such as wood chips and pellets, biocrude, and platform chemicals to decouple the upstream and downstream activities of the bioconversion stage. This will provide an opportunity to synergistically benefit from all three economies' principles, namely, scale, scope, and numbers. This is complemented by performing a detailed techno-economic assessment for the design alternatives to provide the necessary knowledge for decision-makers.

4

**Technical alternatives: Marketable anchor products.** Although it was previously discussed that marketable anchor products could be enablers for the biohub development, they can also aid in addressing the conflicts between the effectiveness and robustness of the biohub design. Effective process or supply chain design focuses on achieving higher efficiency, better consistency, improved quality, and better economic performance, such as return on investment of the end-product. On the other hand, robustness of the process design addresses the uncertainty to reduce the sensitivity of the functional output to input variations. The design approach to address the former and the latter is quite different and has significant real-time impacts. For example, a robust biobased process design that can uptake all types of residues consists of various unit operations to address the heterogeneity in biomass feedstock before the biomass conversion stage. This makes the design cost-intensive and also not optimised in terms of the working efficiency of the equipment. On the other hand, a dedicated value chain with a specific feedstock-technology-end product pathway can be optimised for its performance, but is highly sensitive to the uncertainties with biomass supply, market scenario, and has less flexibility to adapt to future needs. Therefore, the choice of intermediate products as the marketable anchor product of the biohub can inherently act as a trade-off between effectiveness and robustness of the value chain. This provides flexibility to the biohub in terms of global market penetration as well as optimising the process of intermediate production to enhance energy and material efficiency.

**Implementation alternatives: Early-stage inclusion of stakeholders.** Social acceptance and the global large-scale deployment of biobased value chains are intricately connected [52]. Social acceptance is predominantly governed by the ability of the alternative proposed value chains to acknowledge and preserve the local cultures and values of communities, along with their perception of the bioeconomy [53]. On the other hand, large-scale global deployment requires a commercial perspective of establishing a value chain, which streamlines the organisational structure with effective tactical and operational decisions in supply chain management. Ruf *et al.* (2022) highlighted the effect and importance of consumer awareness and their perception in the commercialisation of bio-based products, along with their purchasing power [54]. In this investigation, some of the small-scale farmers showed a preference to practice their traditional method of cultivation and residue handling, with the possibility to participate in the future. A Spanish olive farmer indicated a strong feeling of pruning their farms with some person who is skilled person rather than a professional third-party. Therefore, the value chain design should include the possibility of procuring field biomass directly from farmers. On the other hand, accommodating farmers' wishes raises supply security risk for the smooth operation of large-scale biorefineries, especially due to a lack of familiarity and trust. Macht *et al.* (2023) reported a lower level of local acceptance for biorefineries when compared to general acceptance rates, mainly due to the NIMBY (Not In My Back Yard) effect [52]. They also highlighted the necessity of effective communication and participation strategies for the successful implementation of a sustainable bioeconomy. Therefore, the approach of early-stage inclusion of stakeholders and organising a multi-stakeholder decision-making workshop during the conceptual process design can address this tension. Furthermore, this approach enables trust building amongst the stakeholders of different sectors and aids in informed decision-making. A Spanish stakeholder, representing a knowledge institution, addressed the value addition of participating in such an early-stage multi-stakeholder workshop, as it created knowledge and awareness of the sector as a whole and led to better and informed decision-making.

**Implementation alternatives: Promoting cross-sector partnerships.** Sustainable transitions, especially transitioning to a circular and sustainable bio-based economy, require collaboration and partnership between various stakeholders from different (public, private, national, and international) sectors along the value chain [51]. Although inclusiveness is discussed as a key parameter for social justice through biohub implementation, it gives rise to tensions in terms of efficiency [55]. From the design propositions, one can infer that early-stage inclusion of diverse stakeholders leads to varying value propositions (such as stakeholders' expectations from the partnership) that might reduce the efficiency of the multi-actor approach [32]. The diversity in capacities and capabilities of potential stakeholders, especially in global cross-sectoral partnerships, will lead to differences in performance speed and standards that will impede efficient project planning and implementation. Diverse stakeholders' inclusion also brings varying degrees of interest and involvement that might threaten project execution on a large scale. Therefore, there is a clear need to define the "stages of inclusion" and "quality of inclusion" that ensure the effectiveness of the multi-actor approach. This can be achieved through minimising the sectoral boundaries between the stakeholders for collaborative work. Creating a shared identity, such as a sustainable biohub or adhering to a mandate (such as IMO 2020), through a continuous, interactive, and iterative engagement approach from the conceptual stage until the implementation of biohubs can enhance awareness. This can address the dynamic nature of the inclusiveness-efficiency paradox that can arise during various stages of the project. On the other hand, there is a need for maintaining well-defined scope or boundaries that retain stakeholders' sectoral identity to efficiently perform their roles and responsibilities. Therefore, biohubs, as an individual entity, can act as a sector-coupler to promote cross-sector partnerships across the globe to promote global sustainable biobased value chains.



**Implementation alternatives: Creation of new markets.** Global partnerships are required to overcome the non-uniform distribution of economic, material, and knowledge resources for combating climate change [51]. It is clearly emphasised through SDG 17. However, in the current era of geopolitical tensions, energy independence and resource security are the most crucial aspects of renewable transitions. Most countries have a national agenda to make their economy both "fossil-free" and "import-independent" to achieve both political and climate targets. Currently, in the globalised fossil economy, there is a clear geographical distinction between the regions of resource supply, value addition, and market demand. But the introduction of a biobased economy will transform the scenarios by creating a new supply-market landscape globally. Currently, the Global South is seen as the supplier of raw materials due to its abundance in feedstock, and the Global North plays the role of market where value addition through technology and commodity sales takes place. In recent years, there has been a rising interest against the concept of importing raw biomass feedstock from the Global South for value addition in the Global North due to its environmental unfriendliness and social unjust due to resource exploitation. Therefore, there is a need to achieve a trade-off to address the conflicting ideas of global partnership and energy independence, with the finite biomass resources. Biohubs promoting maximum value addition near the biomass production site can act as a market for intermediate products that can be traded globally, similar to fossil fuels. Therefore, biohubs enabling the creation of new regional, national, and international markets can promote and transform global sustainable production and consumption patterns.

**Sustainability alternatives: Addressing local SDGs for global sustainability.** The current global perspective of sustainable transition for climate change mitigation and adaptation is predominantly focused and assessed only for economic feasibility and global greenhouse gas emissions. However, the contribution to and challenges of climate change are not geographically uniform; there is a need to understand the local context to promote local sustainability [48]. For example, in Namibia, one interviewee highlighted that the impact of the EU's perception of forests as carbon sinks has restricted them from valorising their encroaching bush due to a lack of market uptake for sustainable reasons. However, in the contextual reality, these bushes cause more local ecological damage than just acting as a carbon sink (which is predominantly emitted due to anthropogenic activities elsewhere) [56]. Therefore, a conflict arises over design strategies for satisfying global needs by exploiting the regional resources without addressing local needs. Also, the urgency to address climate change adaptation and mitigation differs geographically, and the impact is higher in the global south, especially in the agricultural sector. In the investigation, due to time and resource limitations, only the Spanish and Namibian stakeholders were asked to select and rank the key performance indicators for evaluating the sustainability of biohub designs. The rankings can be found in Appendix 7.4.3. In both case studies, the stakeholders prioritised indicators related to environmental aspects with more weightage than the economic, social, and technical aspects. In Spain and Namibia, the technical and social aspects were given second priority, respectively. Furthermore, the indicators chosen to evaluate the sustainability aspects of biohub, especially the environmental and social aspects, were context-dependent. For example, the indicators to analyse the ecosystem health (areas of protection) are selected to be climate change, eutrophication, and acidification. However, in Namibia, the indicators for the same area of protection are identified to be climate change, land degradation, and fauna restoration. Likewise, the indicators of social aspects were found to be different across the two case studies due to differences in the socio-economic status and impact of feedstock on the livelihood of the local communities. Overall, a pattern of prioritising indicators to ascertain local sustainability (such as biodiversity restoration, avoidance of land degradation, etc.) over global sustainability (such as GHG emissions) has been found. Therefore, to overcome this conflict, which can be expanded to other renewable energy sources such as solar or wind, biohub designs should aim to address the local sustainable development goals (SDGs), which inherently contribute to the global sustainable transition.

## 4.4 CONCLUSIONS

This investigation analyses the novel trans-disciplinary approach for early-stage inclusion of stakeholders' perspectives, especially capabilities, into conceptual process design for developing context-specific biohubs in Spain, Colombia, and Namibia using mismanaged or under-utilised residues. The establishment of a value chain for marine biofuel production with novel hydrothermal liquefaction technology is focused on as an initial design, from a designer's perspective. The analysis of the first-of-its-kind empirical study of the co-designed biohub design alternatives, based on derived design propositions, involving local potential stakeholders, for real-life implementation of biohubs, highlighted the importance and impacts of contextual knowledge for technical choices. The desired or ideal technical biohub characteristics, such as feedstock (choice of feedstock, pre-processing, transportation, and procurement) and biorefinery aspects (biorefinery technology, products, ownership, configuration, and location), were found to be highly dependent on the local prevailing context and the capabilities of the potential local stakeholders. With the help of SWOT analysis, the key enablers for commercial deployment of biobased value chains in these regions were identified, along with the context-specific target purposes of the biohubs. The learnings from this investigation addressed the blind spots of the conventional approach for a sustainable biobased project development. By developing multiple, context-specific, capability-sensitive biohubs, we developed a win-win scenario wherein the biomass producers benefit from valorising underutilised biomass, at large volumes, for addressing the (economic, environmental, or social) needs prevailing for sustainable development, while the biorefineries or end-users are provided a secure supply of high-quality feedstock with minimal modifications made to the existing business models.

The presented approach enabled the early-stage integration of technical and non-technical aspects of biohub (or any bio-based value chain) development based on the local context and stakeholders' capabilities during conceptual design. Early stage inclusion of local stakeholders led to identifying potential new technical opportunities and potential showstoppers for the commercial deployment of bioeconomy in the region. The multi-actor approach led to knowledge sharing, capabilities recognition, trust building, and informed decision-making by stakeholders with biohub realisation as the end goal. Local stakeholder involvement allowed for the identification of context-specific key sustainability performance indicators of the case studies. Although not all sustainability and inclusivity aspects were addressed, the early phase consideration of integrating social aspects with technology commercialisation allowed for the perception of tensions related to the consideration of various design alternatives, and identified pathways to achieve a sustainable and just transition. This knowledge will enable stakeholders to understand the differences in values and capabilities and enhance the stakeholder network for biohub development. To achieve this, collaboration between social sciences and energy research concepts is found to be highly beneficial. Overall, the approach can also be implemented in other case study regions, for other bio-based value chains and renewable energy systems in the efforts for an inclusive, sustainable, and just transition from a fossil economy. The current approach still lacks perspectives on certain topics of responsible research and innovation (such as safe by design). Hence, we recommend the need for a transdisciplinary framework for early-stage consideration of non-technical and technical aspects using the concepts of engineering and social sciences for the development and assessment of a circular, inclusive, sustainable, and holistic system that promotes local development by addressing global issues. The framework should incorporate both qualitative and quantitative indicators for truly evaluating the overall performance of the developed systems and for effective representation of the context for decision makers.

## 4.5 SUPPLEMENTARY DATA

Supplementary data for this study can be found in Appendix C ( see section 7.4).

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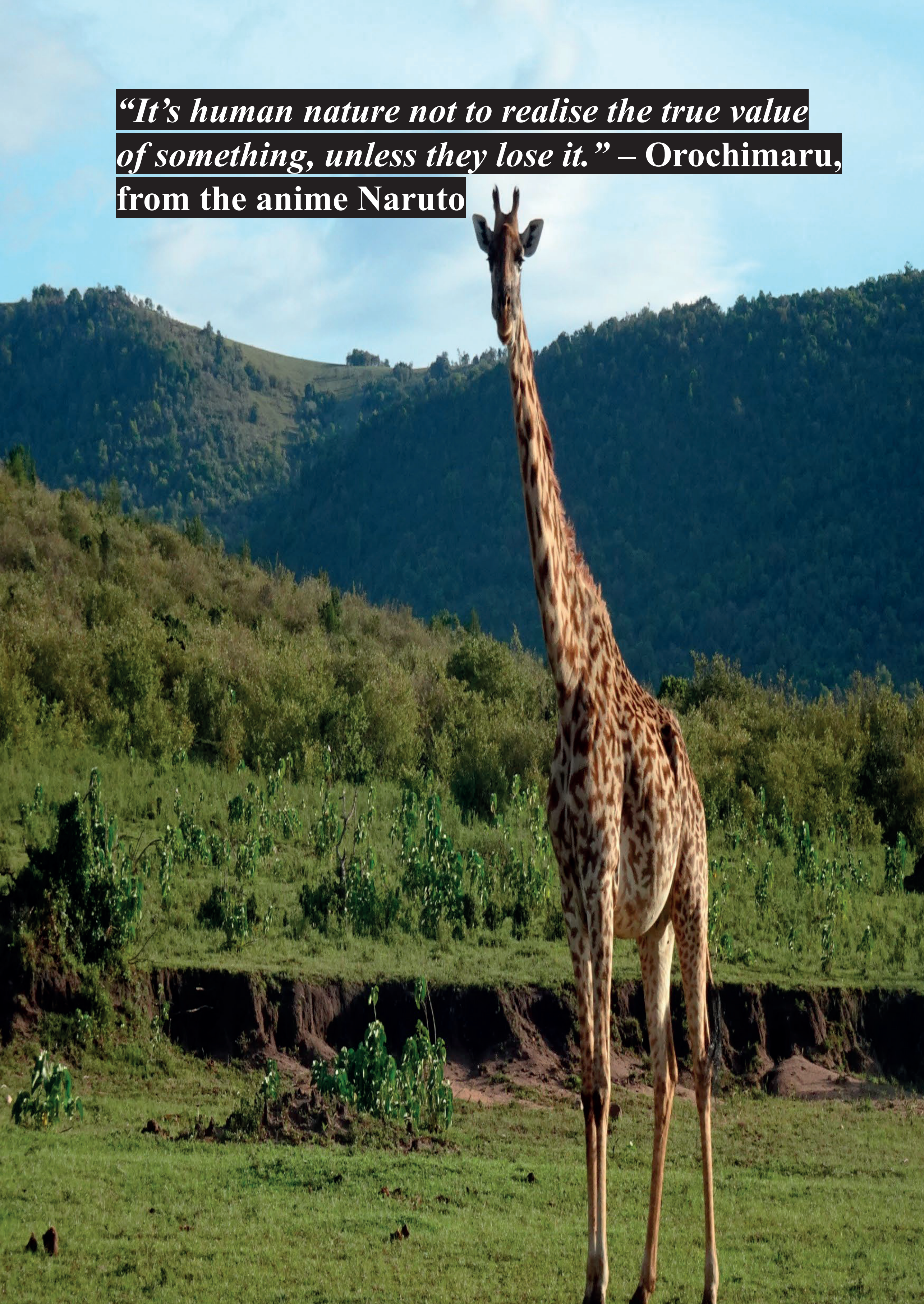
***"It's human nature not to realise the true value of something, unless they lose it."* – Orochimaru, from the anime Naruto**

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# 5

# Conclusions

## 5.1 GENERAL CONCLUSIONS

At the end, I find the performed work to resemble a selection debate between the two idioms “Too many cooks spoil the broth” and “the more the merrier”!

It all started with highlighting the need for a fossil-free economy to combat global climate change by reducing the greenhouse gas emissions from anthropogenic activities, in **Chapter 1**. The transportation sector, especially the shipping sector, which serves as the lifeline for the modern globalised economy, is one of the largest consumers of fossils and is classified as a “hard-to-abate” sector where defossilisation strategies are recommended over decarbonisation, mainly in the large ocean-going vessels [1]. Although various environmentally friendly fossil-free energy carriers, such as hydrogen, methanol, and ammonia, from renewable energy sources have been identified by the scientific community [2], [3], [4], the large-scale global transformation of shipping fleets with renewable alternative fuels is primarily dependent on the techno-economic feasibility (such as fuel price, global fuel supply availability, and compatibility of the alternative fuel with existing “on-board” and “off-board” infrastructure) [2], [5]. To adhere to the stringent regulations and policy mandates such as IMO2020, RED III, and FuelEU maritime, “drop-in” biofuels are commonly seen as a short-term to mid-term solution for the shipping sector due to their significant advantages over their renewable counterparts. Advanced “drop-in” biofuels produced through thermochemical liquefaction techniques, such as hydrothermal liquefaction, based on non-edible feedstocks, are proven to show promising economic and environmental potential, at lab-scale, for replacing fossil-based heavy fuel oil in large ocean-going vessels [6], [7], [8], [9], [10]. Therefore, the development and deployment of large-scale commercial biobased value chains hold the key to a successful transition of the shipping fleet to accommodate biofuels. Moreover, developing biofuel value chains will potentially promote the bioeconomy as a means for a sustainable future.

However, despite decades of scientific research and numerous pilot-scale projects, significant technical, social, economic, and environmental challenges must be addressed while developing biobased value chains to maximise their full realisation potential [11]. Social acceptance and feedstock supply security have been two of the most crucial challenges while scaling up the bio-based technologies for societal implementation. Contrary to the “technical design followed by social acceptance” approach, the early stage consideration of stakeholders’ perspectives and the context prevailing in the region of interest during the conceptual development has been proposed as a pathway for promoting a socially inclusive and just bioeconomy [12], [13], [14]. Therefore, in this dissertation, the potential of an early stage consideration and inclusion of the local contextual knowledge and stakeholders’ perspectives into the technical conceptual design

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of a global biobased value chain for "drop-in" marine biofuel production using lignocellulosic residues through novel hydrothermal liquefaction technology has been investigated. The sustainability performance of the co-designed inclusive value chains has been evaluated through integrated sustainability assessments such as techno-economic evaluation and environmental life cycle assessment. In this chapter, an overall conclusion from the three case studies performed will be presented as solutions to the three research questions stated in Chapter 1 (RQ 1-3). Based on the discussion provided, the authors' response to the main problem statement: *"How can we design and evaluate the performance of context-specific sustainable and inclusive bio-based value chains, with a special focus on marine biofuel production through hydrothermal liquefaction (HTL)?"* will be provided. Furthermore, the limitations of this work and potential avenues for future research to address the knowledge gaps will be mentioned. Finally, based on the learnings and discussions from this work, a framework to perform transdisciplinary research for the conceptual design of sustainable and inclusive biobased value chains, integrating technical and non-technical aspects of value chains, to promote global large-scale deployment of bioeconomy, will be presented.

Initially, with a pre-selected end-user segment and the biomass conversion technology, as mentioned in **Chapter 1**, a maximum variation case study investigation method was used in this thesis for developing biobased value chains for marine biofuels. Unlike the conventional approach [15], a novel systemic approach for case study selection is performed to standardise the selection protocol. The selection process involved three phases: divergent (Phase 1), convergent (Phase 2), and selection (Phase 3), to engage various academic and industrial experts at various stages of case study selection for considering technical, economic, environmental, social, and institutional aspects of the sustainable and inclusive development of biobased value chains. In Phase 1, all countries with coastal areas near primary chokepoints in maritime routes are considered. In Phase 2, the selection criteria used for choosing case study countries and feedstocks (such as RED approval, data availability and accessibility, infrastructure, political stability, and enabling policies for commercial development of bioenergy projects) represented various aspects such as scientific, commercial, social, and institutional dimensions, making the approach holistic and robust. This broad consideration of selection criteria enabled the identification of case study locations with promising potential for commercial scale implementation, as well as eliminating the potential No-Go's at the very early stage of the project. Furthermore, the inclusion of stakeholder-specific categories and indicators as selection criteria builds confidence, trust, and promotes knowledge awareness and exchange amongst the stakeholders involved. After Phase 2, the contextual features, mentioned in section 1.3.3, on the intermediary selection, were aimed at narrowing and selecting case studies with diverse archetypes to capture the diversity in contexts for maximum knowledge generation (which includes opting for feedstocks with minimal experimental data available, as the project consortium included an experimental team). Based on the features and project partners' vote, the olive sector in Spain, the coffee sector in Colombia, and the encroaching bush sector in Namibia were identified as case study choices. This thesis aims to provide a knowledge contribution through the generated results of inter-disciplinary work performed in a multi-disciplinary team using a trans-disciplinary approach, as shown in *Figure 5.1*. The case studies were developed and analysed to understand the impact of the novel trans-disciplinary approach on different scopes in the different chapters of the thesis.

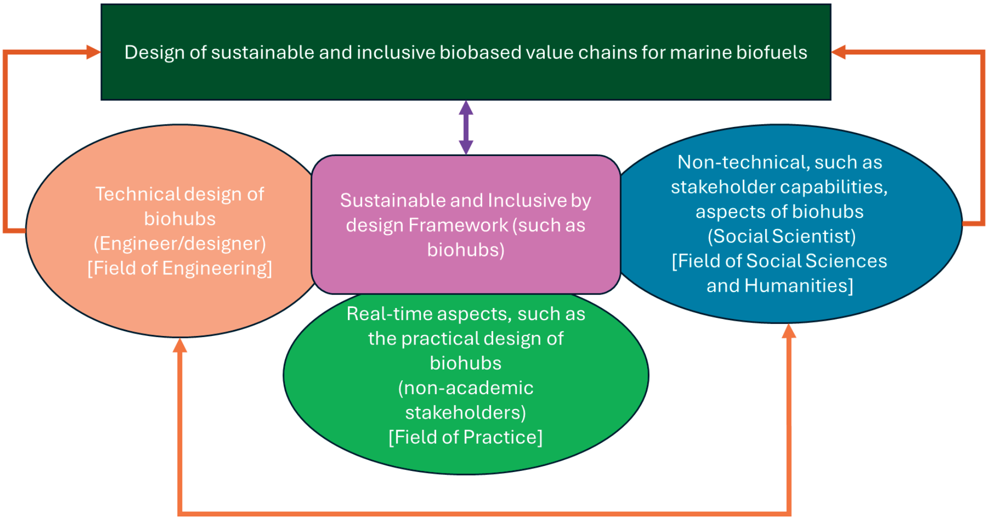


Figure 5.1: Various interactions amongst different disciplines to address the complex problem of designing inclusive and sustainable biobased value chains for marine biofuels. Brown weighted lines indicate a multidisciplinary aspect, Orange weighted line indicates an interdisciplinary connection, and Purple double-headed arrow indicates the transdisciplinary approach

**Chapter 2** focuses on addressing the RQ1, *"Can we, and if so, under what conditions, design socially just and economically feasible biohubs for marine biofuel production based on olive residues in Jaén via hydrothermal liquefaction (HTL)?"*. The Chapter showcases how to incorporate stakeholders' perspectives in the early stage of the conceptual process and value chain design to achieve context-specific, economically feasible, and socially just biohubs, mainly from a designer's perspective. The concepts of Value Sensitive Design (VSD) and the capability approach were used to incorporate non-technical aspects (values, needs, stakeholder capacities, capabilities, skill sets, etc.) of the value chain into the technical design of the capability-sensitive biohubs. As a leading global producer of olive oil, Spain faces challenges with the generation and handling of abundant, diverse residues on an annual basis. With a well-established infrastructure and organisation in a developed country, representing other regional producers in the Mediterranean, the

Andalusian region of Spain was investigated. With access to a primary chokepoint in the maritime route, Andalusia can benefit from the development of context-specific biohubs to produce marine "drop-in" biofuels with the use of existing infrastructures. At the start, a field visit was performed, spanning over 5-6 weeks, in a multidisciplinary team along with a social scientist in the region of interest to gain contextual knowledge and social perspectives of local stakeholders who could participate in the potential biohub. Participatory techniques, such as semi-structured interviews and multistakeholder workshops, aided in elucidating the social values, stakeholder capabilities, and identifying ideal biohub characteristics for potential commercial implementation of biohubs, enabling local development. Even in a well-established and organised sector like the Olive sector, there was a lack of communication between the stakeholders of the same value chain. The novel approach based on a multistakeholder workshop enabled value-added knowledge exchange between the stakeholders of the current and potential value chain across different nodes, further leading to informed decision making and choice selection. The knowledge exchange led to the identification of potential opportunities (such as new feedstocks hidden in an existing process value chain that are often overlooked without contextual knowledge, such as crude olive pomace), threats, and conditional preferences, which will often go unnoticed in a conventional in-silico development of conceptual process design. For conceptual design, the Design Space and Design Propositions for the biohubs were derived from the identified values, capacities, capabilities, preferred choices, needs, infrastructure available, and skillsets of the local stakeholders. Various conceptual processes and value chain design alternatives were developed to accommodate different choices of design variables to understand the potential trade-off and uncertainties for sustainability. For the HTL process, the experimental data from the literature were used to develop a process simulation in Aspen Plus for obtaining mass and energy balances under steady-state conditions. Process integration, such as heat recovery and water recycling, was used to improve the technical performance of the design. The contextual knowledge guided the designer to build upon the learnings and experiences obtained from the stakeholders in previous projects performed in the region (such as potential biomass competition) to avoid duplication of efforts. With this approach, the team also gained local stakeholders' trust, which is crucial for any follow-up initiatives or large-scale commercial implementation. Finally, crude olive pomace was identified to be the preferred feedstock for the HTL-based biohubs in Andalusia.

The multistakeholder inclusive design approach for early stage consideration of stakeholder perspectives and the techno-economic feasibility studies of the design alternatives indicate the potential positive impacts of integrating the upstream and downstream activities of any new biobased value with the existing infrastructures available in the region. The integration provides economic benefits for the new bioproduct in terms of reduction in capital and operating expenditures. Furthermore, using existing infrastructure offers a pathway with minimal changes or modifications in the existing sectors, enabling stakeholders to make a smooth transition into fossil fossil-free economy. For instance, co-processing of biocrude in the existing refineries can enable the existing petrochemical sectors to replace fossil crude and reduce their environmental footprint. Based on the results obtained, it is recommended for downstream integration of co-processing HTL biocrudes in petrochemical refineries for future work.

The technical design of the biorefinery process and the biohub can serve as a means of inclusion by addressing the necessities of the local region. For instance, opting for feedstocks such as crude olive pomace can benefit more farmers than choosing exhausted olive pomace sourced from privately owned secondary extraction mills. Also, in case of an energy-intensive process, byproducts are to be valorised primarily to satisfy process energy demand, to reduce the dependency on non-renewable energy usage. A trade-off between technical design for process efficiency and context suitability is inevitable, in which the latter should be given more importance for enabling implementation. From an economic perspective, the minimum fuel selling price of the drop-in biofuels was found to be competitive at scale with potential room for improvement. The contextual knowledge consideration further provides space for synergistic integration of new value chain development efforts with other regional renewable projects, such as green hydrogen, carbon capture and utilisation, or renewable (solar/wind) electricity, with the bio-based value chains to further improve the techno-economic performance in the region of interest. Similar to other processing residues, crude olive pomace (COP) based HTL biohubs benefit from choice feedstock as a processing residue, thereby eliminating the need for significant feedstock collection and transportation. Therefore, processing of residues (from the agriculture and forestry sector) should be seen as a short- to mid-term transition pathway to achieve the global bioeconomy, with processing mills acting as the point of feedstock collection. However majority of the global biomass is located in the global south, in low and middle-income countries, as field residues, with intricate social arrangements and less developed infrastructures. Furthermore, a more detailed sustainability assessment that includes environmental lifecycle analysis is required in addition to techno-economic analysis for a better understanding of the impact of early-stage consideration of non-technical aspects. Also, the opportunities and challenges of the inclusion of stakeholder perspectives for context-specific biohubs in Global South countries, where infrastructures are not fully developed and are culturally different from Europe, are to be investigated.

In **Chapter 3**, the RQ 2: *"What are the economic feasibility and environmental impacts of the co-designed inclusive field residue-based biohubs for marine biofuel production in Spain, Colombia, and Namibia?"* is discussed where the scope is broadened to understand the impact of contextual and stakeholder value consideration when field residues in the global south countries are considered, by addressing the knowledge gaps and building upon the learnings of Chapter 2. The goal is to design and assess (techno-economic and environmental performance of) agrarian (or non-forestry) biohubs in the emerging bioeconomies (such as Spain, Colombia, and Namibia) based on field residues (olive tree pruning, coffee pulp, and encroacher bush). Unlike processing residues, field residues pose a challenge in terms of collection and the necessity of pretreatment (such as baling, chipping, cleaning). The need for pretreatment techniques and transportation of low-energy-dense feedstocks over large distances increases the costs of production and the environmental footprint, which reduces the overall sustainability performance of the biohubs. Similar to Chapter 2, biohubs were developed by identifying stakeholders' capabilities and (sustainability and well-being) values, along with process simulation for mass and energy balances.

The impact of contextual knowledge was found to be more profound in the considered biohub systems than in Chapter 2, as the technical design choices were highly sensitive to the prevailing scenario (such as availability of infrastructure and technical skill sets, etc.). Design strategies, validated during the multistakeholder workshop, aimed at transforming field residues into processing residue-like streams by performing pre-processing treatment near or at the site of biomass production are potential ways to improve the sustainability performance of the agrarian field-residue-based biohubs. For instance, in Spain, the primary mills can be used as pre-processing facilities to perform chipping and cleaning of pruning residues before transportation. The co-operative-owned primary mills can provide access to equipment (through leasing or renting) which are otherwise economically expensive to small-scale farmers and also play the role of sharing the benefits obtained amongst its farmers, if needed. In Colombia, opting for a regional, centralised coffee processing facility addresses the current issue of variation in the quality of coffee beans while simultaneously converting coffee pulp into a processing residue rather than a field residue from a farmer's backyard. Finally, in Namibia, by opting for a regional, centralised facility for chipping of the acacia bush, the hurdle of access to equipment by communal and resettled farmers while overcoming the challenges of the availability of skilled labour is addressed. Furthermore, the choice of the nature (or pre-processing) of the feedstock (such as wood chips or bales) can act as a means of inclusion of vulnerable upstream (small-scale) biomass producers who are otherwise overlooked. The contextual knowledge also plays a crucial role in understanding the needs and opportunities while making (strategic, tactical, and operational) decisions for the new biohubs, while promoting local regional development.

Technically, as expected, it was inferred that the feedstock selection and process conditions impact the HTL product composition and final quality of the biofuels. Based on the context, the economic performance of the biohubs can be improved either through scaling up (in Spain and Namibia) or by opting for processing multiple feedstocks (such as in Colombia). Environmentally, based on the application of the system expansion approach, the valorisation of the under-utilised or mismanaged residues reduced the overall GHG impact of the biofuel production significantly, on a well-to-wake basis, mainly attributed to avoided emissions. Therefore, under-utilised or mismanaged biomass residues, such as wheat and rice straws (currently being burned in South and Southeast Asia), are to be promoted for biobased projects over dedicated energy crops or edible food crops that raise sustainability concerns. Furthermore, the valorisation of agricultural residues, especially in the global south, can act as a valuable source of additional income for the farmers, as the ongoing climate crisis negatively influences their main crop yield [16]. In certain regions, such as in Namibia, the biobased value chains can provide material independence and energy security by reducing imports from other countries under the current prevailing geopolitical tensions. Therefore, early-stage inclusion of stakeholders' perspectives and context consideration in the value chain design for context-specific biohubs, especially in the global south countries, can enable the unlocking of the untapped potential to mobilise huge reserves of biomass feedstocks, with supply security, needed for commercial-scale bioeconomy deployment globally. In general, technically, all the considered case studies were able to produce marine biofuels with potential for scale-up and replication in other similar biomass-producing regions. Economically, the HTL biofuels, without carbon credits, at a large scale were able to compete the fossils. The HTL marine biofuels in the three case studies showed immense potential (at least 89% in comparison with the fossils) for greenhouse gas emission reduction. Therefore, overall, it was inferred that the non-consideration of the non-technical aspects in the technical design of biobased value chains has been the blind spot of the conventional approach by designers, leading to the everlasting significant gap between scientific potential and societal implementation of real-time projects. The proposed approach can overcome the above drawback for the global bioeconomy transition.

In **Chapter 4**, an overall reflection on the effectiveness of the novel integrated and trans-disciplinary approach, across the three diverse case studies, has been investigated by answering to the RQ 4: *"What are the empirical outcomes of operationalising early-stage regional multi-stakeholder inclusion on the conceptual design of bio-based value chains across three different case study locations?"* to decipher some of the, if any, common characteristics, purposes, enablers, challenges, and implementation pathways for the commercialisation of bioeconomy. The goal of the investigation is to determine some generalisations, in terms of global and regional levels, for streamlining global efforts in terms of academic, industrial, and institutional frameworks to facilitate transitions to the bioeconomy. To determine the general characteristics, the technical phase of the

VSD approach, i.e., the co-design of design alternatives and evaluation, was the focus of the investigation. The results from stakeholder interviews and the multistakeholder workshops, which include the roadmaps for implementing a commercial-scale biohub in the case study location, were analysed from the perspective of technical design characteristics and the potential impact of the biohubs. From a technical dimension, in general, the designers of biomass value chains should aim at maximum value addition at or near the biomass site. In addition to improving the economic performance by reducing transportation costs, valorising biomass near the biomass producing regions promotes retention of elements in the regional nutrient cycle, which eliminates the need for additional (anthropogenic) activities for production, transportation, and recovery of valuable resources. Although the principles of cascading improve the economies of scope, the value chains should have a marketable anchor product to make a business case. The overall sustainability performance improves with the integration of upstream and downstream activities with existing infrastructures, thereby enabling brownfield biorefineries (such as integrated biorefineries shown in Chapters 2 and 3) instead of resource-intensive greenfield biorefineries (stand-alone biorefineries shown in Chapter 3) projects. Value chain integration also offers a path of fewer modifications that are often attractive to the value chain actors. For instance, the petrochemical refineries can reduce their emissions by coprocessing biocrude instead of installing new infrastructure for carbon capture, utilisation and sequestration systems. Likewise, using the farmer's existing mode of crop transportation can avoid the need for implementing a new transportation fleet for biomass transportation from farms to biorefineries. From an institutional framework, efforts should be developed to promote knowledge and technology transfer along with resources for capacity building, between the global north (technology leaders) and the global south (biomass leaders), to hasten the fossil-free transition. Based on stakeholder interviews, it is deduced that international public-private partnerships bring diverse, needed expertise for value chain development and implementation in society. The international partnerships will prevent the abrupt transfer or "looting" of biomass resources resembling neo-colonisation.

Although the general aspects can be replicated globally, the contextual understanding of biomass production is needed for identifying the purpose of biohubs. The biohub's purpose is found to be context-specific (such as strengthening the existing agricultural sector in Colombia and Spain, energy and material security in Namibia, and local SDG targets in Spain, Colombia, and Namibia). As prevailing sustainability issues are context-specific, the (qualitative and quantitative) key performance indicators, in addition to standard global indicators, included in the sustainability evaluation framework should be context-specific. Due to differences in the importance of the multiple aspects of sustainable development across the globe, the performance indicators should be ranked and weighed by the local stakeholders. In addition to identifying threats and opportunities, the combination of technical and non-technical aspects while co-designing biohubs through a multiactor approach also identifies the opportunity conflicts and trade-offs amongst the different dimensions of sustainability at a very early stage. This provides both space and time for decision-making by stakeholders for better resolution.

From a designers' perspective, especially implementing the novel early stage inclusion based design approach as a chemical or process engineer, the design approach was greatly influenced, more often for the better. The novel co-design approach identified potential showstoppers and opportunities at the design stage, such as no cascading in Namibia due to prior experience, avoiding controversial feedstocks such as Palm oil due to the strong values of direct stakeholders of the value chain, and choice to benefit from the infrastructure of olive mills to mobilise crude olive oil in Spain. Understanding stakeholder's perspective, values, capabilities, and local contextual knowledge, aided the design approach to concretely select design variables, which are otherwise "assumed" based on literature data followed by various risk assessment techniques on the selection choices such as sensitivity analysis or uncertainty analysis, thereby reducing the resources consumed while improving the resolution of the conceptual process and value chain designs. In future, the prospect of effectively combining process systems engineering with social sciences should be encouraged to improve the implementation of ovel technologies into the society.

The overall conclusion, as a response to the main problem statement, is to co-design biobased value chains for local needs, by prioritising contextual prevailing societal problems (in contrast to technological advancement or commercial needs) for achieving local SDG targets, which further contributes to global climate health. Thereby, implementing technologies in a suitable and required ecosystem as opposed to the conventional approach of modifying societal arrangements, in the name of commercialisation, urbanisation, globalisation, or modernisation, for economic growth. The biohub concept is a technology "plug-in" model that enables biomass mobilisation for global needs while offering local development. Biohubs have the potential to transform the current landscape of linear, large-scale, global, fossil-based, market economy focused on economic development into a circular, multiple small-scale, regional, bio-based, supply economy with the aim of sustainable, just and responsible development. With an inclusive design, especially considering the welfare of upstream stakeholders (biomass producers) through local development, biohubs offer a pathway for a socially just transition to the bioeconomy.

## 5.2 LIMITATIONS OF THE RESEARCH

The present study acknowledges the influence of limited scope due to practical reasons (such as language barriers and the COVID-19 pandemic during case study selection) and is based on the assumptions made (such as the use of different experimental data for HTL process from the literature for specific feedstock-location combinations) during the investigation. Beyond the limitations due to the technological maturity of HTL, the investigation acknowledges the following limitations,

1. Although the case study selection methodology was aimed at standardisation of protocol to identify the most promising case studies, the current selection was largely limited by travel restrictions due to the COVID-19 pandemic and language barriers of the multidisciplinary team to conduct efficient stakeholder engagement. For example, countries like Brazil, India, and Vietnam showed immense potential but were not able to be shortlisted. Therefore, future works in these case study locations are highly recommended due to the immense availability of underutilised or mismanaged residues that can be used for local development. Proof of concept in Brazil and India can attract global attention due to their current participation in the "Global Biofuel Alliance" [17].
2. During the field visits in the case study locations, the stakeholder identification was limited to the networking capacity of the local collaborator. This led to the exclusion of certain stakeholder groups with a potential role for biohub implementation. In certain cases, such as Namibia and Colombia, stakeholders such as the petrochemical sector were not included, who could play a potential positive role in the development of the biohubs. Similarly, the port authorities were excluded in the cases of Namibia and Colombia. Therefore, incorporation of the perspectives from "missed" stakeholder groups should be made to improve the reliability of the design scenarios.
3. Due to COVID-19 and the delay due to real-life logistical hurdles for procuring feedstock from the case study locations, the data used for process simulations, in Aspen Plus, to obtain mass and energy balances, were obtained from the literature for the same feedstock from different locations (for COP, coffee pulp, and acacia) or different feedstock with similar biochemical composition (for olive pruning). Therefore, fine-tuning for simulation models with experimental data performed for context-specific feedstock is crucial to validate the process design. Also, the process models need to be optimised for process conditions yielding maximum biofuel quantity with the implementation of robust kinetic models.
4. In terms of sustainability assessments, performing macro-socio-economic analysis for the different design scenarios in the case study regions can further provide a

holistic understanding of the impact of design decisions made by incorporating local stakeholders' perspectives.

5. Due to the limited period of the project, the learnings were not validated with the local stakeholders, and to perform the trade-off analysis or multi-criteria decision analysis, local stakeholder inputs in weighing and ranking the relevant sustainability indicators are needed.
6. Finally, the preselection of the end-user segment and the biomass conversion technology aided the research approach, including the case study selection. However, the investigation lacks a comparative analysis when different bioproduct value chains or biomass conversion technologies are to be selected. For instance, the ThermoCatalytic Reforming (TCR) process, an intermediate pyrolysis technique, could be more suitable for processing dry biomass feedstocks, such as olive pruning or acacia bush, in a water-scarce region like Andalusia or Namibia, in comparison with HTL.

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*It is the small everyday deeds of ordinary folk that keep the darkness at bay. Small acts of kindness and love."* **- J.R.R. Tolkien**


6

# 6

# Outlook

## 6.1 RECOMMENDATIONS FOR FUTURE RESEARCH

From a technology perspective, there is significant room for development concerning the process performance of the novel hydrothermal liquefaction (HTL) technology. For instance, the aqueous phase containing organics can be valorised, using biochemical conversion techniques, to produce biochemicals. Furthermore, the integration of Carbon Capture, Utilisation, and Sequestration (CCUS) and electrification strategies with the HTL process can significantly improve the environmental impacts of the HTL biocrudes. From a system's perspective, future works should aim at normalising the practice of embedding social aspects within the technical design of biobased value chains, a socio-technical system. With various developments, in every field, every day, everywhere, there is a huge potential to further strengthen the investigation performed in this thesis by addressing its limitations and further broadening the scope of the work at micro-, meso-, and macro-levels of social integration with technological solutions for deploying bioeconomy. Some of the potential follow-ups to strengthen the work performed are mentioned below as research questions,

1) What are the integral sustainability and circularity impacts of crude olive pomace-based biohubs for marine biofuel production?
   a) This research question should be aimed at incorporating local stakeholders' input into the selection and weightage of ranking the sustainability criteria. The sustainability impact (opportunities, conflicts, and trade-offs) of various design alternatives to promote inclusive conceptual design should be investigated to identify the benefits of early-stage consideration for non-technological values.
   b) Furthermore, the principle of circularity should be combined with sustainability to assess the potential of the bioeconomy and ensure maximum positive impact (or reduction of negative impacts) through conceptual design.
2) From a systems perspective and supply chain aspect, what are the advantages and disadvantages of implementing the hydrothermal liquefaction technology (HTL) in comparison with Pyrolysis for feedstocks with less moisture content (less than 20%) in a water-scarce region, such as in Namibia?
   a) Although from a quality perspective, hydrothermal liquefaction is proven to produce higher quality biocrude in comparison with Fast Pyrolysis, there is still a lack of understanding of the comparative analysis for their performance across the entire life cycle. Therefore, this research question can address whether novel technologies like HTL are indeed suitable and can perform better when the contextual knowledge (such as a water-scarce region or a lack of well-developed technological infrastructure) is combined in the analysis.

3) How resilient is the context-specific capability sensitive biohub approach and case study selection methodology when a fine chemical or speciality chemical is considered as an end-product, such as food products or nutraceuticals?
a) The robustness of the investigation methodology and trans-disciplinary approach is yet to be verified; furthermore, the compatibility of the proposed framework with other concepts under the theme of responsible research and innovation (RRI), such as Safe and Sustainable by Design (SSbD) will open the new avenues for research and development.

Based on the learnings from the approach followed and the novelty of the research design in this thesis, I further propose a trans-disciplinary framework, Sustainable and Inclusive by Design (SIbD), in addition to the well-established frameworks such as SSbD under the RRI theme, as a research methodology for designing a socially responsible and just biobased value chain.

## 6.2 SUSTAINABLE AND INCLUSIVE BY DESIGN (SIBD) - A TRANS-DISCIPLINARY FRAMEWORK FOR A SOCIALLY JUST AND SUSTAINABLE DEVELOPMENT OF BIO-BASED VALUE CHAINS

From the learnings obtained from this investigation, the following framework is proposed for developing inclusive value chains for the bioeconomy for sustainable development across the globe. This framework is designed based on biobased value chains; however, the author foresees no reason not to apply the same to other socio-technical systems where social values can be integrated into the technological design solutions for the welfare of society.

Unlike the conventional approach, this framework ventures beyond the borders of developing technological solutions to address the environmental issues of global climate change in a particular end sector. With this framework, the aim is to

a) Combine all pillars, namely technological, economic, environmental, social, and institutional aspects, of sustainability from diverse disciplines (engineering and social sciences),
b) Bridge the existing academia-industry-society gap by early-stage inclusion of various stakeholders (industries, academia, government, NGOs, farmers, etc.) during conceptual design,
c) Develop a context-specific inclusive design by considering local stakeholders' values and capacities for participation,

d) Identify potential, technical and non-technical opportunities and threats during the early stage of project development to enable smooth real-life implementation to minimise resources and efforts to achieve a sustainable future
e) Maximise the potential positive impact for the holistic fossil-free transition of various sectors while addressing the needs and necessities of relevant stakeholders, and
f) De-risk and streamline the global efforts for minimising scaling and deployment time needed for technological solutions, such as commercial bio-based value chains for the global bioeconomy

In Figure 6.1, the framework is presented specifically to develop value chains for marine biofuels as an example; however, the steps can be extrapolated to other biobased value chains for bioproducts.

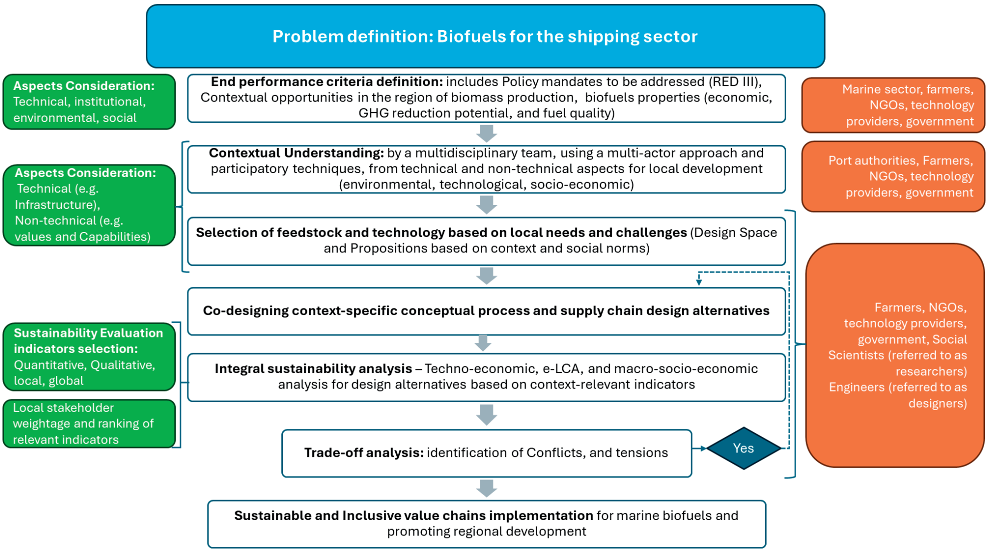


Figure 6.1: Trans-disciplinary approach involving diverse stakeholders and aspects of sustainability to co-design socially just biohubs using a multiactor approach. The orange boxes indicate the stakeholder groups involved in the decision-making process at the design stage. The green boxes indicate the different aspects of the decision variable considered at the design stage.

- **Problem definition:** Similar to any traditional conceptual design project, problem definition is the first part of the SIbD framework. This entails defining primary goals and the scope of the project (usually in alignment with the funding calls or societal needs), along with identifying the stakeholders and project partners to be included in the process. Some of the current avenues for biobased value chains relate to the Water-Energy-Food (WEF) nexus, transportation fuels, and bioplastics. In the SIbD framework, the project partners should be as diverse as possible, ideally comprising public-private consortia with academia and industry partners, with at least one partner representing each stakeholder group along the value chain. For the design group, a collaborative multi-disciplinary team of engineer(s) with a background in sustainable process and value chain design, along with social scientist(s) knowledgeable in technology ethics and anthropology, is needed to effectively engage diverse stakeholders and integrate relevant non-technical aspects into the technical design of the value chains. At this stage, including diverse stakeholder groups broadens the design scope beyond the primary goal, which is essential for a holistic perspective of the system design.
- **End performance criteria definition:** The second step of the SIbD makes it unique as it focuses on "start with the end impact". In this step, various aspects of sustainability (technical, social, environmental, and institutional) and criteria for real-life implementation (based on the previous relevant real-world practical experience of project developers) are considered. Initially, from a technical perspective, the definition of quality and quantity of the target product is very important, which can be obtained from various standards (such as ASTM for biofuels and the United States Food and Drug Administration [FDA] for food and nutraceutical bioproducts) and market analysis, respectively. Secondly, before conventional feedstock selection, for global value chains such as marine biofuels, the targeted end-market location (for example, Europe in this PhD work) is to be selected. The selection of the end-market region not only determines the policy mandates (such as RED III) that are to be adhered to while producing the bio-based alternatives, but also in identifying the promising feedstocks near the end-market that have the potential for market penetration. These policy mandates establish threshold criteria for feedstocks or end-products, predominantly in terms of environmental and social aspects. For instance, the market share for biofuels produced from the feedstocks is decided on its classification under Annex IX, and can be introduced into the market with relative ease. Thirdly, concerning the real-life implementation of biobased value chains, practical insights from previous research and project development, along with current geo-political aspects, are to be understood to productively build upon previous learning and also to identify relevant design scenarios for politically tension-free project development. For instance, the industry partners can provide valuable practical insights regarding the potential No-Go's for certain technologies

or feedstocks (for example, avoiding feedstocks with sustainability concerns, such as edible crops, or feedstocks with potential competition, such as sugarcane bagasse for marine biofuel production). The insights furthermore include the end-users' acceptance, reluctance, or challenges with introducing certain biobased products in the current market, highlighting the need to address the relevant knowledge gaps in the project for successful implementation of the project, thereby bridging academia and industry. The convergent phase of the case-study selection approach mentioned in Chapter 1 can support this step. The uniqueness of the SIbD framework is the shift from a "feedstock to end-user market with better economic and environmental performance" approach to an "end-segment market satisfaction with valorising feedstocks that can bring necessary holistic development in the region of biomass production" approach.

- **Contextual Understanding:** The third step is a logical follow-up of the second, requiring a collaborative approach of the multi-disciplinary team to understand the context prevailing in the country of interest. This step is supported by the second half of the convergent phase of the case study selection and the trans-disciplinary approach followed, including field visits to the case study locations discussed in Chapter 1. Initially, a national-level contextual knowledge, in terms of various technical and non-technical aspects, is gathered through literature studies and interviews with potential collaborators in the region of interest. The learnings are verified and further enhanced during the field visit. The skill sets of the multidisciplinary team enable them to actively engage potential diverse direct and indirect value chain actors and to effectively elucidate technical and social values through participatory techniques. This leads to the definition of biohubs' characteristics, purpose, and enablers as mentioned in Chapter 4.
- **Selection of feedstock and technology based on local needs:** Based on the elicited social and technical values during the field visit, design space and design propositions are derived for the conceptual design of the process and value chain. Furthermore, unlike the conventional approach in which (novel) technology is pre-selected or the principles of cascading are applied, in the SIbD framework, the feedstock and technology are chosen based on the prevailing context at the biomass producing region (such as feedstocks that are under-utilised or mismanaged, and technology producing byproducts for local needs or based on its potential to integrate with existing infrastructure). In case of a particular chosen technology, the choice of feedstocks and process design can be modified to meet the local demands (such as water recycling or byproducts valorisation in the HTL systems in Chapters 2 and 3).
- **Co-designing context-specific conceptual process and supply chain design alternatives:** Process and value chain designs are identified as a means of inclusion, as they involve decision making at various nodes and levels (strategic, tactical, and operational) of bio-based value chains in the form of design variables. The SIbD

framework implements the multi-actor approach, in the form of a multi-stakeholder workshop at the end of the field visit to co-design value chain alternatives. The social arrangements are incorporated into the technical concept development through design propositions over the design aspects of a BBVCs. Various design alternatives are developed, representing diverse scenarios to accommodate the varied or conflicting social norms, thereby visualising the extreme possible alternatives. The different designs are evaluated for their sustainability for further development. These steps are highlighted in Chapters 2 and 3. In addition, for more accurate mass and energy balances (in extension conceptual design), process simulation should be based on experimental data obtained for a specific chosen feedstock-technology-location combination, thereby minimising or eliminating the assumptions and uncertainties in the design process.

- **Integral Sustainability analysis:** After co-designing value chain alternatives, they are investigated for their sustainability performance through integral sustainability analysis (ISA) using key performance indicators (KPIs). ISA consists of three phases, namely, KPI selection, KPI ranking, and KPI evaluation. Unlike the conventional approach, where indicators are selected based on scientific reports, in the first phase, the technical, economic, environmental, and social KPIs are identified based on the literature studies and stakeholder engagement, with the aim of context relevancy. Based on the nature of KPIs, they are classified into global (which are valid across all BBVCs irrespective of location, such as minimum fuel selling price), local (which are relevant to the local region based on contexts, such as impact on biodiversity), qualitative, and quantitative. The chosen indicators allow the comparison of context-specific design alternatives to other similar global value chains, but simultaneously evaluate them for their suitability in the region of interest with local indicators. Moreover, the social values, or indicators, which are most often qualitative, are integrated with technical quantitative indicators to make robust assessments. Moreover, this makes the sustainability assessment framework more suitable for decision makers across the globe to gather realistic, relevant data for developing implementation strategies. With the local stakeholders' input, the context-specific selection of indicators is weighed and ranked based on the impact of the BBVCs in the local region of implementation. In the final phase, the design alternatives are evaluated through technoeconomic assessments (TEA, for technical and economic aspects), environmental and social life cycle assessment (e-/S-LCA, for environmental and social aspects), and macro socio-economic impact analysis ( for socio-economic aspects) to evaluate the chosen KPIs.
- **Trade-off analysis:** The design alternatives are optimised for their performance using robust mathematical modelling techniques such as the multi-objective optimisation technique or the multi-criteria decision analysis based on chosen indicators. The assessment results of design alternatives are compared against each other across

different aspects of sustainability. Uncertainties, risks, and sustainability conflicts and tensions are identified for framing context-related improvement opportunities and strategies for further research. At this stage, the designers organise a multi-stakeholder workshop, involving project partners and local stakeholders, to receive feedback, identification of potential new opportunities, and discuss the impacts of design choices on the sustainability performance to oversee the conflicts and tensions. As an iterative step, design alternatives are modified, if needed, to address the tensions and conflicts.

- **Implementation of sustainable and inclusive value chains:** Upon identification of a suitable design configuration from the previous steps, decisions are made for developing biobased value chains in the case study location. Based on the rigorous nature and promising nature of the analysis, the follow-up decision can vary from an iterative step for more detailed, intricate design and evaluation up to piloting or demonstration activities of the BBVCs, including business case development for commercial purposes. In this PhD work, the follow-up activities are being performed in terms of consortia development to obtain public funding for piloting projects (in Spain) and business case development in collaboration with technology developers and investors for a demonstration-scale project (in Namibia). Conceptually, the implementation phase can also be used as a platform to integrate other novel approaches (such as safe and sustainable by design, or CCUS for capturing biogenic $CO_2$) and perform feasibility studies for other novel technologies.

As the form and severity of the impacts due to global phenomena, such as climate change, are sensitive to the region, the approaches for climate change mitigation and adaptation should also be tailored to the context prevailing in the region, along with social inclusion, especially for socio-technical systems. Therefore, a global, unified, trans-disciplinary effort, promoting SDG 12 and SDG 17, is a prerequisite for the holistic understanding and solving of the “borderless” issues such as global warming.

## 6.3 PROJECT FOLLOW-UP INITIATIVE: TU DELFT IMPACT BOOSTER FUND

To address one of the previously mentioned future recommendations, the author was granted an impact booster fund from the TU Delft Global Initiative of 5000 Euros. The fund was used to conduct experimental trials with the Acacia bush in Namibia via Fraunhofer's ThermoCatalytic Reforming (TCR) technology, with a TRL 7, in collaboration with a Dutch start-up. The results of this prefeasibility study include a full analysis of the elemental composition and energy of raw materials and products (biooil, biochar, and biogas). Based on mass and energy balances, business models will be developed by partners to understand the economic feasibility. The author, along with the team, will form a proposal for a pilot project by deploying a multidisciplinary consortium with a public-private partnership.


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# 7

# Appendices

# 7.1. APPENDIX I

The link to the Master Excel sheet can be found in
https://surfdrive.surf.nl/files/index.php/s/sGXEDUAZ0R1wvqp/download

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# 7.2. APPENDIX A

## 7.2.1. Raw material availability

### *7.2.1.1. List of Primary mills in Jaén. Source: Field visit*

Table 7.1: List of all primary mills in the province of Jaén along with their annual olive processing capacity. Source: Field visit

| PROVINCIA | MUNICIPIO | NOMBRE_ALM | Hojas (Ton) |
|---|---|---|---|
| JAÉN | ESCAÑUELA | AZAHAROLIVA, S.L. | 162 |
| JAÉN | CARBONEROS | COOPERATIVA SAN EULOGIO | 237 |
| JAÉN | CAZALILLA | S.C.A.SAN BLAS | 237 |
| JAÉN | CAROLINA (LA) | SCA OLIV. SAN ANTONIO | 241 |
| JAÉN | GUARROMAN | SATURNINO ARIAS RIVERO | 258 |
| JAÉN | GENAVE | SIERRA DE GENAVE,S.C.A. | 268 |
| JAÉN | ALBANCHEZ DE MAGINA | ALMAZARA EL PICON, S.L. | 310 |
| JAÉN | ORCERA | POTOSI 10, S.A. | 318 |
| JAÉN | JAMILENA | S.C.A- NTRA. SRA. DEL ROSARIO | 319 |
| JAÉN | SILES | S.C.A.SAN ISIDRO | 320 |
| JAÉN | BELMEZ DE LA MORALEDA | OLEO MAGINA SL | 356 |
| JAÉN | SEGURA DE LA SIERRA | S.C.A.NTRA.SRA.DEL PILAR | 367 |
| JAÉN | LUPION | S.L.GARCIA LA MONEDA | 371 |
| JAÉN | ESPELUY | ACEITES LAS ALMENAS, S.L. | 379 |
| JAÉN | BAÑOS DE LA ENCINA | S.C.A.NTRO PADRE JESUS DEL LLANO | 416 |
| JAÉN | FRAILES | JOSE Y RAFAEL SERRANO LOPEZ, C.B. | 437 |
| JAÉN | CAMPILLO DE ARENAS | SAT. SANTA LUCIA | 443 |
| JAÉN | CARCHELES | S.C.A.SAN ANTONIO ABAD | 445 |
| JAÉN | TORRES DE ALBANCHEZ | S.A.ACEITES EL CARRASCAL | 457 |
| JAÉN | BEGIJAR | S.L.OLEICOLA SAN FRANCISCO | 466 |
| JAÉN | ARQUILLOS | S.A.ACEITES EL CONDADO | 490 |
| JAÉN | GUARDIA DE JAÉN (LA) | AIRLUX S.L. | 492 |
| JAÉN | MENGIBAR | INSTTTUTO ANDALUZ DE INVESTIGACIÓN Y FOR | 496 |
| JAÉN | HUESA | S.C.A.NTRA SRA DE LA CABEZA | 501 |
| JAÉN | MARMOLEJO | ACEITUNERA SANTA MARIA DE MARMOLEJO, S.L | 511 |
| JAÉN | SORIHUELA DEL GUADALIMAR | S.C.A.SANTA AGUEDA | 526 |
| JAÉN | CHICLANA DE SEGURA | S.C.A.SAN PABLO | 542 |

Table 7.1: List of all primary mills in the province of Jaén along with their annual olive processing capacity. Source: Field visit (*continued*)

| PROVINCIA | MUNICIPIO | NOMBRE_ALM | Hojas (Ton) |
|---|---|---|---|
| JAÉN | RUS | S.C.A.NTRA.SRA.ROSARIO Y SAN | 554 |
| JAÉN | FUERTE DEL REY | S.C.A.NTRA.SRA.DEL ROSARIO | 570 |
| JAÉN | PUENTE DE GENAVE | S.C.A.SAN JUAN BAUTISTA | 575 |
| JAÉN | TORREBLASCOPEDRO | S.C.A.NTRA.SRA.DEL CAMPILLO | 581 |
| JAÉN | HIGUERA DE CALATRAVA | ACEITES CAMARA Y LUQUE, S.L. | 586 |
| JAÉN | IZNATORAF | S.C.A.AGRARIA SAN ISIDRO | 614 |
| JAÉN | SANTIAGO DE CALA-TRAVA | S.C.A.SANTISUR | 673 |
| JAÉN | PUERTA DE SEGURA (LA) | MOLINO DE SEGURA | 707 |
| JAÉN | CABRA DEL SANTO CRISTO | S.C.A.LA UNION | 724 |
| JAÉN | NOALEJO | S,COOP.AND.HOYA DEL SALOBRAL | 763 |
| JAÉN | LAHIGUERA | S.C.A.SANTA CLARA | 792 |
| JAÉN | CAMBIL | JOSE JAVIER RUIZ MILLAN | 831 |
| JAÉN | JIMENA | HERMANOS TORRES GONZALEZ,C.B. | 840 |
| JAÉN | VALDEPEÑAS DE JAÉN | OLEICOLA VALDEPEÑAS DE JAÉN S.C.A. | 843 |
| JAÉN | JABALQUINTO | S.C.A.SANTA LUCIA | 850 |
| JAÉN | CHILLUEVAR | S.C.A. LA UNION DE CHILLUEVAR | 856 |
| JAÉN | MONTIZON | SAN JUAN BAUTISTA, S.C.A | 858 |
| JAÉN | VILCHES | S.L.ACEITES VILCHES | 860 |
| JAÉN | SANTO TOME | S.C.A.STO TOMAS APOSTOL | 884 |
| JAÉN | LINARES | HACIENDA OLIVAR DE SANTA MARIA, S. A. | 906 |
| JAÉN | BEDMAR Y GARCIEZ | OLEO VIANA,S.L. | 925 |
| JAÉN | ANDUJAR | S.C.A.SAN RAFAEL | 984 |
| JAÉN | LOPERA | S.C.A .DESARROLLO LOPERANO | 1012 |
| JAÉN | TORRES | S.C.A.STA ISABEL | 1024 |
| JAÉN | CANENA | S.C.A. SAN ISIDRO LABRADOR | 1103 |
| JAÉN | SANTISTEBAN DEL PUERTO | OLIVARERA DEL CONDADO, S.A. | 1122 |
| JAÉN | ARJONILLA | C.B.MIGUEL GUZMAN AVILES,HNOS | 1196 |
| JAÉN | POZO ALCON | ALMAZARA LA ANDALUZA S.L.U. | 1274 |
| JAÉN | JAÉN | DEL AGUILA GOICOECHEA, ANTO-NIO | 1383 |
| JAÉN | FUENSANTA DE MARTOS | GONZALEZ E HIJOS C.B. | 1384 |
| JAÉN | SABIOTE | S.C.A.VIRGEN DE LA ASUNCION | 1417 |
| JAÉN | HUELMA | THUELMA, S.L. | 1487 |
| JAÉN | VILLARES (LOS) | ALMAZARA JIMENEZ S.L. | 1523 |

Table 7.1: List of all primary mills in the province of Jaén along with their annual olive processing capacity. Source: Field visit (*continued*)

| PROVINCIA | MUNICIPIO | NOMBRE_ALM | Hojas (Ton) |
|---|---|---|---|
| JAÉN | CASTILLO DE LOCUBIN | ACEITES SAN AGUSTIN,S.L. | 1639 |
| JAÉN | NAVAS DE SAN JUAN | S.C.A FUENTE DEL ROSAL | 1705 |
| JAÉN | PEGALAJAR | S.L. AGROPECUARIA EL PUERTO | 1748 |
| JAÉN | IBROS | S.C.A.LA REMEDIADORA | 1784 |
| JAÉN | CASTELLAR | ALMAZARA DEL OLIVAR S.L. | 1926 |
| JAÉN | TORREPEROGIL | ACEITES ZARATE, S.A. | 1936 |
| JAÉN | QUESADA | EXPLT. AGRO. TRAME S.L. | 2009 |
| JAÉN | JODAR | S.C.A.NTRA.SRA.DEL PILAR | 2043 |
| JAÉN | BAILEN | SL ALMAZARA SAN PABLO | 2080 |
| JAÉN | VILLATORRES | FRANCISCO RODRIGUEZ MARQUEZ | 2216 |
| JAÉN | VILLANUEVA DE LA REINA | S.C.A. ACEITES VEGA ESPEJO | 2441 |
| JAÉN | BEAS DE SEGURA | S.C.A.SAN ANTON | 2492 |
| JAÉN | CAZORLA | LA ALMEDINA DE CAZORLA | 2599 |
| JAÉN | TORRE DEL CAMPO | ACEITES MORAL,S.L. | 2602 |
| JAÉN | ARJONA | Mª JOSE CONTRERAS GOMEZ DE LAS CORTINAS | 2774 |
| JAÉN | PEAL DE BECERRO | S.L.ACEITES TOYA | 2790 |
| JAÉN | PORCUNA | S.C.A.AGRARIA DE PORCUNA | 3127 |
| JAÉN | TORREDONJIMENO | S.L. ALMAZARA ACAPULCO | 3421 |
| JAÉN | MARTOS | PYDASA | 3538 |
| JAÉN | MANCHA REAL | SAT NTRA SRA DE LA ESPERANZA | 3593 |
| JAÉN | CAMBIL | S.C.A. UNIÓN OLEÍCOLA CAMBIL | 3831 |
| JAÉN | ALCAUDETE | OLEICOLA SABARIEGO,S.L. | 3839 |
| JAÉN | VILLANUEVA DEL ARZOBISPO | S.C.A.LA VERA CRUZ | 3998 |
| JAÉN | ALCALA LA REAL | CUSTODIO SERRANO RAMOS | 4538 |
| JAÉN | UBEDA | S.L. TRUJAL DE LA LOMA | 5210 |
| JAÉN | BAEZA | S.L.FABRICA DE ACEITE VIRGEN DE LA SALUD | 5269 |
| JAÉN | VILLACARRILLO | AREVALO DEL MORAL S.L. | 6025 |

#### *7.2.1.2. List of secondary mills in Jaén. Source: Field visit*

Table 7.2: List of all secondary mills in the province of Jaén. Source: Field visit

| Name | Location | Raft Capacity (tons) |
|---|---|---|
| Aceites del sur - coosur SA | Baeza | 150000 |
| Oleicola Jaén S.A. | Baeza | 50000 |
| Bioland | Carolina (LA) | 125000 |
| Oleocastellar S.A. | Castellar | 250000 |
| Ecologia del olivar S.L. | Jabalquinto | 350000 |
| Daniel espuny S.A. | Linares | 50000 |
| Compania orujera de linares S.A. | Linares | 175000 |
| Oleicola tejar S.C.A. | Mancha real | 75000 |
| Ecologia la marca S.A. | Martos | 100000 |
| Aceites Aseal S.L. | Navas de San Juan | 50000 |
| El Puente, Aceites y subproductos, S.L | Puente de genave | 200000 |
| San Miguel Arcangel, S.A. | Villanueva del arzobispo | 500000 |
| | **Total** | **2075000** |

### 7.2.2. Raw material characteristics

#### *7.2.2.1. Proximate analysis of crude olive pomace used in experiments obtained from a field visit in Jaén.*

Table 7.3: Proximate analysis of crude olive pomace (in wt.%). (Source: [1])

| | |
|---|---|
| Volatile Matter | 24.4% |
| Fixed carbon | 14.8% |
| Moisture | 57.2% |
| Ash | 3.6% |
| HHV (MJ/kg) | 18.6 |

#### *7.2.2.2. Ultimate analysis of crude olive pomace used in experiments obtained from the field visit in Jaén.*

Table 7.4: Ultimate Analysis of crude olive pomace (in wt.%). (Source: [1])

| | |
|---|---|
| C | 50.0% |
| H | 6.5% |
| N | 1.5% |
| S | 0.0% |
| O | 63.9% |

### 7.2.3. Product Composition

#### *7.2.3.1. HTL off-gas composition obtained from literature*

Table 7.5: HTL off gas composition (Source: [2])

| | |
|---|---|
| $CO_2$ | 90.2 vol.% |
| $H_2$ | 0.9 vol.% |
| $CH_4$ | 3.0 vol.% |
| $C_2H_6$ | 2.5 vol.% |
| $C_3H_8$ | 1.9 vol.% |
| $C_4H_{10}$ | 1.5 vol.% |

### 7.2.4. HTL system

#### *7.2.4.1. Chemical composition of bio-crude.*

Table 7.6: Composition of HTL bio-crude from crude olive pomace (adapted from [3])

| **Name of compound** | **Molecular Formula** | **Relative Area, %** |
|---|---|---|
| Cyclopentanone | C5H8O | 0.88 |
| 2-Cyclopenten-1-one | C5H6O | 2.19 |
| 2-Methyl-2-cyclopenten-1-one | C6H8O | 4.33 |
| 1-(2-Furanyl)ethanone | C6H6O2 | 0.92 |
| γ-Butyrolactone | C4H6O2 | 1.10 |
| 2,5-Hexanedione | C6H10O2 | 1.39 |
| 3-Methyl-2-cyclopenten-1-one | C6H8O | 1.75 |
| 3,4-Dimethyl-2-cyclopenten-1-one | C7H10O | 0.77 |
| 2,3-Dimethyl-2-cyclopenten-1-one | C7H10O | 2.58 |

Table 7.6: Composition of HTL bio-crude from crude olive pomace (adapted from [3]) (*continued*)

| **Name of compound** | **Molecular Formula** | **Relative Area, %** |
|---|---|---|
| 3-Methyl-1,2-cyclopentanedione | C6H8O2 | 2.94 |
| 3,4-Dimethyl-2-hydroxycyclopent-2-en-1-one | C7H10O2 | 0.62 |
| 1-(4-Hydroxy-3-methoxyphenyl)ethanone | C9H10O3 | 1.48 |
| 1-(2,4,6-Trihydroxyphenyl)-2-pentanone | C11H14O4 | 1.63 |
| Dihydro-5-tetradecyl-2(3H)furanone | C18H34O2 | 1.97 |
| Phenol | C6H6O | 1.67 |
| 3-Methylphenol | C7H8O | 1.16 |
| 2-Methoxyphenol | C7H8O2 | 20.61 |
| 4-Ethylphenol | C8H10O | 0.62 |
| 2-Methoxy-4-methylphenol | C8H10O2 | 3.27 |
| 1,2-Benzenediol | C6H6O2 | 2.27 |
| 3-Methoxy-1,2-benzenediol | C7H8O3 | 4.60 |
| 3-Methyl-1,2-benzenediol | C7H8O2 | 0.57 |
| 4-Ethyl-2-methoxyphenol | C9H12O2 | 3.90 |
| 4-Methyl-1,2-benzenediol | C7H8O2 | 0.83 |
| 2,6-Dimethoxyphenol | C8H10O3 | 17.25 |
| 2-Methoxy-3-(2-propenyl)phenol | C10H12O2 | 0.97 |
| 2-Methoxy-4-propylphenol | C10H14O2 | 2.34 |
| n-Hexadecanoic acid | C16H32O2 | 0.39 |
| (E)-9-Octadecenoic acid | C18H34O2 | 0.57 |
| Hexadecanoic acid methyl ester | C17H34O2 | 3.06 |
| 8,11-Octadecadienoic acid methyl ester | C19H34O2 | 0.59 |
| 8-Octadecenoic acid methyl ester | C19H36O2 | 8.02 |
| 11-Octadecenoic acid methyl ester | C19H36O2 | 2.76 |

## 7.2.5. Upgrading and fractionation system

### *7.2.5.1. Chemical reactions in Hydrotreatment.*

Table 7.7: Hydrotreatment reactions in the hydrotreater, Adapted from [4], [5]

| Biocrude components | No: of moles of hydrogen | Biooil components | No: of moles of Water | No: of moles of Methane |
|---|---|---|---|---|
| Cyclopentanone | 5 | Decane | 2 | |
| 2-Cyclopenten-1-one | 4 | Pentane | 2 | |
| 2-Methyl-2-cyclopenten-1-one | | 2-Methyl-2-cyclopenten-1-one | | |
| 1-(2-Furanyl)ethanone | 11 | Dodecane | 4 | |
| γ-Butyrolactone | 4 | Butane | 2 | |
| 2,5-Hexanedione | 4 | Hexane | 2 | |
| 3-Methyl-2-cyclopenten-1-one | 4 | Hexane | 1 | |
| 3,4-Dimethyl-2-cyclopenten-1-one | | 3,4-Dimethyl-2-cyclopenten-1-one | | |
| 2,3-Dimethyl-2-cyclopenten-1-one | | 2,3-Dimethyl-2-cyclopenten-1-one | | |
| 3-Methyl-1,2-cyclopentanedione | 4 | Methyl cyclopentane | 2 | |
| 3,4-Dimethyl-2-hydroxycyclopent-2-en-1-one | 4 | Dimethyl cyclopentane | 2 | |
| 1-(4-Hydroxy-3-methoxyphenyl) ethanone | | 1-(4-Hydroxy-3-methoxyphenyl) ethanone | | |
| 1-(2,4,6-Trihydroxyphenyl)-2-pentanone | | 1-(2,4,6-Trihydroxyphenyl)-2-pentanone | | |
| Dihydro-5-tetradecyl-2(3H)furanone | 3 | Octadecene | 2 | |
| Phenol | | Phenol | | |
| 3-Methylphenol | | 3-Methylphenol | | |
| 2-Methoxyphenol | | 2-Methoxyphenol | | |
| 4-Ethylphenol | | 4-Ethylphenol | | |
| 2-Methoxy-4-methylphenol | | 2-Methoxy-4-methylphenol | | |
| 1,2-Benzenediol | | 1,2-Benzenediol | | |
| 3-Methoxy-1,2-benzenediol | | 3-Methoxy-1,2-benzenediol | | |
| 3-Methyl-1,2-benzenediol | | 3-Methyl-1,2-benzenediol | | |
| 4-Ethyl-2-methoxyphenol | | 4-Ethyl-2-methoxyphenol | | |
| 4-Methyl-1,2-benzenediol | | 4-Methyl-1,2-benzenediol | | |
| 2,6-Dimethoxyphenol | | 2,6-Dimethoxyphenol | | |
| 2-Methoxy-3-(2-propenyl)phenol | 5 | 2-propyl, methoxycyclohaxne | 1 | |
| 2-Methoxy-4-propylphenol | | 2-Methoxy-4-propylphenol | | |
| n-Hexadecanoic acid | | n-Hexadecanoic acid | | |
| (E)-9-Octadecenoic acid | | (E)-9-Octadecenoic acid | | |
| Hexadecanoic acid methyl ester | 4 | Hexadecane | | 2 |

Table 7.7: Hydrotreatment reactions in the hydrotreater, Adapted from [4], [5] (*continued*)

| **Biocrude components** | **No: of moles of hydrogen** | **Biooil components** | **No: of moles of Water** | **No: of moles of Methane** |
|---|---|---|---|---|
| 8,11-Octadecadienoic acid methyl ester | 6 | Octadecane | | 2 |
| 8-Octadecenoic acid methyl ester | 5 | Octadecane | | 2 |
| 11-Octadecenoic acid methyl ester | 5 | Octadecane | | 2 |

## 7.2.6. Case study – field visit participatory techniques

### *7.2.6.1. Protocol of the case study*

*A sample of the interview and workshop materials is shown. The full case study protocol, including workshop outcomes, can be shared upon request.
*Interviews and workshop materials were translated into Spanish

#### *7.2.6.1.1. General interview guide stakeholders.*

| | |
|---|---|
| 1. Introduction | Personal introduction<br>a. Personal introduction, introduction to the organization, to confirm the role<br>b. Current role in the organization and activities involved with<br>Sector introduction<br>a. Explanation of the current system in place<br>b. Purpose behind the current practice<br>c. What are the biggest challenges and issues faced in the current system?<br>d. If improvement can be made, what are the suggested measures or focal points? |
| 2. Sustainability | a. Present and expected challenges regarding sustainability<br>b. Current projects/activities related to improving sustainability (e.g. trainings, certification, organic fertilisers etc.) |
| 3. Impact (goals, challenges, benefits, and harms) of new bio-based supply chain in the region *(show biohub infographic)* | Impact<br>a. Interest to play a role in a new bio-based supply chain?<br>a. Identify their foreseen role in the supply chain and elaborate<br>b. Possible benefits for the organization from the new supply chain<br>c. Reason for participating in a new supply chain<br>d. Why is that important?<br>Hurdles<br>a. What is preventing them currently in doing so (lack of capacity, funding, policies, infrastructure, trade agreements, knowledge, partnership etc.)<br>Harms<br>a. What could threaten the existence/operation of a new bio-based supply chain?<br>b. What are the disruptions that will happen in the sector and for the sectors associated? |

| | |
|---|---|
| 4. Stakeholder analysis (*show power-interest grid)* | a. Which actors do you think should be included in a new bio-based supply chain?<br>b. Which actors are missing in the power-interest grid?<br>c. What do yous think of the positions on the power interest grid? |
| 5. Sector specific questions | |
| 6. Closing | a. Summarize and ask if there is nothing more to say<br>b. Follow-up contact<br>c. Confirm agreements on records, publication<br>d. Willingness to participate in the workshop |

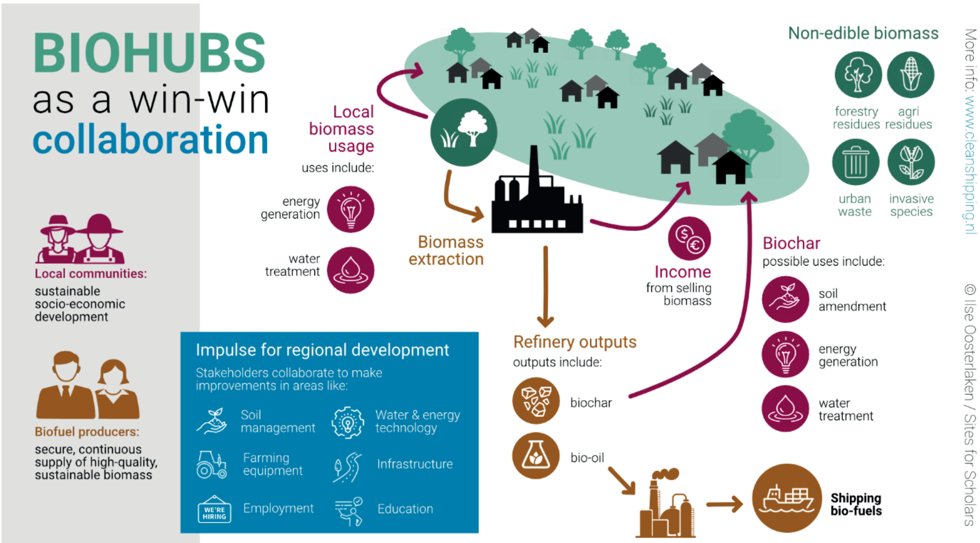


*Figure 7.1: Infographic of a potential Biohub/value chain*

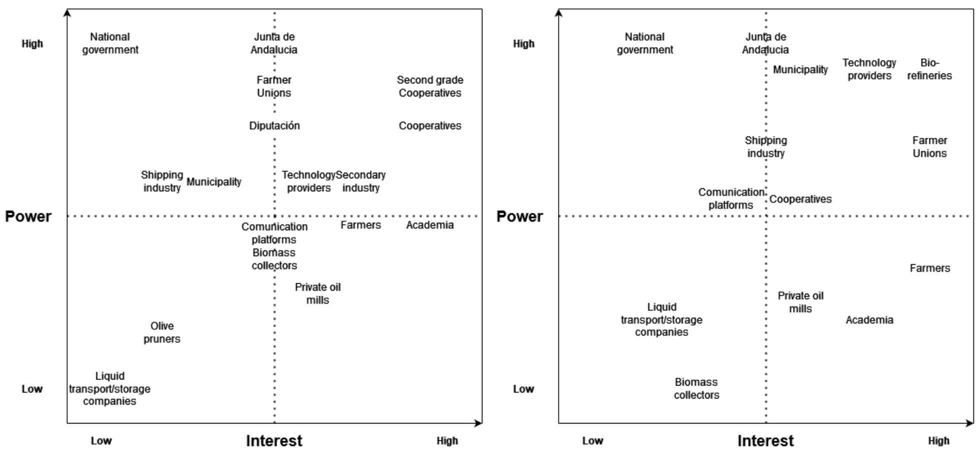


*Figure 7.2: Representation of power- interest grid of potential stakeholders, prior and post feedback from interviewees*

### *7.2.6.2. Interview materials*

## 7.2.7. Workshop Protocol

1. Present general scenarios with design variables and options for the same
2. Split participants in 3 smaller groups, representing a mix of stakeholders

o <u>Break-out session 1</u>:

- Discuss different variables along with their pros and cons for the choices to be made along the value chain of the biofuel system. A representation of the biohub and its elements was shown as depicted in *Figure 7.3*, *Figure 7.4*, and *Figure 7.5* .
- Example of different elements and variables discussed is shown in *Figure 7.5*

o <u>Break-out session 2 –</u>

- Stakeholders were asked to choose options along different technical and non-technical elements and impacts that biohub could create by co creating a design. The poster format used for the same is indicated in *Figure 7.6.*

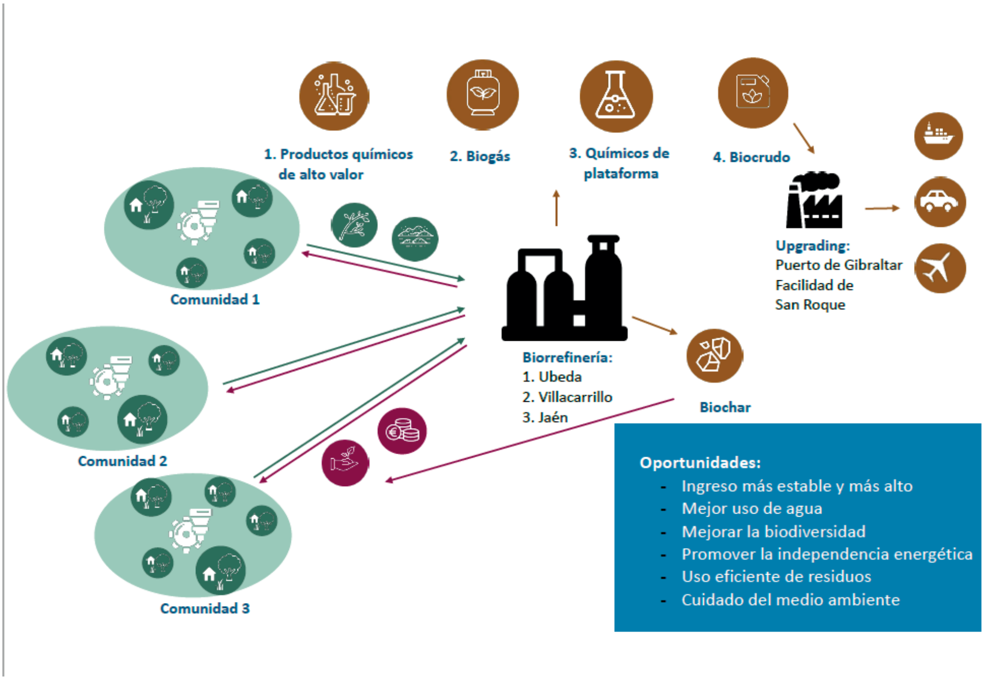


Figure 7.3: Representation of a possible biohub with some variables



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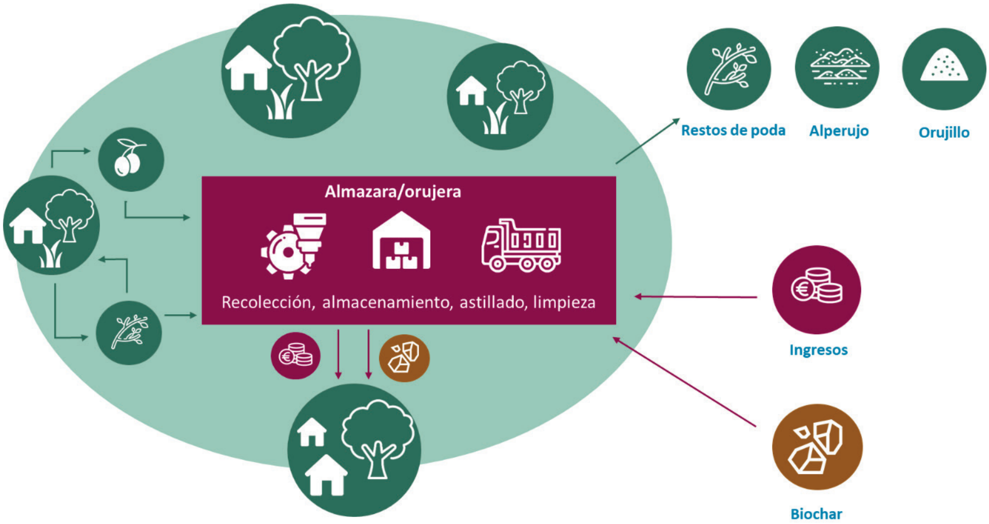


Figure 7.4: A zoomed-in version of one community where primary mills can act as points of collection, processing, and storage of pruning and olives.

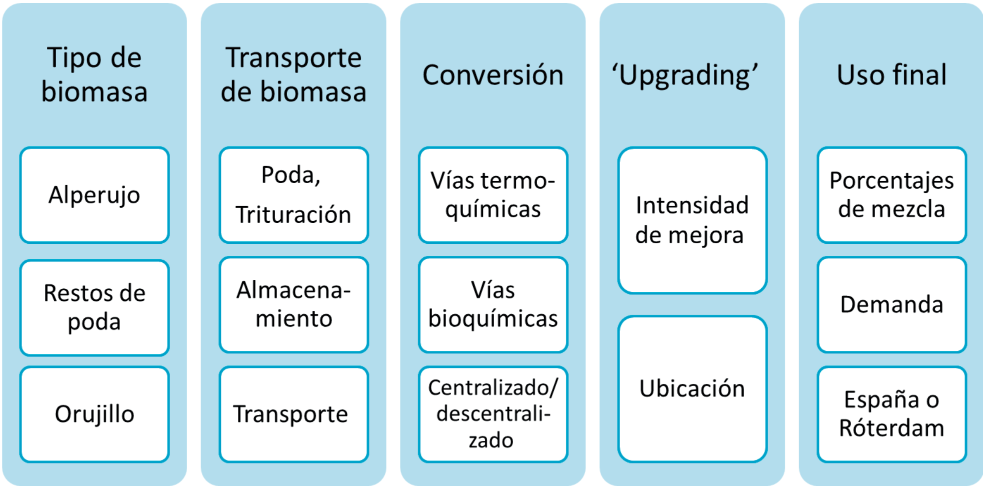


Figure 7.5: Elements and corresponding variables for developing a biofuel value chain in Jaén

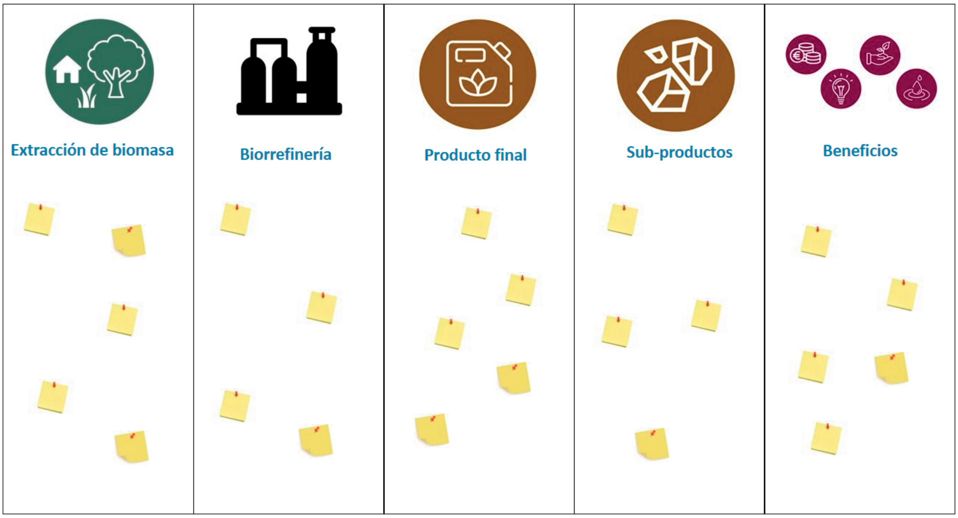


Figure 7.6: Representation of posters used to collect participants' choices (incl. justification) for different technical and non-technical elements and impacts of biohub in Jaén.

## 7.2.8. Economic parameters

### *7.2.8.1. CEPCI values. Source: [7]*

| Month | CEPCI | Month | CEPCI | Month | CEPCI | Month | CEPCI | Year | CEPCI | Year | CEPCI |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 2024 Mar | 800.7 | 2023 May | 808.8 | 2022 Jul | 829.8 | 2021 Sep | 754 | 2018 | 603.1 | 2008 | 575.4 |
| 2024 Feb | 800.0 | 2023 Apr | 803.3 | 2022 Jun | 832.6 | 2021 Aug | 735.2 | 2017 | 567.5 | 2007 | 525.4 |
| 2024 Jan | 795.4 | 2023 Mar | 799.1 | 2022 May | 831.1 | 2021 Jul | 720.2 | 2016 | 541.7 | 2006 | 499.6 |
| 2023 Dec | 789.6 | 2023 Feb | 798 | 2022 Apr | 816.3 | 2021 Jun | 701.4 | 2015 | 556.8 | 2005 | 468.2 |
| 2023 Nov | 789.2 | 2023 Jan | 802.6 | 2022 Mar | 803.6 | 2021 May | 686.7 | 2014 | 576.1 | 2004 | 444.2 |
| 2023 Oct | 790.7 | 2022 Dec | 802.9 | 2022 Feb | 801.3 | 2021 Apr | 677.1 | 2013 | 567.3 | 2003 | 402.0 |
| 2023 Sep | 793.3 | 2022 Nov | 814.6 | 2022 Jan | 797.6 | 2022 | 816.0 | 2012 | 584.6 | 2002 | 395.6 |
| 2023 Aug | 798.7 | 2022 Oct | 816.2 | 2021 Dec | 776.3 | 2021 | 708.8 | 2011 | 585.7 | 2001 | 394.3 |
| 2023 Jul | 798.7 | 2022 Sep | 821.3 | 2021 Nov | 773.1 | 2020 | 596.2 | 2010 | 550.8 | 1957-1959 | 100.0 |
| 2023 Jun | 803.3 | 2022 Aug | 824.5 | 2021 Oct | 761.4 | 2019 | 607.5 | 2009 | 521.9 | | |

### *7.2.8.2. Currency conversion*

1 Euro = 1.06123 USD in 2023. Source: [8]

### *7.2.8.3. Expense Variables*

#### *7.2.8.3.1. Capital expense parameters [9]*

| **Capital Expense Parameters** | | |
|---|---|---|
| **Investment Factors** | | |
| Installation Costs (Install Factor - 1) | % of TPEC | 1.5 |
| Indirect | % of Direct | 0.34 |
| Contractor's Fee | % of TPEC | 0.23 |
| Base Contingency | % of TPEC | 0.5 |
| Working Capital | % Sales Rev | 0.2 |
| Start Up Costs | % of Fixed Cap | 0.1 |
| Location Factor | % of CapEx | 0.9 |
| | | |
| **Equipment Scaling Factors** | | |
| Scaling power factors | | |
| Hydrothermal Liquefaction | - | 0.75 |
| Hydrotreating | - | 0.75 |
| Hydrogen Production | - | 0.65 |
| Cogeneration & Utilities | - | 0.7 |
| Storage | - | 0.7 |

### *7.2.8.3.2. Operational expense parameters [10], [11]*

| **Operating Expense Parameters** | | |
|---|---|---|
| Interest Rate | % | 13% |
| of which, ROI | % | 0.034 |
| of which, inflation | % | 0.026 |
| of which, risk premium | % | 0.065 |
| | | |
| *Labor Expense Parameters* | | |
| Operators per Shift, HTL | # | 6 |
| Shifts per Day | # | 3 |
| Hours per Shift | # | 8 |
| Supervision & Operating Supplies | | 0.5 |
| | | |
| *Manufacturing Expense Parameters* | | |
| Maintenance | % Fixed Cap | 0.1 |
| Plant Overhead | % Total labor | 0.7 |
| Depreciation | % Total cap | 0.14 |
| Local Taxes | % Fixed Cap | 0.015 |
| Income Taxes | % Revenue | 0.25 |
| Insurance | % Fixed Cap | 0.01 |
| General Expenses | % Sales | 0.1 |
| Base Contingency | % of Direct Prod | 0.2 |

### *7.2.8.4. Variable expenses parameters*

| **Feedstock Variables and Related** | **EUR per** | |
|---|---|---|
| Olive pomace (in EUR) | wet ton | 25 |
| | | |
| **Product Prices** | | |
| MGO (fossil) | per ton (2023) (in Gibraltor) | 890 |
| *MGO, per GJ* | *GJ* | *21.4* |
| electricity, wholesale | Eur/MWh (in 2023) | 103 |
| *electricity, wholesale, per GJ* | *GJ* | *28.6* |
| VLSFO (fossil) | Eur per ton (2023) (in Gibraltor) | 640 |
| | | |
| **Comparison Product Prices** | | |
| *Crude Price* | *Barrel of Brent Crude* | *82.9* |
| | | |
| **Logistics Prices** | | |
| Truck transport, fixed | ton | 12.00 |
| Truck transport, variable | ton km | 0.27 |
| | | |
| **Operating Expenses** | EUR (2023) per … | |
| waste processing: gas | ton | 6.00 |
| waste processing: water, black | ton | 0.60 |
| waste processing: solids | ton | 135 |
| Water | ton | 0.08 |
| Natural Gas | ton | 1389 |
| Natural gas, per GJ | GJ | 27.78 |
| Base Salary | hour | 12 |
| Hydrotreating Catalyst | ton | 91657.79332 [2] |

### *7.2.8.5. Equipment Costs [II]*

| **Equipment Prices** | EUR per | All equipment prices are in Millions EUR per unit, corresponding to the reference capacity in the unit column |
|---|---|---|
| **Hydrothermal Liquefaction** | units/day | 2023 M EUR |
| Feedstock Handling and Prep [wet tons feedstock] | 4000 | 12.6 |
| Oil Production [reactor wet feed tons] | 24330 | 124.7 |
| Hydrotreating [tons biocrude] | 734 | 23.6 |
| Hydrogen Plant [t H2] | 50 | 21.4700866 |
| Cogeneration [MW] | 500 | 36.79607594 |

### 7.2.9. References


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[11] C. C. da Silva, "Techno-Economic and Environmental Analysis of Oil Crop and Forestry Residues Based Integrated Biorefineries in Brazil," PD Engg thesis, Delft University of Technology, 2016.

# 7.3. APPENDIX B

## 7.3.1. Case study – field visit participatory technique

### *7.3.1.1. Protocol for interviews*

*A sample of the interview and workshop materials is shown. The full case study protocol, including workshop outcomes, can be shared upon request.

*Interviews and workshop materials were translated into Spanish when necessary

#### *7.3.1.1.1. General interview guide stakeholders – Same as section 7.2.6.1*

#### *7.3.1.1.2. Interview materials – Same as section 7.2.6.2*

### *7.3.1.2. Workshop Protocol*

1. Present general scenarios with design variables and options for the same
2. Split participants in 3 smaller groups, representing a mix of stakeholders

o Break-out session 1:

§ Discuss different variables along with their pros and cons for the choices to be made along the value chain of the biofuel system. A representation of the biohub and its elements is shown as depicted in following figures.

§ Example of different elements and variables discussed is shown in *Figure 7.15*

o Break-out session 2 –

§ Stakeholders were asked to choose options along different technical and non-technical elements and impacts that biohub could create by co creating a design. The poster format used for the same is indicated in *Figure 7.14* and *Figure 7.17*

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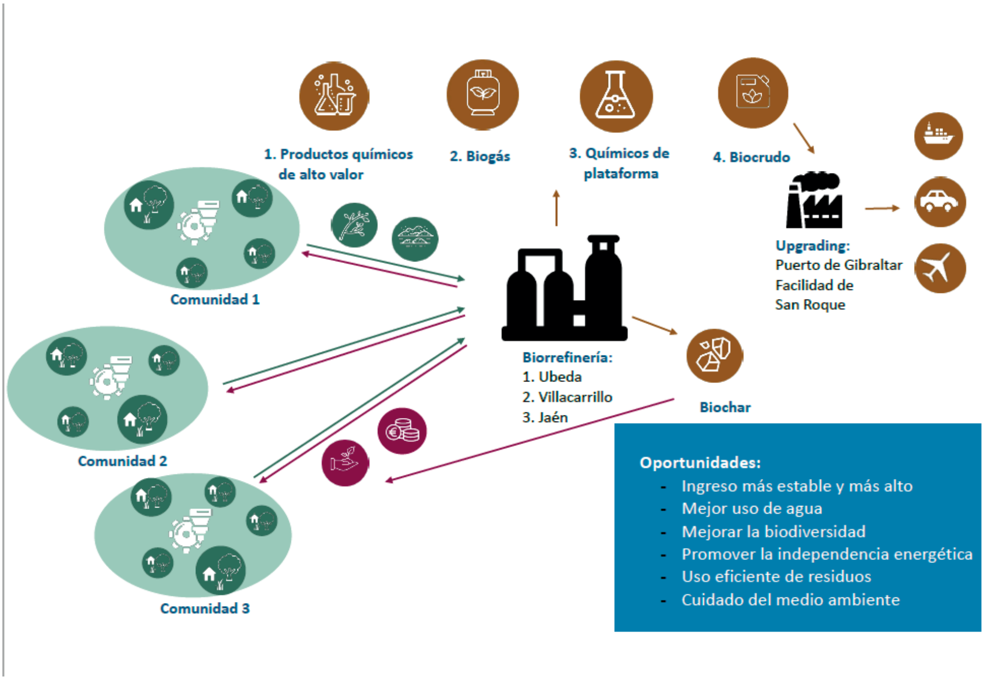


Figure 7.7: Representation of a possible biohub with some variables in Spain

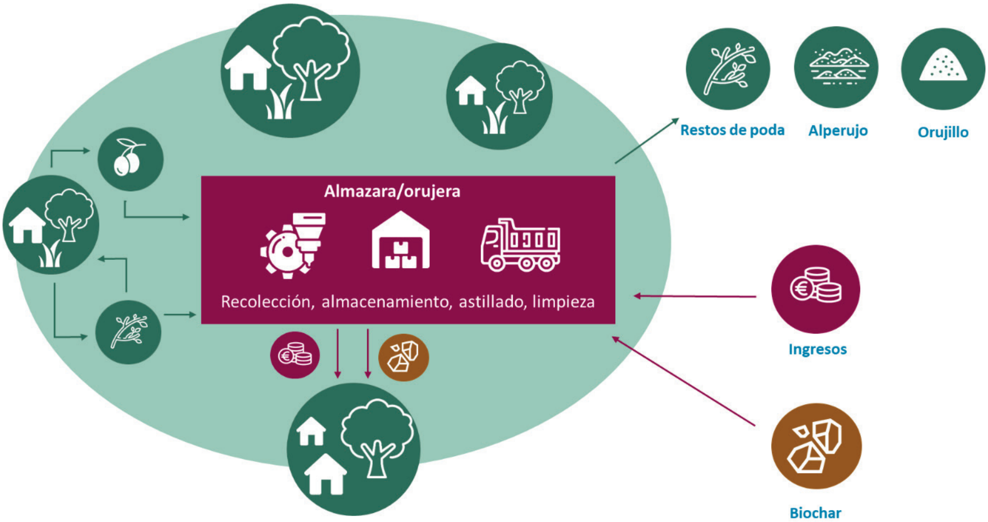


Figure 7.8: A zoomed-in version of one community where primary mills can act as points of collection, processing, and storage of pruning and olives.

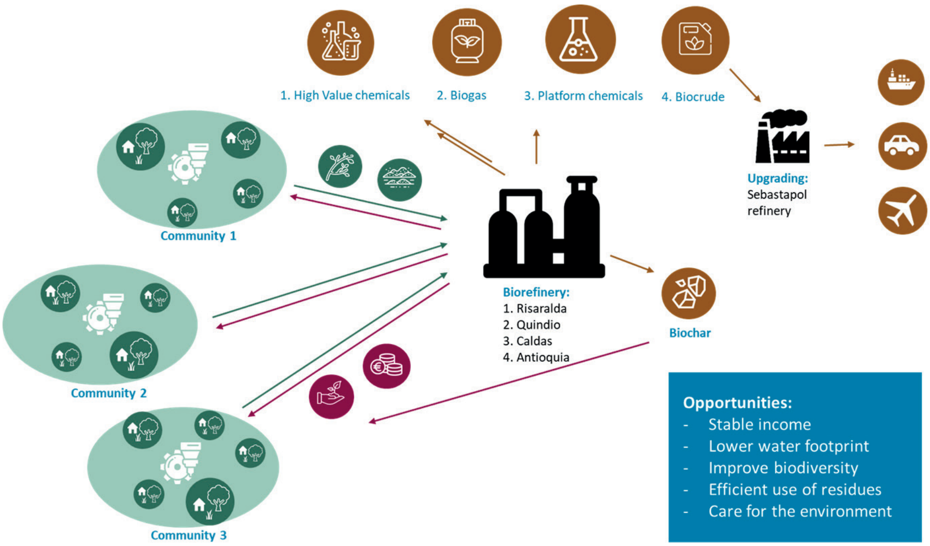


Figure 7.9: Representation of a possible biohub with some variables in Colombia

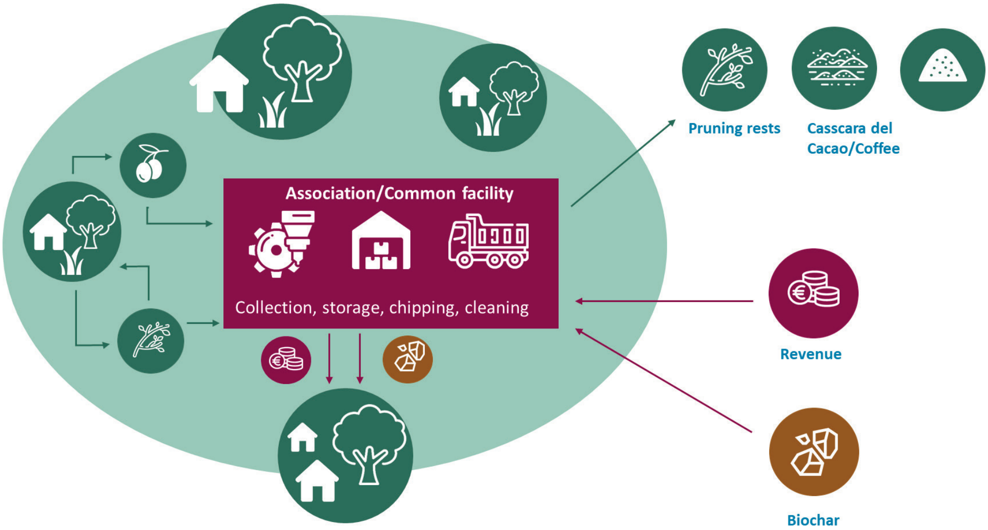


Figure 7.10: A zoomed-in version of one region where coffee cherries can be processed in a centralised processing facility (possibly owned by a cooperative). The facility could also act as a processing and storage facility for coffee-cut stems

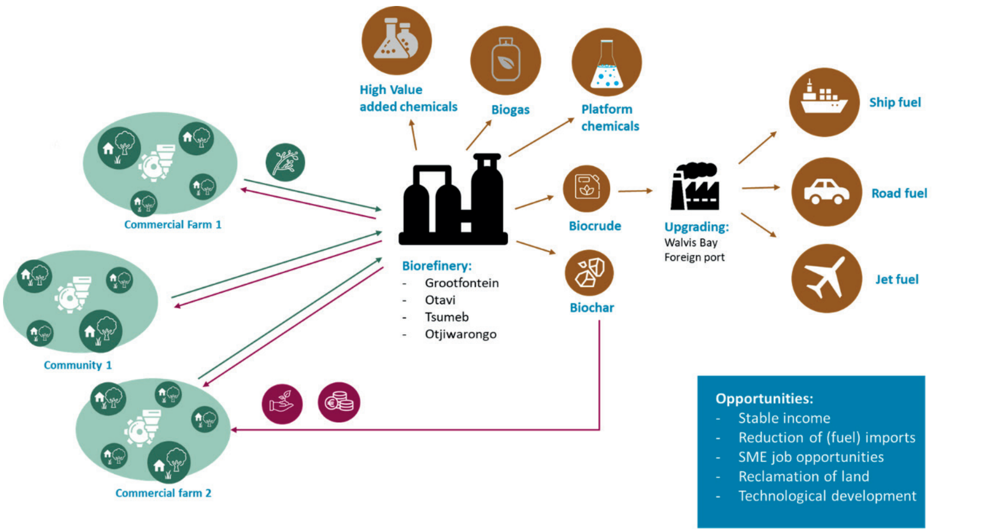


Figure 7.11: Representation of a possible biohub with some variables in the region of Otjozondjupa, Namibia

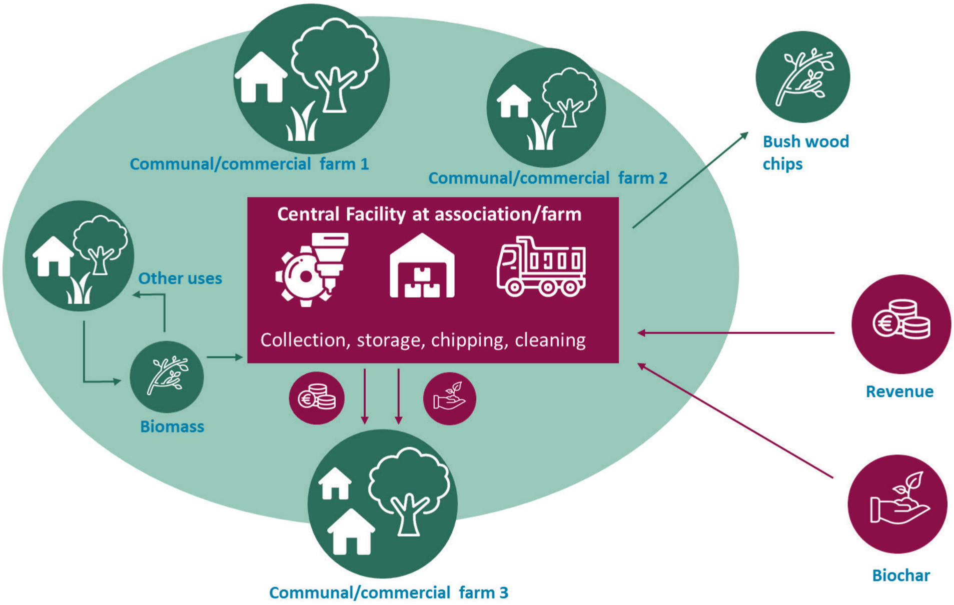


Figure 7.12: A zoomed-in version of one region where encroacher bush can be processed in a centralised processing facility (possibly owned by a cooperative or municipality). The facility could also produce other bush-based products

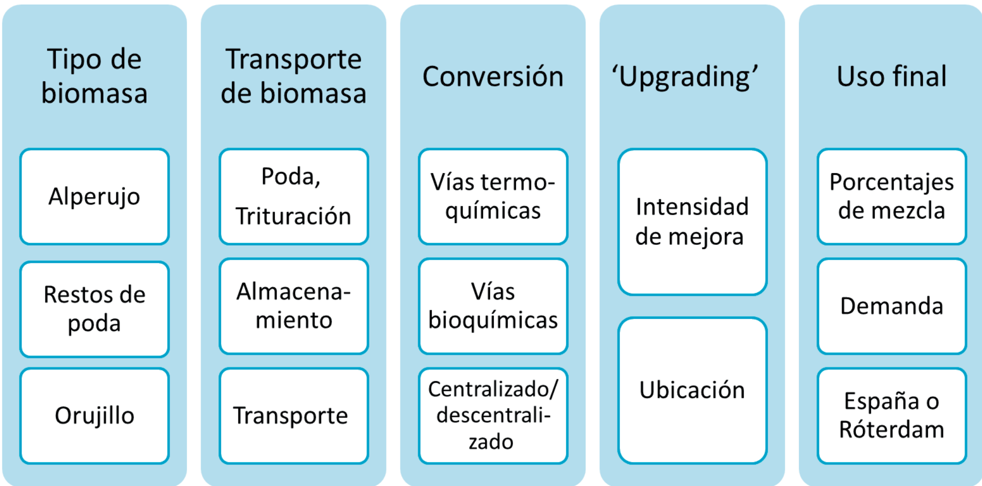


Figure 7.13: Elements and corresponding variables for developing a biofuel value chain in Jaén

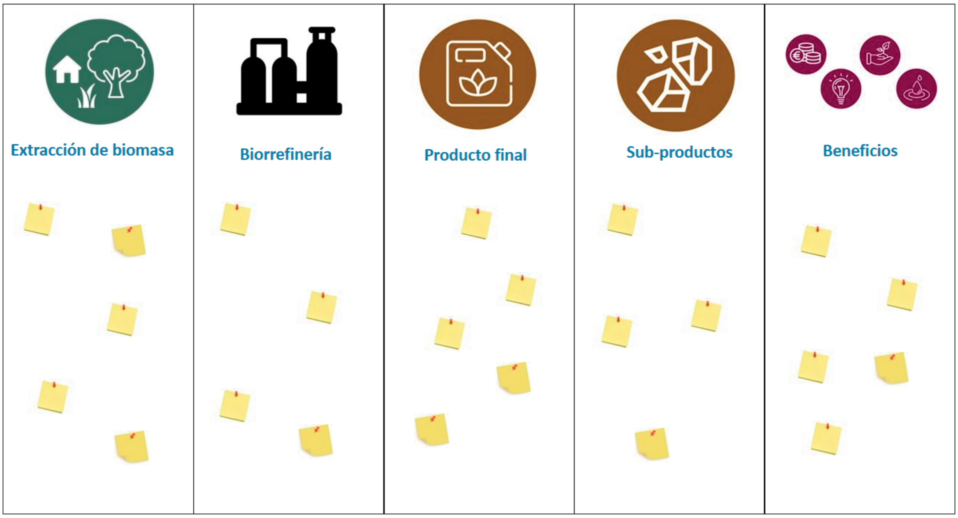


Figure 7.14: Representation of posters used to collect participants' choices (incl. justification) for different technical and non-technical elements and impacts of biohub in Jaén.

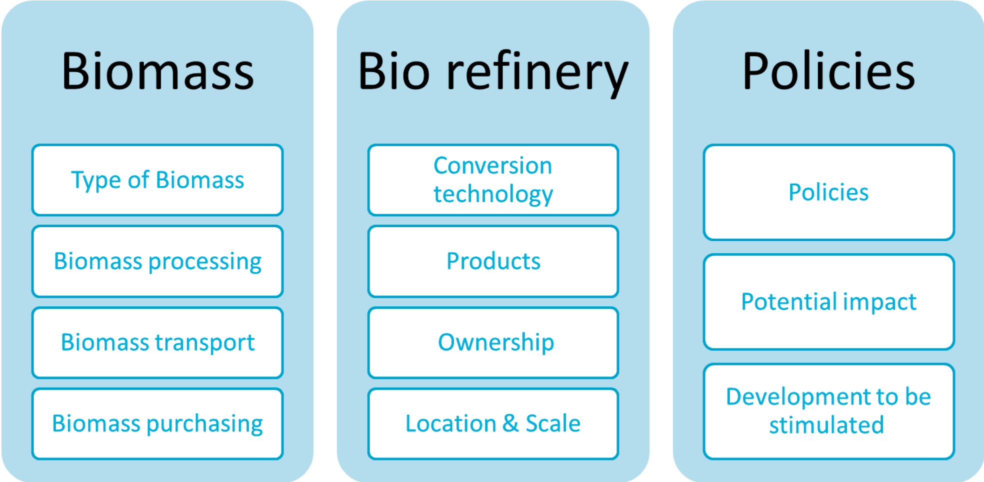


Figure 7.15: Elements and corresponding variables for developing a biofuel value chain in Risaralda, Colombia

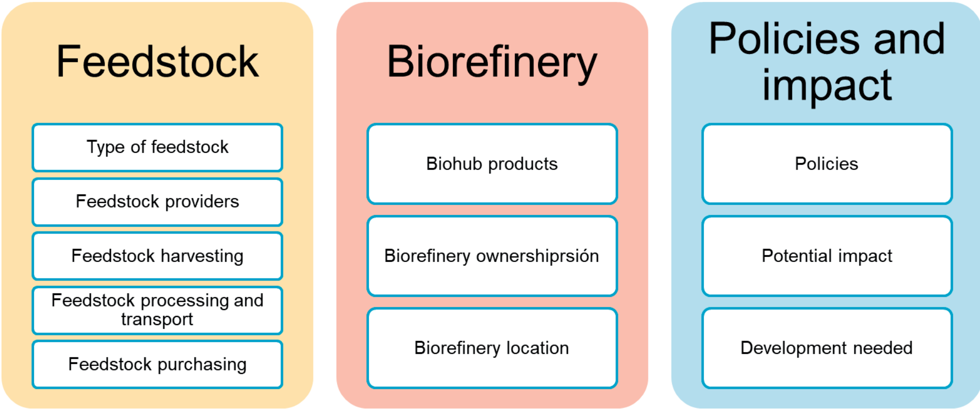


Figure 7.16: Elements and corresponding variables for developing a biofuel value chain in Namibia

| | | | |
|---|---|---|---|
| **Feedstock** | **Feedstock providers** | **Feedstock harvesting method** | **Feedstock processing (ownership)** |
| **Feedstock transport** | **Feedstock purchasing (contracts)** | **Biohub products** | **Biorefinery ownership** |
| **Biorefinery location** | **Policies** | **Potential contribution of Biohub to local development needs** | **Development needed in region** |

Figure 7.17: Representation of posters used to collect participants' choices (incl. justification) for different technical and non-technical elements and impacts of biohub in Colombia and Namibia.

## 7.3.2. Raw material characteristics

### *7.3.2.1. Proximate analysis of feedstocks.*

Table 7.8: Proximate analysis of crude olive pomace (in wt.%).

| | **Olive tree pruning** [1] | **Coffee Pulp** [2] | **Acacia Mellifera** [3] |
|---|---|---|---|
| Volatile Matter | 83.45 | 67.24 | 76.77 |
| Fixed carbon | 16.32 | 16.61 | 19.21 |
| Moisture | 6.49 | 7.42 | 3.79 |
| Ash | 0.23 | 8.73 | 0.55 |
| HHV (MJ/kg) | 16.9 | 15.39 | 19.7 |

### *7.3.2.2. Ultimate analysis of feedstocks.*

Table 7.9: Ultimate Analysis of crude olive pomace (in wt.%).

| | **Olive tree pruning** [1] | **Coffee Pulp** [2] | **Acacia** [3] |
|---|---|---|---|
| C | 47.60 | 42.40 | 48.90 |
| H | 6.30 | 5.71 | 5.90 |
| N | 0.00 | 2.17 | 0.20 |
| S | 0.00 | 0.00 | 0.00 |
| O | 45.90 | 49.57 | 44.50 |

## 7.3.3. Product Composition

### *7.3.3.1. HTL off-gas composition obtained from the literature (in vol.%)*

| | **Olive pruning** [4] | **Coffee Pulp** [2] | **Acacia Mellifera** [4] |
|---|---|---|---|
| $CO_2$ | 90.2 | 68.7 | 90.2 |
| $H_2$ | 0.9 | 12.1 | 0.9 |
| $CH_4$ | 3.0 | 6.0 | 3.0 |
| $C_2H_6$ | 2.5 | 0.0 | 2.5 |
| $C_3H_8$ | 1.9 | 0.0 | 1.9 |
| $C_4H_{10}$ | 1.5 | 0.0 | 1.5 |
| CO | 0.0 | 10.5 | 0.0 |

## 7.3.4. HTL system

### *7.3.4.1. Chemical composition of bio-crude.*

Table 7.10: Composition of HTL bio-crude from olive tree pruning biomass [1]

| **Name of compound** | **Molecular Formula** | **Relative Area, %** |
|---|---|---|
| 2-Pentanone, 4-hydroxy-4-methyl- | C6H12O2 | 0.074 |
| 2-Cyclopenten-1-one, 2-methyl- | C6H80 | 0.010 |
| 4,4-Dimethyl-2-cyclopenten-1-one | C7H10O | 0.010 |
| 2-Cyclopenten-1-one, 2,3-dimethyl- | C7H10O | 0.007 |
| Phenol, 2-methoxy- | C7H8O2 | 0.073 |
| Ethanone, 1-(1-cyclohexen-1-yl)- | C8H12O | 0.014 |
| Creosol | C7H80 | 0.026 |
| 3-Trifluoroacetoxypentadecane | C17H32O2 | 0.007 |
| Phenol, 4-ethyl-2-methoxy- | C9H12O2 | 0.056 |
| Phenol, 2-methoxy-4-propyl- | C10H14O2 | 0.033 |
| 8-Hexadecenal, 14-methyl-, (Z)- | C17H34O | 0.004 |
| Phenol, 2-methoxy-6-(1-propenyl)- | C10H12O2 | 0.016 |
| Phenol, 3-methoxy-2,4,6-trimethyl- | C10H14O2 | 0.009 |
| 2-Propanone, 1-(4-hydroxy-3-methoxyphenyl)- | C10H12O | 0.023 |
| Phenol, 4-(ethoxymethyl)-2-methoxy- | C9H10O3 | 0.022 |
| Phenacetic acid, 2,3,5,a,a-pentamethyl-6-carboxy- | C14H18O2 | 0.010 |

Table 7.11: Composition of HTL bio-crude from coffee pulp. Based on [2]

| Name of compound | Formula | Relative area, in % |
|---|---|---|
| N-DECANE | C10H22 | 7.965 |
| 2-ETHYL-4-METHYL-1,3-HEXADIENE | C9H16 | 1.15 |
| N-OCTADECANE | C18H38 | 1.155 |
| CYCLOHEXADECANE | C16H32 | 1.865 |
| CIS-5-OCTADECENE | C18H36 | 1.855 |
| N-HEPTADECANE | C17H36 | 0.55 |
| N-HEXADECANOIC-ACID | C16H32O2 | 6.16 |
| STEARIC-ACID | C18H36O2 | 0.93 |
| LINOLEIC-ACID | C18H32O2 | 1.36 |
| OLEIC-ACID | C18H34O2 | 0.74 |
| 2-METHYL-2-CYCLOPENTEN-1-ONE | C6H8O | 2.725 |
| 3-METHYL-2-CYCLOPENTEN-1-ONE | C6H8O | 4.1 |
| 2,4-DIMETHYL-2-CYCLOPENTEN-1-ONE | C7H10O | 1.005 |
| C8H12O-N9 | C8H120 | 0.505 |
| 2,4-DIMETHYL-2-CYCLOPENTEN-1-ONE | C7H10O | 6.765 |
| C8H12O-N9 | C8H120 | 1.505 |
| 2-ETHYL-2-CYCLOPENTENONE | C7H10O | 1.225 |
| 2-HYDROXYACETOPHENONE | C8H802 | 0.965 |
| C7H10O2-N11 | C7H1002 | 0.425 |
| 2-METHYLBENZOFURAN | C9H80 | 0.96 |
| 2,4-DIMETHYL-2-CYCLOPENTEN-1-ONE | C7H100 | 0.57 |
| 1-CYCLOHEXENYL-ETHYL-KETONE | C9H160 | 0.33 |
| PHENOL | C6H60 | 11.93 |
| O-CRESOL | C7H80 | 1.33 |
| M-CRESOL | C7H80 | 2.975 |
| SYRINGOL | C8H10O3 | 0.815 |
| 4-ETHYL-2-METHOXYPHENOL | C9H12O2 | 1.405 |
| M-ETHYLPHENOL | C8H10O | 0.635 |
| P-ETHYLPHENOL | C8H10O | 1.44 |
| 4-METHYL-2-METHOXYPHENOL | C8H10O2 | 1.225 |
| GUAIACOL | C7H8O2 | 3.405 |
| 4-PROPYLGUAIACOL | C10H14O2 | 0.345 |
| 1,2-BENZENEDIOL | C6H6O2 | 4.72 |
| 1-METHYLCYCLOHEPTENE | C8H14 | 0.34 |
| CYCLOHEXA-2,5-DIEN-1-ONE | C6H60 | 0.55 |
| 1-CYCLOHEXENYLMETHYL-ETHANOATE | C9H1602 | 1.195 |
| 2-METHYLBICYCLO[2.2.2]OCTANE | C9H16 | 1.59 |
| 4-PYRIDINOL | C5H5NO | 3.42 |
| 3-HYDROXYPYRIDINE | C5H5NO | 2.435 |

Table 7.11: Composition of HTL bio-crude from coffee pulp. Based on [2] (*continued*)

| **Name of compound** | **Formula** | **Relative area, in %** |
|---|---|---|
| P-HYDROXYANILINE | C6H7NO | 2.345 |
| N-CAPROYL-PYRAZINAMIDE | C11H15N3O | 0.21 |
| 8-ETHYLTHEOPHYLLINE | C9H12N4O2 | 3.58 |
| 1-METHYL-2,5-PYRROLIDINEDIONE | C5H7NO2 | 0.575 |
| N-CAPRYL-PYRAZINAMIDE | C15H23N3O | 0.56 |
| N-METHYL-2-PYRROLIDONE | C5H9NO | 1.25 |
| M-TOLUONITRILE | C8H7N | 0.64 |
| INDOLE,-4,7-DIMETHYL- | C10H11N | 0.285 |
| 3-METHOXYCATECHOL | C7H8O3 | 2.405 |
| HYDROQUINONE,-METHYL- | C7H8O2 | 2.14 |
| 1,3-DIHYDROXY-4-METHYLBENZENE | C7H8O2 | 1.18 |
| 1,3-DIHYDROXY-2-METHYLBENZENE | C7H8O2 | 0.265 |

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Table 7.12: Composition of HTL bio-crude from Acacia Mellifera[3].

| Name of Compound | Relative area, in % |
|---|---|
| Hexadecanoic acid methyl ester | 0.00951 |
| Octadecenoic acid methyl ester | 0.0317 |
| Phenol | 0.03487 |
| Phenol, 2-methyl- | 0.01268 |
| Phenol, 4-ethyl-2-methoxy- | 0.00317 |
| Phenol, 2-methoxy- | 0.00951 |
| Hydroquinone | 0.01585 |
| 1,2-Benzenediol, 3-methoxy- | 0.01585 |
| 1,3-Benzenediol, 2-methyl- | 0.01585 |
| 1,4-Benzenediol, 2-methyl- | 0.00951 |
| 3,5-Dihydroxytoluene | 0.00634 |
| 2,5-Cyclohexadien-1-one, 3,5-dihyd | 0.00951 |
| 1,2-Cyclopentanedione, 3,3,5,5-tetramethyl- | 0.02219 |
| Propionaldehyde | 0.004755 |
| Furfural | 0.004755 |
| n-Hexadecanoic acid | 0.02219 |
| Octadecanoic acid | 0.00634 |
| 9,12-Octadecadienoic acid (Z,Z)- | 0.00951 |
| Oleic Acid | 0.00951 |
| 2-Cyclopenten-1-one, 2-methyl- | 0.00634 |
| 2-Cyclopenten-1-one, 3-methyl- | 0.00317 |
| 2-Cyclopenten-1-one, 2,3-dimethyl- | 0.01268 |
| 2-Cyclopenten-1-one, 2,3,4-trimethyl | 0.00317 |
| Decane | 0.00634 |
| Octadecane | 0.00317 |
| Cyclohexadecane | 0.001585 |
| 5-Octadecene | 0.001585 |
| butanol | 0.00317 |
| hexanol | 0.00317 |
| octanol | 0.00317 |
| 4-Pyridinol | 0.011095 |
| 3-Pyridinol | 0.00317 |
| Phenol, 4-amino- | 0.001585 |

## 7.3.5. Upgrading and fractionation system

### *7.3.5.1. Chemical reactions in Hydrotreatment, Adapted from [5], [6]*

Table 7.13: Hydrotreatment reactions in the hydrotreater for Olive pruning HTL biocrude

| **Biocrude components** | **No: of moles of hydrogen** | **Biooil components** | **No: of moles of Water** | **No: of moles of Methanol** |
|---|---|---|---|---|
| 2-Pentanone, 4-hydroxy-4-methyl- | 3 | isohexane(2-MET-02) | 2 | |
| 2-Cyclopenten-1-one, 2-methyl- | 3 | 2 methylcyclopentane (METHY-01) | 1 | |
| 4,4-Dimethyl-2-cyclopenten-1-one | 3 | 3,4 - di methyl cyclopentane (1:1-D-01) | 1 | |
| 2-Cyclopenten-1-one, 2,3-dimethyl- | 3 | 3,4 - di methyl cyclopentane (CIS-1-01) | 1 | |
| Phenol, 2-methoxy- | 1 | phenol | | 1 |
| Ethanone, 1-(1-cyclohexen-1-yl)- | 3 | Ethylcyclohexane (ETHYL-01) | 1 | |
| Creosol | 0 | Creosol | | |
| 3-Trifluoroacetoxypentadecane | 4 | heptadecane (HEPTADEC) | 2 | |
| Phenol, 4-ethyl-2-methoxy- | 1 | P-ETHYLPHENOL (P-ETH-01) | | 1 |
| Phenol, 2-methoxy-4-propyl- | 1 | P-PROPYLPHENOL (PHENO-01) | | 1 |
| 8-Hexadecenal, 14-methyl-, (Z)- | 2 | heptadecane (HEPTADEC) | 1 | |
| Phenol, 2-methoxy-6-(1-propenyl)- | 2 | P-PROPYLPHENOL (PHENO-01) | | 1 |
| Phenol, 3-methoxy-2,4,6-trimethyl- | 1 | Mesitol (MESIT-01) | 0 | 1 |
| 2-Propanone, 1-(4-hydroxy-3-methoxyphenyl)- | 2 | Isobutylbenzene (ISOBU-02) | 1 | |
| Phenol, 4-(ethoxymethyl)-2-methoxy- | 3 | P-ETHYLPHENOL (P-ETH-01) | 1 | 1 |
| Phenacetic acid, 2,3,5,a,a-pentamethyl-6-carboxy- | 6 | 1,1*-METHYLENEBISCYCLOHEXANE (1:1:--01) | 1 | 1 |

Table 7.14: Hydrotreatment reactions in the hydrotreater for coffee pulp HTL biocrude

| **Biocrude components** | **No: of moles of hydrogen** | **Biooil components** | **No: of moles of Water** |
|---|---|---|---|
| N-DECANE | 0 | N-DECANE | |
| 2-ETHYL-4-METHYL-1,3-HEXADI-ENE | 2 | 1-Ethyl-4-methylhexane (4-ETH-02) | |
| N-OCTADECANE | 0 | N-OCTADECANE | |
| CYCLOHEXADECANE | 0 | CYCLOHEXADECANE | |
| CIS-5-OCTADECENE | 1 | octadecane | |
| N-HEPTADECANE | 0 | N-HEPTADECANE | |
| N-HEXADECANOIC-ACID | 3 | hexadecane(N-HEX-02) | 2 |
| STEARIC-ACID | 3 | Octadecane | 2 |
| LINOLEIC-ACID | 5 | Octadecane | 2 |
| OLEIC-ACID | 4 | Octadecane | 2 |
| 2-METHYL-2-CYCLOPENTEN-1-ONE | 3 | 2 methylcyclopentane (ETHYL-01) | 1 |
| 3-METHYL-2-CYCLOPENTEN-1-ONE | 3 | 3 methyl cyclopentane (ETHYL-01) | 1 |
| 2,4-DIMETHYL-2-CYCLOPENTEN-1-ONE | 3 | 3,4 - di methyl cyclopentane (1:1-D-01) | 1 |
| C8H12O-N9 | 3 | 2,3,4 - trimethyl cyclopentane | 1 |
| 2,4-DIMETHYL-2-CYCLOPENTEN-1-ONE | 3 | 2,3 - di methyl cyclopentane (1:1-D-01) | 1 |
| C8H12O-N9 | 3 | 2,3,4 - on trimethyl cyclopentane (1:1:2-01) | 1 |
| 2-ETHYL-2-CYCLOPENTENONE | 3 | 3 ethylcyclopentane (ETHYL-02) | 1 |
| 2-HYDROXYACETOPHENONE | 6 | ethylcyclohexane (ETHYL-03) | 2 |
| C7H10O2-N11 | 3 | 3,4 - di methyl cyclopentane (1:1-D-01) | 2 |
| 2-METHYLBENZOFURAN | 5 | octahydro-1H-indene (CIS-H-01) | 1 |
| 2,4-DIMETHYL-2-CYCLOPENTEN-1-ONE | 4 | 4,4 dimethlcyclopentane (1:1-D-01) | 1 |
| 1-CYCLOHEXENYL-ETHYL-KE-TONE | 3 | Propyl cyclohexane(N-PRO-01) | 1 |
| PHENOL | 0 | PHENOL | |
| O-CRESOL | 0 | O-CRESOL | |
| M-CRESOL | 0 | M-CRESOL | |
| SYRINGOL | 2 | Phenol, 2 methanol | |
| 4-ETHYL-2-METHOXYPHENOL | 1 | P-ETHYLPHENOL(O-ETH-01), methanol | |
| M-ETHYLPHENOL | 0 | M-ETHYLPHENOL (M-ETH-02) | |
| P-ETHYLPHENOL | 0 | P-ETHYLPHENOL (O-ETH-01) | |
| 4-METHYL-2-METHOXYPHENOL | 1 | P-CRESOL, methanol | |

Table 7.14: Hydrotreatment reactions in the hydrotreater for coffee pulp HTL biocrude (*continued*)

| **Biocrude components** | **No: of moles of hydrogen** | **Biooil components** | **No: of moles of Water** |
|---|---|---|---|
| GUAIACOL | 1 | phenol , methanol | |
| 4-PROPYLGUAIACOL | 1 | 4-propyl phenol (2-PRO-01), methanol | |
| 1,2-BENZENEDIOL | 0 | 1,2-BENZENEDIOL | |
| 1-METHYLCYCLOHEPTENE | 1 | methylcycloheptane (METHY-01) | |
| CYCLOHEXA-2,5-DIEN-1-ONE | 4 | cyclohexane (CYCLO-03) | 1 |
| 1-CYCLOHEXENYLMETHYL-ETH-ANOATE | 4 | methylethylcyclohexane ((N-PRO-01) | 2 |
| 2-METHYLBICYCLO[2.2.2]OCTANE | 0 | 2-METHYLBICYCLO[2.2.2]OCTANE (2-MET-04) | |
| 4-PYRIDINOL | 5 | cyclopentane (CYCLO-04), NH3 | 1 |
| 3-HYDROXYPYRIDINE | 5 | cyclopentane (CYCLO-04), NH3 | 1 |
| P-HYDROXYANILINE | 5 | Cyclohexane (CYCLO-03), NH3 | 1 |
| N-CAPROYL-PYRAZINAMIDE | 13 | hexane (N-HEX-03), propane (PRO-PA-01), ethane (ETHANE), 3 NH3 | 2 |
| 8-ETHYLTHEOPHYLLINE | 17 | 4 methane, 1 ethane, 1 propane, 4 NH3 | 2 |
| 1-METHYL-2,5-PYRROLIDINEDI-ONE | 7 | methane, butane, NH3 | 2 |
| N-CAPRYL-PYRAZINAMIDE | 13 | decane, propane, ethane, 3 NH3 | 2 |
| N-METHYL-2-PYRROLIDONE | 5 | methane, butane, NH3 | 1 |
| M-TOLUONITRILE | 3 | xylene (XYLENE), NH3 | |
| INDOLE,-4,7-DIMETHYL- | 4 | xylene, ethane, NH3 | |
| 3-METHOXYCATECHOL | 1 | Catechol, methanol | |
| HYDROQUINONE,-METHYL- | 0 | catechol | |
| 1,3-DIHYDROXY-4-METHYLBEN-ZENE | 0 | methylcatechol | |
| 1,3-DIHYDROXY-2-METHYLBEN-ZENE | 0 | methylcatechol | |

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Table 7.15: Hydrotreatment reactions in the hydrotreater for acacia HTL biocrude

| Biocrude components | No: of moles of hydrogen | Biooil components | No: of moles of Water |
|---|---|---|---|
| Hexadecanoic acid methyl ester | 4 | hexadecane(Hexadeca), methane | 2 |
| Octadecenoic acid methyl ester | 5 | Octadecane (N-OCT-02), methane | 2 |
| Phenol | 0 | Phenol | |
| Phenol, 2-methyl- | 0 | Phenol, 2-methyl- | |
| Phenol, 4-ethyl-2-methoxy- | 1 | P-ETHYLPHENOL(P-ETH-01), methanol | |
| Phenol, 2-methoxy- | 1 | phenol , methanol | |
| Hydroquinone | 0 | Hydroquinone | |
| 1,2-Benzenediol, 3-methoxy- | 1 | catechol (1:2-B-02), methanol | |
| 1,3-Benzenediol, 2-methyl- | 0 | 1,3-Benzenediol, 2-methyl- | |
| 1,4-Benzenediol, 2-methyl- | 0 | 1,4-Benzenediol, 2-methyl- | |
| 3,5-Dihydroxytoluene | 0 | 3,5-Dihydroxytoluene | |
| 2,5-Cyclohexadien-1-one, 3,5-dihyd | 4 | cyclohexane (CYCLO-03) | 1 |
| 1,2-Cyclopentanedione, 3,3,5,5-tetra-methyl- | 4 | methylethylcyclohexane (ISOPR-01) | 2 |
| Propionaldehyde | 1 | propanol (1-PRO-01) | |
| Furfural | 2 | 2-methylfuran (3-MET-05) | 1 |
| n-Hexadecanoic acid | 3 | hexadecane(N-HEX-02) | 2 |
| Octadecanoic acid | 3 | Octadecane | 2 |
| 9,12-Octadecadienoic acid (Z,Z)- | 5 | Octadecane | 2 |
| Oleic Acid | 4 | Octadecane | 2 |
| 2-Cyclopenten-1-one, 2-methyl- | 3 | 2 methylcyclopentane (METHY-03) | 1 |
| 2-Cyclopenten-1-one, 3-methyl- | 3 | 3 methyl cyclopentane (METHY-03) | 1 |
| 2-Cyclopenten-1-one, 2,3-dimethyl- | 3 | 2,3 - di methyl cyclopentane (CIS-1-01) | 1 |
| 2-Cyclopenten-1-one, 2,3,4-trimethyl | 3 | 2,3,4 - trimethyl cyclopentane (1:1:2-01) | 1 |
| Decane | 0 | Decane | |
| Octadecane | 0 | Octadecane | |
| Cyclohexadecane | 0 | Cyclohexadecane | |
| 5-Octadecene | 1 | octadecane | |
| butanol | 1 | butane | 1 |
| hexanol | 1 | hexane | 1 |
| octanol | 1 | octane | 1 |
| 4-Pyridinol | 5 | cyclopentane (CYCLO-04), NH3 | 1 |
| 3-Pyridinol | 5 | cyclopentane (CYCLO-04), NH3 | 1 |
| Phenol, 4-amino- | 5 | Cyclohexane (CYCLO-03), NH3 | 1 |

## 7.3.6. Economic parameters

### *7.3.6.1. CEPCI values. Source: [7]*

| Month | CEPCI | Month | CEPCI | Month | CEPCI | Month | CEPCI | Year | CEPCI | Year | CEPCI |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **2024 Mar** | 800.7 | 2023 May | 808.8 | 2022 Jul | 829.8 | 2021 Sep | 754 | 2018 | 603.1 | 2008 | 575.4 |
| **2024 Feb** | 800.0 | 2023 Apr | 803.3 | 2022 Jun | 832.6 | 2021 Aug | 735.2 | 2017 | 567.5 | 2007 | 525.4 |
| **2024 Jan** | 795.4 | 2023 Mar | 799.1 | 2022 May | 831.1 | 2021 Jul | 720.2 | 2016 | 541.7 | 2006 | 499.6 |
| **2023 Dec** | 789.6 | 2023 Feb | 798 | 2022 Apr | 816.3 | 2021 Jun | 701.4 | 2015 | 556,8 | 2005 | 468.2 |
| **2023 Nov** | 789.2 | 2023 Jan | 802.6 | 2022 Mar | 803.6 | 2021 May | 686.7 | 2014 | 576.1 | 2004 | 444.2 |
| **2023 Oct** | 790.7 | 2022 Dec | 802.9 | 2022 Feb | 801.3 | 2021 Apr | 677.1 | 2013 | 567.3 | 2003 | 402.0 |
| **2023 Sep** | 793.3 | 2022 Nov | 814.6 | 2022 Jan | 797.6 | 2022 | 816.0 | 2012 | 584.6 | 2002 | 395.6 |
| **2023 Aug** | 798.7 | 2022 Oct | 816.2 | 2021 Dec | 776.3 | 2021 | 708.8 | 2011 | 585.7 | 2001 | 394.3 |
| **2023 Jul** | 798.7 | 2022 Sep | 821.3 | 2021 Nov | 773.1 | 2020 | 596.2 | 2010 | 550.8 | 1957-1959 | 100.0 |
| **2023 Jun** | 803.3 | 2022 Aug | 824.5 | 2021 Oct | 761.4 | 2019 | 607.5 | 2009 | 521.9 | | |

### *7.3.6.2. Currency conversion*

1 Euro = 1.06123 USD in 2023. Source: [8]

### *7.3.6.3. Expense Variables*

#### *7.3.6.3.1. Capital expense parameters [9]*

| **Capital Expense Parameters** | | **Spain** | **Colombia** | **Namibia** |
|---|---|---|---|---|
| **Investment Factors** | | | | |
| Installation Costs (Install Factor - 1) | % of TPEC | 1.5 | 1.5 | 1.5 |
| Indirect | % of Direct | 0.34 | 0.34 | 0.34 |
| Contractor's Fee | % of TPEC | 0.23 | 0.23 | 0.23 |
| Base Contingency | % of TPEC | 0.5 | 0.5 | 0.5 |
| Working Capital | % Sales Rev | 0.2 | 0.2 | 0.2 |
| Start Up Costs | % of Fixed Cap | 0.1 | 0.1 | 0.1 |
| Location Factor | % of CapEx | 0.9 | 0.8 | 0.9 |
| | | | | |
| **Equipment Scaling Factors** | | | | |
| Feedstock pre-processing | - | 0.7 | - | 0.7 |
| Hydrothermal Liquefaction | - | 0.75 | 0.75 | 0.75 |
| Hydrotreating | - | 0.75 | 0.75 | 0.75 |
| Hydrogen Production | - | 0.65 | 0.65 | 0.65 |
| Cogeneration & Utilities | - | 0.7 | 0.7 | 0.7 |
| Storage | - | 0.7 | 0.7 | 0.7 |

### *7.3.6.3.2. Operational expense parameters [10], [11]*

| **Operating Expense Parameters** | | **Spain** | **Colombia** | **Namibia** |
|---|---|---|---|---|
| Interest Rate | % | 13 | 27 | 25 |
| of which, ROI | % | 0.034 | 0.1 | 0.075 |
| of which, inflation | % | 0.026 | 0.1 | 0.05 |
| of which, risk premium | % | 0.065 | 0.074 | 0.12 |
| | | | | |
| *Labor Expense Parameters* | | | | |
| Operators per Shift, HTL | # | 18 | 6 | 9 |
| Shifts per Day | # | 3 | 3 | 3 |
| Hours per Shift | # | 8 | 8 | 8 |
| Supervision & Operating Supplies | | 0.5 | 0,5 | 0,5 |
| | | | | |
| *Manufacturing Expense Parameters* | | | | |
| Maintenance | % Fixed Cap | 0.1 | 0.1 | 0.1 |
| Plant Overhead | % Total labor | 0.7 | 0.7 | 0.7 |
| Depreciation | % Total cap | 0.14 | 0.28 | 0.25 |
| Local Taxes | % Fixed Cap | 0.015 | 0.015 | 0.015 |
| Income Taxes | % Revenue | 0.25 | 0.25 | 0.25 |
| Insurance | % Fixed Cap | 0.01 | 0.01 | 0.01 |
| General Expenses | % Sales | 0.1 | 0.1 | 0.1 |
| Base Contingency | % of Direct Prod | 0.2 | 0.2 | 0.2 |

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### *7.3.6.3.3. Variable expenses parameters*

| **Feedstock Variables and Related** | **EUR per** | **Spain** | **Colombia** | **Namibia** |
|---|---|---|---|---|
| Feedstock (in EUR) | wet ton | 100 | 48 | 46 |
| **Product Prices** | | | | |
| MGO (fossil) | per ton (2023) (in Gibraltor) | 890 | 803 | 800 |
| *MGO, per GJ* | *GJ* | *21.4* | *19.3* | *19.2* |
| electricity, wholesale | Eur/MWh (in 2023) | 103 | 130 | 107 |
| *electricity, wholesale, per GJ* | *GJ* | *28.6* | *36.1* | *29.7* |
| **Comparison Product Prices** | | | | |
| *Crude Price* | Eur for Brent Crude/ Barrel | 82.9 | 69.2 | 82.9 |
| **Logistics Prices** | | | | |
| Truck transport, fixed | ton | 12.00 | 6.00 | 12.00 |
| Truck transport, variable | ton km | 0.27 | 0.16 | 0.27 |
| **Operating Expenses** | EUR (2023) per … | | | |
| waste processing: gas | ton | 6.00 | 6.00 | 6.00 |
| waste processing: water, black | ton | 0.60 | 0.60 | 0.30 |
| waste processing: solids | ton | 135 | 135 | 135 |
| Water | ton | 0.08 | 0.08 | 0.28 |
| Natural Gas | ton | 1389 | 641 | 1389 |
| Natural gas, per GJ | GJ | 27.78 | 12.83 | 27.78 |
| Base Salary | hour | 12 | 6 | 12 |
| Hydrotreating Catalyst [4] | ton | 91657.79 | 91657.79 | 91657.79 |

### *7.3.6.3.4. Equipment Costs [11]*

| **Equipment Prices** | EUR per | All equipment prices are in Millions EUR per unit, corresponding to the reference capacity in the unit column |
|---|---|---|
| **Hydrothermal Liquefaction** | units/day | 2023 M EUR |
| Feedstock Handling and Prep [wet tons feedstock] | 4000 | 12.6 |
| Oil Production [reactor wet feed tons] | 24330 | 124.7 |
| Hydrotreating [tons biocrude] | 734 | 23.6 |
| Hydrogen Plant [t H2] | 50 | 21.4700866 |
| Cogeneration [MW] | 500 | 36.79607594 |

## 7.3.7. Environmental emission parameters

### *7.3.7.1. Spain*

#### *7.3.7.1.1. Feedstock stage*

| | | olive production | Olive pruning | emissions due to burning on field | pruning transport | wood chipping | Chips transport |
|---|---|---|---|---|---|---|---|
| Source | | Ecoinvent | | [12] | Ecoinvent | Ecoinvent | Ecoinvent |
| FU | | 1 kg olives | 1 kg | 1 ton | 1tkm | 1kg woodchips | 1 tkm |
| Impact category | Unit | Olive {GLO}\| market for olive \| Cut-off. S | | | Transport, tractor and trailer, agricultural {CH}\| market for transport, tractor and trailer, agricultural \| Cut-off, S | Wood chipping, industrial residual wood, stationary electric chipper {RER}\| processing \| Cut-off, S | Transport, freight, lorry 16-32 metric ton, euro5 {RER}\| market for transport, freight, lorry 16-32 metric ton, EURO5 \| Cut-off, S |
| Global warming | kg $CO_2$ eq | 0.437580004 | 0 | -7.37 | 0.354011189 | 0.008797925 | 0.166188121 |
| Stratospheric ozone depletion | kg CFC11 eq | 6.65052E-06 | 0 | -0.0000159 | 1.5716E-07 | 4.87427E-09 | 1.25422E-07 |
| Ionizing radiation | kBq Co-60 eq | 0.010829223 | 0 | -0.416 | 0.009615767 | 0.004261878 | 0.003843866 |
| Ozone formation, Human health | kg $NO_x$ eq | 0.002718354 | 0 | 4.94 | 0.00231087 | 1.64164E-05 | 0.000540486 |
| Fine particulate matter formation | kg PM2.5 eq | 0.001537976 | 0 | 0.49 | 0.000872704 | 1.34296E-05 | 0.000181916 |
| Ozone formation, Terrestrial ecosystems | kg $NO_x$ eq | 0.002756681 | 0 | 5.18 | 0.002362148 | 1.66223E-05 | 0.000555139 |
| Terrestrial acidification | kg $SO_2$ eq | 0.006578964 | 0 | 1.59 | 0.001618554 | 3.33105E-05 | 0.000413486 |
| Freshwater eutrophication | kg P eq | 0.000160787 | 0 | -0.00153 | 9.42126E-05 | 8.40438E-06 | 1.22114E-05 |
| Marine eutrophication | kg N eq | 0.001026541 | 0 | -0.000241 | 6.99491E-06 | 5.97933E-07 | 1.04843E-06 |

| | | olive production | Olive pruning | emissions due to burning on field | pruning transport | wood chipping | Chips transport |
|---|---|---|---|---|---|---|---|
| Terrestrial ecotoxicity | kg 1,4-DCB | 2.758165005 | 0 | 115 | 1.406654269 | 0.011446585 | 2.967082856 |
| Freshwater ecotoxicity | kg 1,4-DCB | 0.02938541 | 0 | 0.314 | 0.025940413 | 0.000407668 | 0.003886768 |
| Marine ecotoxicity | kg 1,4-DCB | 0.036776381 | 0 | 0.842 | 0.033181135 | 0.000540721 | 0.006673662 |
| Human carcinogenic toxicity | kg 1,4-DCB | 0.013927028 | 0 | 1.53 | 0.028049646 | 0.000646254 | 0.003482097 |
| Human non-carcinogenic toxicity | kg 1,4-DCB | 1.147159029 | 0 | 8.22E+03 | 1.170143555 | 0.011467701 | 0.121708898 |
| Land use | m2a crop eq | 1.697976497 | 0 | -0.25 | 0.028248208 | 0.000315434 | 0.007078407 |
| Mineral resource scarcity | kg Cu eq | 0.004839605 | 0 | -0.104 | 0.004893806 | 2.41971E-05 | 0.000634611 |
| Fossil resource scarcity | kg oil eq | 0.09734636 | 0 | -2.43 | 0.095929965 | 0.002313886 | 0.057142093 |
| Water consumption | m3 | 0.061873302 | 0 | -0.122 | 0.001584599 | 0.000148025 | 0.000264708 |

### 7.3.7.1.2. HTL stage and Biocrude transport

| | | HTL | | Energy | | |
|---|---|---|---|---|---|---|
| | | tap water | KOH | electricity mix | Electricity from CHP | Biocrude transport |
| Source | | Ecoinvent | Ecoinvent | Ecoinvent | Ecoinvent | Ecoinvent |
| FU | | 1 kg | 1 kg | 1 kWh | 1 kWh | 1 tkm |
| Impact category | Unit | Tap water {Europe without Switzerland}\| market for \| Cut-off, S | Potassium hydroxide {RER}\| production \| Cut-off, S | Electricity, high voltage {ES}\| market for \| Cut-off, S | Electricity, high voltage {ES}\| heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014 \| Cut-off, S | Transport, freight, lorry >32 metric ton, euro6 {RER}\| market for transport, freight, lorry >32 metric ton, EURO6 \| Cut-off, S |
| Global warming | kg CO2 eq | 0.00034257 | 1.77328195 | 0.316416716 | 0.06541592 | 0.086892666 |
| Stratospheric ozone depletion | kg CFC11 eq | 1.7674E-10 | 9.5495E-07 | 1.69441E-07 | 4.4066E-07 | 6.41109E-08 |
| Ionizing radiation | kBq Co-60 eq | 0.00010893 | 0.45394672 | 0.203392298 | 0.00132194 | 0.002052539 |
| Ozone formation, Human health | kg NOx eq | 8.2294E-07 | 0.00365243 | 0.001032044 | 0.00154736 | 0.000173685 |
| Fine particulate matter formation | kg PM2.5 eq | 6.0947E-07 | 0.00263345 | 0.000725856 | 0.00037051 | 9.31863E-05 |
| Ozone formation, Terrestrial ecosystems | kg NOx eq | 8.4653E-07 | 0.00371111 | 0.001038105 | 0.00157281 | 0.00018422 |
| Terrestrial acidification | kg SO2 eq | 1.3593E-06 | 0.00677096 | 0.001890597 | 0.00120281 | 0.000181602 |
| Freshwater eutrophication | kg P eq | 2.5331E-07 | 0.00118362 | 0.000119992 | 1.4284E-05 | 6.43753E-06 |
| Marine eutrophication | kg N eq | 2.4158E-08 | 7.874E-05 | 1.12125E-05 | 1.7354E-06 | 5.28293E-07 |
| Terrestrial ecotoxicity | kg 1,4-DCB | 0.00103332 | 9.74600886 | 0.358456889 | 1.65776668 | 2.211517645 |
| Freshwater ecotoxicity | kg 1,4-DCB | 1.8046E-05 | 0.18744879 | 0.006751627 | 0.00349725 | 0.001673902 |
| Marine ecotoxicity | kg 1,4-DCB | 2.4398E-05 | 0.24218894 | 0.009122095 | 0.00566322 | 0.003353549 |
| Human carcinogenic toxicity | kg 1,4-DCB | 0.00011683 | 0.09648183 | 0.011744924 | 0.00303248 | 0.001651694 |

| | | HTL | | Energy | | |
|---|---|---|---|---|---|---|
| Human non-carcino-genic toxicity | kg 1,4-DCB | 0.00046678 | 3.20823901 | 0.254421579 | 0.36062254 | 0.060967606 |
| Land use | m2a crop eq | 1.1236E-05 | 0.09367006 | 0.010295422 | 0.70111765 | 0.006860213 |
| Mineral resource scarcity | kg Cu eq | 4.5735E-06 | 0.01145887 | 0.000489328 | 0.00035575 | 0.00025437 |
| Fossil resource scarcity | kg oil eq | 9.0256E-05 | 0.52059751 | 0.083857584 | 0.01760852 | 0.032217798 |
| Water consumption | m3 | 0.00100583 | 0.02704928 | 0.003169156 | 0.00020619 | 0.00016101 |

### *7.3.7.1.3. Upgrading and end-use*

| | | Upgrading | | | | Waste | | |
|---|---|---|---|---|---|---|---|---|
| | | Green Hydrogen | Catalyst | Pipeline to bunker | Combustion HTL fuel | liquid | solid | gas |
| Source | | [13] | Ecoinvent | Ecoinvent | [14] | Ecoinvent | Ecoinvent | Ecoinvent |
| FU | | 1 kg | 1 kg | 1tkm | 1 MJ | 1 m3 | 1 kg | 1MJ |
| Impact category | Unit | | Nickel, 99.5% {GLO}\| market for \| Cut-off, S | Transport, pipeline, onshore, petroleum {RER}\| market for transport, pipeline, onshore, petroleum \| Cut-off, S | | Wastewater, average {Europe without Switzerland}\| market for wastewater, average \| Cut-off, S | Inert waste, for final disposal {CH}\| market for inert waste, for final disposal \| Cut-off, S | Waste refinery gas {GLO}\| treatment of, burned in flare \| Cut-off, S |
| Global warming | kg CO2 eq | 0.773 | 13.69273892 | 0.01383576 | 0.0015 | 0.495959 | 0.007698 | 0.056244 |
| Stratospheric ozone depletion | kg CFC11 eq | 4.58E-08 | 2.30064E-05 | 6.9712E-09 | | 1.44E-06 | 5.06E-09 | 0 |
| Ionizing radiation | kBq Co-60 eq | | 0.744182784 | 0.00441717 | | 0.056985 | 0.000285 | 9.22E-06 |
| Ozone formation, Human health | kg NOx eq | | 0.097769337 | 5.0185E-05 | | 0.001865 | 6.03E-05 | 0.000193 |
| Fine particulate matter formation | kg PM2.5 eq | | 0.798404064 | 2.5102E-05 | | 0.00137 | 1.59E-05 | 0.000238 |
| Ozone formation, Terrestrial ecosystems | kg NOx eq | | 0.099583254 | 5.1327E-05 | 0.00175624 | 0.001897 | 6.15E-05 | 0.000193 |
| Terrestrial acidification | kg SO2 eq | | 2.686052195 | 5.4182E-05 | 3.0714E-06 | 0.00375 | 3.5E-05 | 0.000798 |

| | | Upgrading | | | Waste | | |
|---|---|---|---|---|---|---|---|
| Freshwater eutrophication | kg P eq | | 0.020336793 | 1.009E-05 | 0.001138 | 5.82E-07 | 0 |
| Marine eutrophication | kg N eq | 9.64E-04 | 0.001361597 | 7.5762E-07 | 0.005868 | 5.09E-08 | 0 |
| Terrestrial ecotoxicity | kg 1,4-DCB | | 693.0582389 | 0.02734343 | 3.014219 | 0.078811 | 0.001918 |
| Freshwater ecotoxicity | kg 1,4-DCB | | 14.15238545 | 0.00068651 | 0.054217 | 0.000145 | 1.4E-09 |
| Marine ecotoxicity | kg 1,4-DCB | | 18.10587138 | 0.00090601 | 0.07105 | 0.000233 | 3.34E-07 |
| Human carcinogenic toxicity | kg 1,4-DCB | | 2.282904533 | 0.00206627 | 0.106491 | 0.000192 | 9.67E-08 |
| Human non-carcinogenic toxicity | kg 1,4-DCB | | 205.0384357 | 0.01608518 | 3.100437 | 0.00392 | 3.45E-05 |
| Land use | m2a crop eq | | 0.628986904 | 0.00040748 | 0.029628 | 0.001012 | 0 |
| Mineral resource scarcity | kg Cu eq | | 3.921565594 | 0.00014284 | 0.010615 | 2.5E-05 | 0 |
| Fossil resource scarcity | kg oil eq | | 3.248353119 | 0.00365894 | 0.10628 | 0.004353 | 0 |
| Water consumption | m3 | 9.05E-01 | 0.142573881 | 0.00020407 | -0.89465 | 0.000175 | 0 |

### *7.3.7.2. Colombia*

#### *7.3.7.2.1. Feedstock stage*

| | | Emissions associated with Coffee Pulp | Emissions due to pulp open dumping | Coffee pulp transport |
|---|---|---|---|---|
| Source | | | [15] | Ecoinvent |
| FU | | | 2.5 kg coffee pulp | 1 tkm |
| Impact category | Unit | | | Transport, freight, lorry with refrigeration machine, 7.5-16 ton, EURO6, carbon dioxide, liquid refrigerant, cooling {GLO}\| market for transport, freight, lorry with refrigeration machine, 7.5-16 ton, EURO6, carbon dioxide, liquid refrig(...)_9 \| Cut-off, S |
| Global warming | kg CO2 eq | 0 | 0.94 | 0.262863595 |
| Stratospheric ozone depletion | kg CFC11 eq | 0 | 0 | 1.87653E-07 |
| Ionizing radiation | kBq Co-60 eq | 0 | 0 | 0.004496145 |
| Ozone formation, Human health | kg NOx eq | 0 | 0 | 0.000395097 |
| Fine particulate matter formation | kg PM2.5 eq | 0 | 0 | 0.000231867 |
| Ozone formation, Terrestrial ecosystems | kg NOx eq | 0 | 0 | 0.000414878 |
| Terrestrial acidification | kg SO2 eq | 0 | 0 | 0.000512182 |
| Freshwater eutrophication | kg P eq | 0 | 0 | 2.42379E-05 |
| Marine eutrophication | kg N eq | 0 | 0 | 3.82206E-06 |
| Terrestrial ecotoxicity | kg 1,4-DCB | 0 | 0 | 3.245224333 |
| Freshwater ecotoxicity | kg 1,4-DCB | 0 | 0 | 0.010602482 |
| Marine ecotoxicity | kg 1,4-DCB | 0 | 0 | 0.014941885 |
| Human carcinogenic toxicity | kg 1,4-DCB | 0 | 0 | 0.006446433 |
| Human non-carcinogenic toxicity | kg 1,4-DCB | 0 | 0.00E+00 | 0.15315546 |
| Land use | m2a crop eq | 0 | 0 | 0.007789463 |
| Mineral resource scarcity | kg Cu eq | 0 | 0 | 0.001197246 |
| Fossil resource scarcity | kg oil eq | 0 | 0 | 0.086980327 |
| Water consumption | m3 | 0 | 0 | 0.000439677 |

##### 7.3.7.2.2. *HTL stage*

| | | HTL | Energy | | |
|---|---|---|---|---|---|
| | | tap water | electricity mix | electricity from CHP | Biocrude transport |
| Source | | Ecoinvent | Ecoinvent | Ecoinvent | Ecoinvent |
| FU | | 1 kg | 1 kWh | 1 kWh | 1 tkm |
| Impact category | Unit | Tap water {CO}\| market for tap water \| Cut-off, S | Electricity, high voltage {CO}\| market for electricity, high voltage \| Cut-off, S | Electricity, high voltage {CO}\| treatment of bagasse, from sugarcane, in heat and power co-generation unit, 6400kW thermal \| Cut-off, S | Transport, freight, lorry 16-32 metric ton, EURO6 {RoW}\| transport, freight, lorry 16-32 metric ton, EURO6 \| Cut-off, S |
| Global warming | kg CO2 eq | 0.00056728 | 0.276367486 | 0.027325 | 0.169743566 |
| Stratospheric ozone depletion | kg CFC11 eq | 2.5724E-10 | 1.21824E-07 | 6.67E-07 | 1.20718E-07 |
| Ionizing radiation | kBq Co-60 eq | 1.1172E-05 | 0.000791446 | 0.000242 | 0.002860179 |
| Ozone formation, Human health | kg NOx eq | 1.3938E-06 | 0.000508623 | 0.002112 | 0.000278327 |
| Fine particulate matter formation | kg PM2.5 eq | 1.0433E-06 | 0.000411992 | 0.001617 | 0.000160761 |
| Ozone formation, Terrestrial ecosystems | kg NOx eq | 1.4357E-06 | 0.000515691 | 0.002136 | 0.000292858 |
| Terrestrial acidification | kg SO2 eq | 2.5158E-06 | 0.001272768 | 0.001043 | 0.00033551 |
| Freshwater eutrophication | kg P eq | 1.5506E-07 | 4.44513E-05 | 9.32E-06 | 1.44966E-05 |
| Marine eutrophication | kg N eq | 2.4451E-08 | 2.97743E-06 | 2.26E-05 | 1.17231E-06 |
| Terrestrial ecotoxicity | kg 1,4-DCB | 0.00193388 | 0.24131192 | 1.524955 | 2.966904893 |
| Freshwater ecotoxicity | kg 1,4-DCB | 2.8959E-05 | 0.002407183 | 0.003929 | 0.003994273 |
| Marine ecotoxicity | kg 1,4-DCB | 3.8559E-05 | 0.003385789 | 0.005874 | 0.006816559 |
| Human carcinogenic toxicity | kg 1,4-DCB | 0.00019012 | 0.004980411 | 0.001391 | 0.003725149 |

| | | HTL | Energy | | |
|---|---|---|---|---|---|
| Human non-carcinogenic toxicity | kg 1,4-DCB | 0.00055352 | 0.086412662 | 0.444936 | 0.126334866 |
| Land use | m2a crop eq | 7.6171E-06 | 0.000808282 | 0.024306 | 0.00700191 |
| Mineral resource scarcity | kg Cu eq | 9.3368E-06 | 0.000163492 | 0.000131 | 0.000645947 |
| Fossil resource scarcity | kg oil eq | 0.0001413 | 0.066222379 | 0.002823 | 0.057555071 |
| Water consumption | m3 | 0.00101162 | 0.003231363 | 0.00982 | 0.000281167 |

### 7.3.7.2.3. *Upgrading and end-use*

| | | Upgrading | | | | Waste | | |
|---|---|---|---|---|---|---|---|---|
| | | Green Hydrogen | Catalyst | Pipeline to bunker | Combustion HTL fuel | liquid | solid | gas |
| Source | | [13] | Ecoinvent | Ecoinvent | [14] | Ecoinvent | Ecoinvent | Ecoinvent |
| FU | | 1 kg | 1 kg | 1tkm | 1 MJ | 1 m3 | 1 kg | 1MJ |
| Impact category | Unit | | Nickel, 99.5% {GLO}\| market for \| Cut-off, S | Transport, pipeline, onshore, petroleum {RoW}\| market for transport, pipeline, onshore, petroleum \| Cut-off, S | | Wastewater, average {RoW}\| market for wastewater, average \| Cut-off, S | Inert waste, for final disposal {RoW}\| market for inert waste, for final disposal \| Cut-off, S | Waste refinery gas {GLO}\| treatment of, burned in flare \| Cut-off, S |
| Global warming | kg CO2 eq | 0.773 | 13.69273892 | 0.02117429 | 0.0015 | 0.565853 | 0.008368 | 0.056244 |
| Stratospheric ozone depletion | kg CFC11 eq | 4.58E-08 | 2.30064E-05 | 7.9582E-09 | | 1.45E-06 | 5.36E-09 | 0 |
| Ionizing radiation | kBq Co-60 eq | | 0.744182784 | 0.00137373 | | 0.023763 | 0.000216 | 9.22E-06 |
| Ozone formation, Human health | kg NOx eq | | 0.097769337 | 7.0151E-05 | | 0.002095 | 6.47E-05 | 0.000193 |
| Fine particulate matter formation | kg PM2.5 eq | | 0.798404064 | 4.7676E-05 | | 0.001633 | 1.82E-05 | 0.000238 |
| Ozone formation, Terrestrial ecosystems | kg NOx eq | | 0.099583254 | 7.1402E-05 | 0.00175624 | 0.002129 | 6.6E-05 | 0.000193 |
| Terrestrial acidification | kg SO2 eq | | 2.686052195 | 7.4481E-05 | 3.0714E-06 | 0.00399 | 4.07E-05 | 0.000798 |
| Freshwater eutrophication | kg P eq | | 0.020336793 | 8.8186E-06 | | 0.001125 | 9.38E-07 | 0 |
| Marine eutrophication | kg N eq | 9.64E-04 | 0.001361597 | 6.456E-07 | | 0.005881 | 7.06E-08 | 0 |

| | | Upgrading | | | Waste | | |
|---|---|---|---|---|---|---|---|
| Terrestrial ecotoxicity | kg 1,4-DCB | | 693.0582389 | 0.03140085 | 3.022633 | 0.06895 | 0.001918 |
| Freshwater ecotoxicity | kg 1,4-DCB | | 14.15238545 | 0.00068388 | 0.054436 | 0.000175 | 1.4E-09 |
| Marine ecotoxicity | kg 1,4-DCB | | 18.10587138 | 0.00090335 | 0.071402 | 0.000267 | 3.34E-07 |
| Human carcinogenic toxicity | kg 1,4-DCB | | 2.282904533 | 0.00213741 | 0.106899 | 0.000243 | 9.67E-08 |
| Human non-carcinogenic toxicity | kg 1,4-DCB | | 205.0384357 | 0.01655161 | 3.127685 | 0.004526 | 3.45E-05 |
| Land use | m2a crop eq | | 0.628986904 | 0.0003093 | 0.02812 | 0.000999 | 0 |
| Mineral resource scarcity | kg Cu eq | | 3.921565594 | 0.00014101 | 0.010584 | 2.65E-05 | 0 |
| Fossil resource scarcity | kg oil eq | | 3.248353119 | 0.00529022 | 0.12532 | 0.004432 | 0 |
| Water consumption | m3 | 9.05E-01 | 0.142573881 | 0.00014687 | -0.89523 | 0.000165 | 0 |

### *7.3.7.3. Namibia*

#### *7.3.7.3.1. Feedstock stage*

| | | Emissions due Acacia removal and Savannah restoration | Emission due to harvesting techniques | Acacia transport | Acacia chipping | Acacia Chips transport |
|---|---|---|---|---|---|---|
| Source | | [16] | [16] | Ecoinvent | Ecoinvent | Ecoinvent |
| FU | | 1 kg Acacia | 1 kg Acacia | 1tkm | 1kg woodchips | 1 tkm |
| Impact category | Unit | | | Transport, freight, lorry 16-32 metric ton, EURO2 {ZA}\| market for transport, freight, lorry 16-32 metric ton, EURO2 \| Cut-off, S | Wood chipping, industrial residual wood, stationary electric chipper {RER}\| processing \| Cut-off, S | Transport, freight train {ZA}\| market for transport, freight train \| Cut-off, S |
| Global warming | kg CO2 eq | -0.05 | 0.006202075 | 0.135253363 | 0.008797925 | 0.032426164 |
| Stratospheric ozone depletion | kg CFC11 eq | 0 | 0 | 6.8126E-08 | 4.87427E-09 | 1.93557E-08 |
| Ionizing radiation | kBq Co-60 eq | 0 | 0 | 0.002721131 | 0.004261878 | 0.001591187 |
| Ozone formation, Human health | kg NOx eq | 0 | 0 | 0.001000329 | 1.64164E-05 | 0.000140149 |
| Fine particulate matter formation | kg PM2.5 eq | 0 | 0 | 0.00025132 | 1.34296E-05 | 7.65063E-05 |
| Ozone formation, Terrestrial ecosystems | kg NOx eq | 0 | 0 | 0.001018164 | 1.66223E-05 | 0.000141824 |
| Terrestrial acidification | kg SO2 eq | 0 | 0 | 0.000628456 | 3.33105E-05 | 0.000212714 |
| Freshwater eutrophication | kg P eq | 0 | 0 | 3.27261E-05 | 8.40438E-06 | 1.71073E-05 |
| Marine eutrophication | kg N eq | 0 | 0 | 2.23162E-06 | 5.97933E-07 | 1.09195E-06 |
| Terrestrial ecotoxicity | kg 1,4-DCB | 0 | 0 | 2.029222313 | 0.011446585 | 0.11770132 |

| | | Emissions due Acacia removal and Savannah restoration | Emission due to harvesting techniques | Acacia transport | Acacia chipping | Acacia Chips transport |
|---|---|---|---|---|---|---|
| Freshwater ecotoxicity | kg 1,4-DCB | 0 | 0 | 0.003945369 | 0.000407668 | 0.001550005 |
| Marine ecotoxicity | kg 1,4-DCB | 0 | 0 | 0.006272448 | 0.000540721 | 0.002060876 |
| Human carcinogenic toxicity | kg 1,4-DCB | 0 | 0 | 0.005058492 | 0.000646254 | 0.003048683 |
| Human non-carcinogenic toxicity | kg 1,4-DCB | 0 | 0.00E+00 | 0.126184712 | 0.011467701 | 0.037562501 |
| Land use | m2a crop eq | 0 | 0 | 0.01114799 | 0.000315434 | 0.002130842 |
| Mineral resource scarcity | kg Cu eq | 0 | 0 | 0.000579392 | 2.41971E-05 | 0.000196503 |
| Fossil resource scarcity | kg oil eq | 0 | 0 | 0.044432544 | 0.002313886 | 0.00906583 |
| Water consumption | m3 | 0 | 0 | 0.000438057 | 0.000148025 | 0.000153908 |

### 7.3.7.3.2. HTL stage

| | | HTL | | Energy | |
|---|---|---|---|---|---|
| | | tap water | Na2CO3 | electricity mix | electricity from CHP |
| Source | | Ecoinvent | Ecoinvent | Ecoinvent | Ecoinvent |
| FU | | 1 kg | 1 kg | 1 kWh | 1 kWh |
| Impact category | Unit | Tap water {ZA}\| market for tap water \| Cut-off, S | Sodium bicarbonate {GLO}\| market for sodium bicarbonate \| Cut-off, S | Electricity, high voltage {ZA}\| market for \| Cut-off, S | Electricity, high voltage {ZA}\| heat and power co-generation, wood chips, 6667 kW \| Cut-off, S |
| Global warming | kg CO2 eq | 0.00139396 | 1.32949183 | 1.047204772 | 0.05741 |
| Stratospheric ozone depletion | kg CFC11 eq | 9.273E-10 | 4.2394E-07 | 8.28356E-07 | 4.37E-07 |
| Ionizing radiation | kBq Co-60 eq | 5.5721E-05 | 0.05044467 | 0.04753604 | 0.000935 |
| Ozone formation, Human health | kg NOx eq | 5.4065E-06 | 0.00366827 | 0.00461637 | 0.002657 |
| Fine particulate matter formation | kg PM2.5 eq | 3.4995E-06 | 0.0035826 | 0.003010681 | 0.000751 |
| Ozone formation, Terrestrial ecosystems | kg NOx eq | 5.4589E-06 | 0.00371686 | 0.004628077 | 0.002677 |
| Terrestrial acidification | kg SO2 eq | 1.0779E-05 | 0.01185943 | 0.010000994 | 0.001118 |
| Freshwater eutrophication | kg P eq | 8.3755E-07 | 0.00067872 | 0.000757542 | 1.44E-05 |
| Marine eutrophication | kg N eq | 6.441E-08 | 4.2639E-05 | 4.59946E-05 | 1.45E-06 |
| Terrestrial ecotoxicity | kg 1,4-DCB | 0.0027089 | 11.6153494 | 0.98625085 | 1.466353 |
| Freshwater ecotoxicity | kg 1,4-DCB | 4.6902E-05 | 0.20191317 | 0.026086129 | 0.003369 |
| Marine ecotoxicity | kg 1,4-DCB | 6.4217E-05 | 0.2599892 | 0.036340013 | 0.005402 |
| Human carcinogenic toxicity | kg 1,4-DCB | 0.00026776 | 0.07266027 | 0.071016834 | 0.003094 |

| | | | | | |
|---|---|---|---|---|---|
| Human non-carcinogenic toxicity | kg 1,4-DCB | 0.001563 | 3.38489365 | 1.217570611 | 0.357344 |
| Land use | m2a crop eq | 1.709E-05 | 0.10603636 | 0.010749586 | 0.679277 |
| Mineral resource scarcity | kg Cu eq | 8.1241E-06 | 0.02748503 | 0.000357079 | 0.000299 |
| Fossil resource scarcity | kg oil eq | 0.00037935 | 0.27754273 | 0.30879096 | 0.014491 |
| Water consumption | m3 | 0.00101124 | 0.04678502 | 0.003373068 | 0.000157 |

### 7.3.7.3.3. *Upgrading and end-use*

| | | Upgrading | | | | Waste | | |
|---|---|---|---|---|---|---|---|---|
| | | Green Hydrogen | Catalyst | Pipeline to bunker | Combustion HTL fuel | liquid | solid | gas |
| Source | | [13] | Ecoinvent | Ecoinvent | [14] | Ecoinvent | Ecoinvent | Ecoinvent |
| FU | | 1 kg | 1 kg | 1tkm | 1 MJ | 1 m3 | 1 kg | 1MJ |
| Impact category | Unit | | Nickel, 99.5% {GLO}\| market for \| Cut-off, S | Transport, pipeline, onshore, petroleum {RoW}\| market for transport, pipeline, onshore, petroleum \| Cut-off, S | | Wastewater, average {RoW}\| market for wastewater, average \| Cut-off, S | Inert waste, for final disposal {RoW}\| market for inert waste, for final disposal \| Cut-off, S | Waste refinery gas {GLO}\| treatment of, burned in flare \| Cut-off, S |
| Global warming | kg CO2 eq | 0.773 | 13.69273892 | 0.02117429 | 0.0015 | 0.565853 | 0.008368 | 0.056244 |
| Stratospheric ozone depletion | kg CFC11 eq | 4.58E-08 | 2.30064E-05 | 7.9582E-09 | | 1.45E-06 | 5.36E-09 | 0 |
| Ionizing radiation | kBq Co-60 eq | | 0.744182784 | 0.00137373 | | 0.023763 | 0.000216 | 9.22E-06 |
| Ozone formation, Human health | kg NOx eq | | 0.097769337 | 7.0151E-05 | | 0.002095 | 6.47E-05 | 0.000193 |
| Fine particulate matter formation | kg PM2.5 eq | | 0.798404064 | 4.7676E-05 | | 0.001633 | 1.82E-05 | 0.000238 |
| Ozone formation, Terrestrial ecosystems | kg NOx eq | | 0.099583254 | 7.1402E-05 | 0.00175624 | 0.002129 | 6.6E-05 | 0.000193 |
| Terrestrial acidification | kg SO2 eq | | 2.686052195 | 7.4481E-05 | 3.0714E-06 | 0.00399 | 4.07E-05 | 0.000798 |
| Freshwater eutrophication | kg P eq | | 0.020336793 | 8.8186E-06 | | 0.001125 | 9.38E-07 | 0 |
| Marine eutrophication | kg N eq | 9.64E-04 | 0.001361597 | 6.456E-07 | | 0.005881 | 7.06E-08 | 0 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Terrestrial ecotoxicity | kg 1,4-DCB | | 693.0582389 | 0.03140085 | | 3.022633 | 0.06895 | 0.001918 |
| Freshwater ecotoxicity | kg 1,4-DCB | | 14.15238545 | 0.00068388 | | 0.054436 | 0.000175 | 1.4E-09 |
| Marine ecotoxicity | kg 1,4-DCB | | 18.10587138 | 0.00090335 | | 0.071402 | 0.000267 | 3.34E-07 |
| Human carcinogenic toxicity | kg 1,4-DCB | | 2.282904533 | 0.00213741 | | 0.106899 | 0.000243 | 9.67E-08 |
| Human non-carcinogenic toxicity | kg 1,4-DCB | | 205.0384357 | 0.01655161 | | 3.127685 | 0.004526 | 3.45E-05 |
| Land use | m2a crop eq | | 0.628986904 | 0.0003093 | | 0.02812 | 0.000999 | 0 |
| Mineral resource scarcity | kg Cu eq | | 3.921565594 | 0.00014101 | | 0.010584 | 2.65E-05 | 0 |
| Fossil resource scarcity | kg oil eq | | 3.248353119 | 0.00529022 | | 0.12532 | 0.004432 | 0 |
| Water consumption | m3 | 9.05E-01 | 0.142573881 | 0.00014687 | | -0.89523 | 0.000165 | 0 |

### 7.3.8. Mass Balances from Aspen

| | | Olive Pruning | Coffee Pulp | Acacia Bush |
|---|---|---|---|---|
| **HYDROTHERMAL LIQUEFACTION** | | per hour | per hour | per hour |
| | | | | |
| **Feedstock Acquisition** | | | | |
| *OUT* | | | | |
| Wet Feedstock | kg | 56250 | 10417 | 31250 |
| of which, dry biomass | kg | 52700 | 8778 | 28813 |
| of which, H2O | kg | 3428 | 729 | 1184 |
| of which, ash | kg | 121 | 909 | 1253 |
| **Hot Water Injection** | | | | |
| **Aqueous Recycling** | | | | |
| *IN* | | 580517 | 218440 | 321150 |
| Ground Feedstock | kg | 56250 | 10417 | 31250 |
| H2O | kg | 110349 | 48500 | 62500 |
| Recycled Aqueous | kg | 413918 | 159523 | 227400 |
| of which, organics | kg | 835 | 104 | 545 |
| of which, H2O | kg | 413083 | 159419 | 226855 |
| | | | | |
| *OUT* | | | | |
| Impregnated Feed | kg | 580740 | 1051439 | 321150 |
| of which, organics in feedstock | kg | 52700 | 0 | 28813 |
| of which, ash in feedstock | kg | 121 | 909 | 1253 |
| of which, organics in recyclate | kg | 835 | 104 | 545 |
| of which, H2O | kg | 527083 | 1050425 | 290539 |
| | | | | |
| **Hydrothermal Liquefaction Reactor** | | | | |
| Impregnated Feed | kg | 580740 | 217530 | 316877 |
| | | | | |
| Hot HTL Slurry | kg | 580739 | 217530 | 316877 |
| of which, total org. in biocrude | kg | 21355 | 2343 | 8834 |
| of which, org. in aqueous | kg | 25863 | 5069 | 13007 |
| of which, solids | kg | 6439 | 1347 | 3568 |
| of which, H2O | kg | 527082 | 207628 | 286726 |
| of which, gas | kg | 0 | 1143 | 4742 |
| | | | | |
| **Cooling/Depressurization** | | | | |
| *IN* | | | | |
| Hot HTL Slurry | kg | 580739 | 217530 | 316877 |

| | | Olive Pruning | Coffee Pulp | Acacia Bush |
|---|---|---|---|---|
| *OUT* | | | | |
| Cooled HTL Slurry | kg | 580739 | 217530 | 316877 |
| | | | | |
| **Filter Solid Liquid Separation** | | | | |
| *IN* | | | | |
| hot HTL Slurry | kg | 580739 | 217530 | 316877 |
| | | | | |
| *OUT* | | 580740 | 217530 | 316877 |
| HTL Slurry, solid-free | kg | 574301 | 216183 | 313309 |
| Solids [to Cogeneration] | kg | 6439 | 1347 | 3568 |
| | | | | |
| **Three Phase Separator: Gas & Liquid** | | | | |
| *IN* | | | | |
| HTL Slurry, solid-free | kg | 574301 | 216183 | 313309 |
| | | | | |
| *OUT* | | 574301 | 216183 | 313309 |
| HTL Liquid | kg | 574301 | 215041 | 308567 |
| Offgases [to Cogeneration & H2] | kg | 0 | 1143 | 4742 |
| **Three Phase Separator: Aqueous & Organic** | | | | |
| *IN* | | | | |
| HTL Liquid | kg | 574301 | 215041 | 308567 |
| | | | | |
| *OUT* | | 574301 | 215040 | 308567 |
| Biocrude | kg | 21428 | 2343 | 9484 |
| of which, organics | kg | 20135 | 2090 | 8834 |
| of which, H2O | kg | 1293 | 253 | 650 |
| of which, ash | kg | 0 | 0 | 0 |
| Aqueous | kg | 552873 | 212697 | 299083 |
| of which, organics | kg | 1221 | 139 | 685 |
| of which, H2O | kg | 551652 | 212558 | 298398 |
| **Three Phase Separator: Aqueous** | | | | |
| *IN* | | | | |
| Aqueous | kg | 552873 | 212697 | 299083 |
| | | | | |
| *OUT* | | 552873 | 212698 | 299082 |
| Aqueous to recycle | kg | 414655 | 159523 | 224311 |
| of which, organics | kg | 916 | 104 | 513 |
| of which, H2O | kg | 413739 | 159419 | 223798 |
| | | | | |
| Waste Aqueous [to WWT] | kg | 138218 | 53174 | 74771 |

| | | Olive Pruning | Coffee Pulp | Acacia Bush |
|---|---|---|---|---|
| **Hydrogen Pressurization** | | | | |
| *OUT* | | | | |
| Pressurized H2 | kg | 1150 | 157 | 484 |
| *of which, from fresh green hydrogen* | *kg* | 859 | 117 | 363 |
| *of which, recovered from PSA [H.2]* | *kg* | 291 | 40 | 122 |
| | | | | |
| **Hydrotreating** | | | | |
| *IN* | | 22578 | 2500 | 9968 |
| Biocrude [equilibrium yield] | kg | 21428 | 2343 | 9484 |
| Pressurized H2 | kg | 1150 | 157 | 484 |
| | | | | |
| *OUT* | | | | |
| Hot hydrotreated biocrude | kg | 22578 | 2500 | 9968 |
| of which, organics | kg | 18817 | 1975 | 8286 |
| of which, H2O | kg | 3179 | 444 | 1439 |
| of which, ash | kg | 0 | 0 | 0 |
| of which, H2 | kg | 582 | 81 | 243 |
| **Cooling and Depressurization** | | | | |
| *IN* | | | | |
| Hot hydrotreated biocrude | kg | 22578 | 2500 | 9968 |
| | | | | |
| *OUT* | | | | |
| Cool hydrotreated biocrude | kg | 22578 | 2500 | 9968 |
| **Flash Separation** | | | | |
| *IN* | | | | |
| Cool hydrotreated biocrude | kg | 22578 | 2500 | 9968 |
| | | | | |
| *OUT* | | 22578 | 2500 | 9968 |
| Flashed biocrude | kg | 20223 | 1901 | 8612 |
| H2O [to WWT] | kg | 1772 | 444 | 742 |
| Gas [to H2] | kg | 582 | 155 | 614 |
| of which, H2 | kg | 582 | 81 | 243 |
| **Pressure Swing Absorption** | | | | |
| *IN* | | | | |
| Gas | kg | 582 | 155 | 614 |
| | | | | |
| OUT | | 582 | 155 | 614 |
| H2 [to Hydrotreatment] | kg | 291 | 40 | 122 |
| h2 to cogen | kg | 291 | 40 | 122 |
| Offgasses [to cogen] | kg | 0 | 74 | 371 |

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| | | Olive Pruning | Coffee Pulp | Acacia Bush |
|---|---|---|---|---|
| **HTL Balance** | | | | |
| **In** | | 240992 | 80129 | 122372 |
| dry Feedstock | kg | 52700 | 8778 | 28813 |
| Water | kg | 113778 | 48500 | 62500 |
| hydrogen | kg | 859 | 117 | 363 |
| Air | kg | 73655 | 22734 | 30697 |
| Natural gas | kg | 0 | 0 | 0 |
| **Out** | | 240429 | 81653 | 123131 |
| Biofuel | kg | 20223 | 1901 | 8612 |
| flue gases | kg | 80094 | 25224 | 37754 |
| Waste Water [to WWT] | kg | 139991 | 53619 | 75513 |
| ash | kg | 121 | 909 | 1253 |
| | | | | |
| Mass Imbalance (in %) | | 0 | 0 | 0 |
| HTL output (in kilotons per annum) | | 171 | 19 | 76 |
| Upgraded biooil output (in kilotons per annum) | | 162 | 15 | 69 |
| Light Naphtha | kg | 3208 | 270 | 3059 |
| Biojet | kg | 9435 | 906 | 2770 |
| Diesel | kg | 7264 | 697 | 2132 |

## 7.3.9. Energy and utilities. Based on Aspen and Tanzer *et al.* (2019) [17]

| | | Spain | Colombia | Namibia |
|---|---|---|---|---|
| Total Heat of Reaction | MJ | 164190 | 86261 | 115848 |
| Energy Generated, Boiler | MJ | 131352 | 69009 | 92678 |
| Max Electric Potential | kwh | 29189 | 15335 | 20595 |
| HTL UTILITY DEMAND TOTALS | | | | |
| Total Electricity Demand | kwh | 5137 | 1269 | 1780 |
| Total Electricity Demand | MJ | 18494 | 4570 | 6407 |
| Boiler Energy Used for Electricity Demand | MJ | 23117 | 5712 | 8008 |
| Unfulfilled Electricity Demand | MJ | 0 | 0 | 0 |
| Boiler Energy Remaining | MJ | 108235 | 63297 | 84670 |
| Total Heat Demand | MJ | 529272 | 271820 | 296319 |
| Process Heat Recovered | MJ | 423418 | 217456 | 237055 |
| Utility Heat Demand | MJ | 105854 | 54364 | 59264 |
| Boiler Energy Used for Heat Demand | MJ | 108235 | 63297 | 84670 |
| Unfufilled Heat Demand | MJ | 0 | 0 | 0 |
| Natural Gas Demand | kg | 0 | 0 | 0 |
| Excess Boiler Energy | MJ | 2381 | 8933 | 25406 |
| Excess Electricity | kwh | 529 | 1985 | 5646 |
| | | | | |
| Total Utility Water Demand | kg | 47256 | 24270 | 26457 |
| Make up water | kg | 41586 | 21357 | 23282 |
| Blow down water | kg | 5671 | 2912 | 3175 |
| Cooling Water | kg | 0 | 0 | 0 |

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## 7.3.10. Detailed economic calculations

| | | Spain | Colombia | Namibia |
|---|---|---|---|---|
| Fixed Capital Investments, including | M EUR | 380 | 174 | 243 |
| Direct Capital Costs, including | M EUR | 233 | 106 | 149 |
| Total Purchased Equipment Cost | M EUR | 93 | 43 | 60 |
| of which, Feedstock Handling & Prep | M EUR | 6 | 0 | 3 |
| of which, Oil Production | M EUR | 82 | 39 | 52 |
| of which, hydrotreatment | M EUR | 0 | 0 | 0 |
| of which, Cogeneration | M EUR | 5 | 3 | 4 |
| Installation Costs | M EUR | 140 | 64 | 89 |
| Indirect Costs | M EUR | 79 | 36 | 51 |
| Contractor's Fee | M EUR | 21 | 10 | 14 |
| Contingency | M EUR | 47 | 21 | 30 |
| Working Capital | M EUR | 25 | 2 | 9 |
| Start-up Costs | M EUR | 38 | 17 | 24 |
| TOTAL CAPITAL INVESTMENT | M EUR | 442 | 193 | 276 |
| LOCATION ADJUSTED CAPEX | M EUR | 398 | 154 | 331 |
| | | | | |
| Direct Production Costs, including | | 108 | 21 | 57 |
| Variable costs | M EUR/year | 71 | 7 | 26 |
| of which, feedstock | M EUR/year | 45 | 4 | 16 |
| of which, hydrogen | M EUR/year | 0 | 0 | 0 |
| of which, wastewater treatment | M EUR/year | 1 | 0 | 0 |
| of which, gas cleaning | M EUR/year | 4 | 1 | 2 |
| of which, ash disposal | M EUR/year | 0 | 1 | 1 |
| of which, catalysts | M EUR/year | 21 | 1 | 6 |
| of which, natural gas | M EUR/year | 0 | 0 | 0 |
| of which, water | M EUR/year | 0 | 0 | 0 |
| Labor Related Costs | M EUR/year | 3 | 0 | 1 |
| of which, direct wage and benefits | M EUR/year | 2 | 0 | 1 |
| of which, supervision, supplies, assistance | M EUR/year | 1 | 0 | 0 |
| Maintenance | M EUR/year | 34 | 14 | 29 |
| Plant Overhead | M EUR/year | 2 | 0 | 1 |
| Contingency | M EUR/year | 22 | 4 | 11 |
| Fixed Charges, including | M EUR/year | 64 | 46 | 89 |
| Local Taxes | M EUR/year | 5 | 2 | 4 |
| Insurance | M EUR/year | 3 | 1 | 3 |
| Depreciation | M EUR/year | 55 | 43 | 82 |
| Total General Expenses | M EUR/year | 12 | 1 | 4 |
| TOTAL OPERATING COSTS (Annual) | M EUR/YEAR | 224 | 73 | 163 |

| | | Spain | Colombia | Namibia |
|---|---|---|---|---|
| Biocrude/biofuel to be transported (in ktpa) | in ktpa | 171 | 19 | 0 |
| Total biocrude transport-distance | t-km | 54855245 | 1405807 | 0 |
| Transport fixed costs (based on tonnes, MEUR per year) | M EUR/YEAR | 2 | 0 | 0 |
| Transport variable costs (based on tkm, in MEUR per year) | M EUR/YEAR | 15 | 0 | 0 |
| Total transportation costs in MEUR per year | M EUR/YEAR | 17 | 0 | 0 |
| Annual Salues Revenue | M EUR/year | 124 | 10 | 43 |
| of which Biocrude | M EUR/year | 52 | 4 | 14 |
| of which biochar | M EUR/year | 0 | 0 | 0 |
| of which Electricity | M EUR/year | 0 | 0 | 0 |
| of which naphtha | M EUR/year | 16 | 1 | 15 |
| of which biojet | M EUR/year | 56 | 5 | 15 |
| Gross Profit | M EUR/year | 52 | 3 | 17 |
| Earninngs Before Tax | M EUR/year | -100 | -63 | -120 |
| Minimum Fuel Selling Price | EUR/ton | 940 | 4447 | 1936 |
| MFSP: MGO Price Ratio | | 1,050 | 5,54 | 2,42 |

## 7.3.11. Energy balances of HTL conversion process

| Case study location | Unit | Spain | Colombia | Namibia |
| --- | --- | --- | --- | --- |
| **Energy In** | | 904750 | 136700 | 506922 |
| Biomass | MJ | 890636 | 135095 | 497505 |
| Natural Gas | MJ | 0 | 0 | 0 |
| Biomass in Recycled Aqueous | MJ | 14113 | 1604 | 9416 |
| **Energy Out** | | | | |
| Biocrude | MJ | 531868 | 57482 | 256635 |
| Biomass Combustion | MJ | 164190 | 60922 | 115848 |
| of which, internal heat | MJ | 13712 | 5712 | 8008 |
| of which, internal electricity | MJ | 10970 | 4570 | 6407 |
| of which, salable electricity | MJ | 6549 | 7146 | 20325 |
| of which, known losses | MJ | 132960 | 43493 | 81108 |
| Aqueous Waste Purge | MJ | 44252 | 6855 | 32618 |
| Aqueous & Other unknown Losses | MJ | 132756 | 20566 | 97855 |
| Error ([Energy In – Energy Out]/Energy In)* | | 3.5% | - 6.7% | 6.6% |
| **Contribution** | | | | |
| Biocrude | | 59% | 40% | 51% |
| Salable Electricity | | 1% | 5% | 4% |
| Process Energy, from Biogas and Char | | 3% | 8% | 3% |
| Process Energy, from Natural Gas | | 0% | 0% | 0% |
| Aqueous Recyclate | | 15% | 15% | 19% |
| Combustion Losses | | 15% | 32% | 16% |
| Waste Aqueous & Unknown Losses | | 8% | 0% | 7% |

* due to differences in assumed HHV value of biomass and product streams due to lack of experimental data

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## 7.4. APPENDIX C

### 7.4.1. Example of a Roadmap from a focus group in Colombia


Figure 7.18: Inputs from Colombian stakeholders in a focus group for a roadmap for biohub implementation

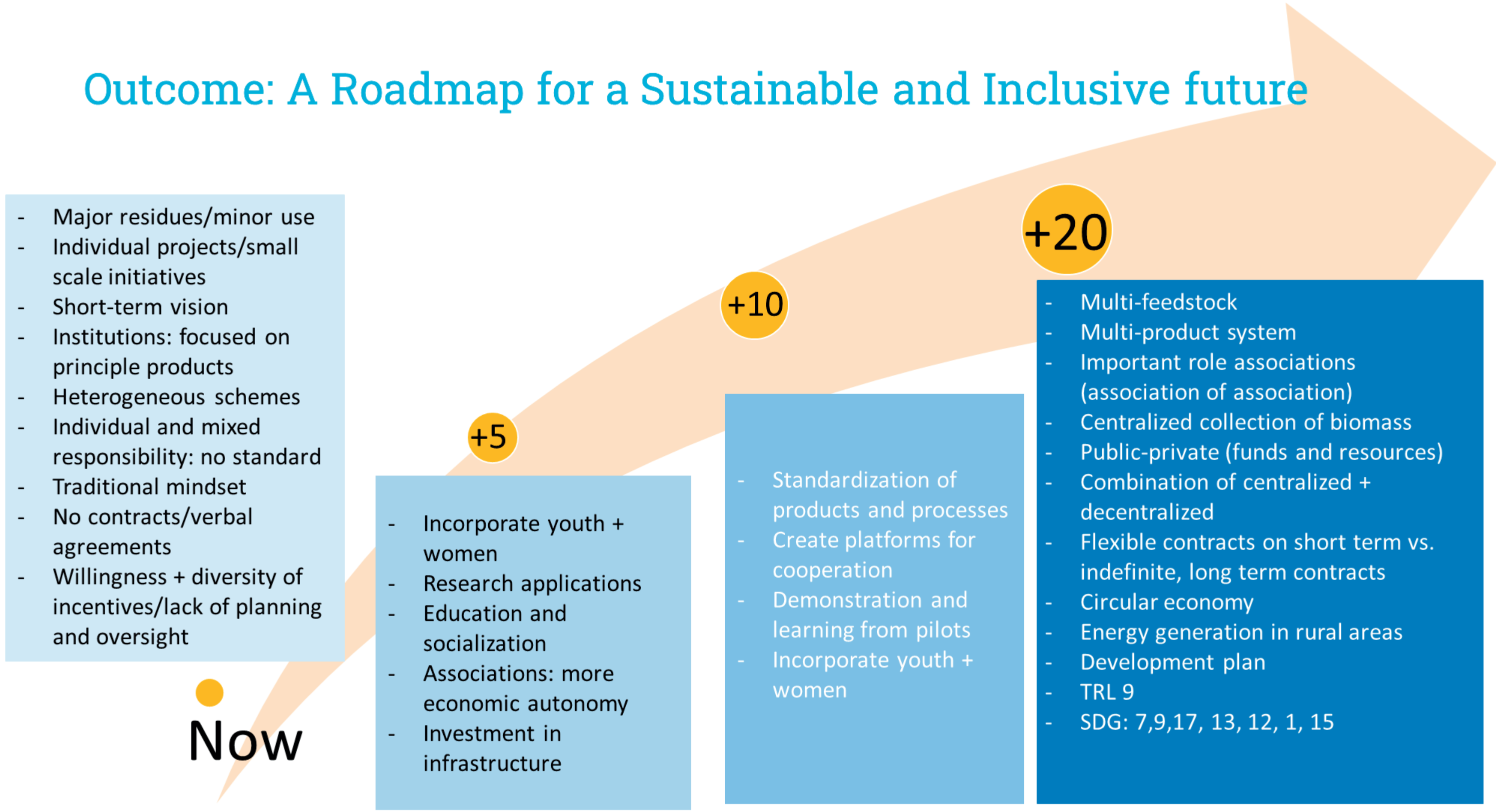


Figure 7.19: Compilation of all inputs for a roadmap for the Colombian case study

### 7.4.2. Performance Indicator Ranking

#### *7.4.2.1. Survey Spain*

*7.4.2.1.1. Ranking KPIs for a potential Marine Biofuel value chain in Spain*

As a part of CLEAN SHIPPING project, as an expert, we ask you to rank different aspects, impact categories and Key Performance Indicators (KPIs) for a potential marine biofuel value chain in Spain based on olive residues. This survey will focus on the technical, economic, environmental and social aspects of the value chain. All the responses will be anonymized and no personal information will be disclosed.

1. Do you consent to participate in this survey?
2. Name, organization
3. Rank the different aspect of the value chain according to priority
   a. Technical
   b. Economical
   c. Environmental
   d. Social
4. Rank the different impact categories of the technical assessment according to priority
   a. Biomass (feedstock) properties
   b. Biocrude properties
   c. Upgraded biofuel properties
   d. Overall Process parameters
5. Which KPI of the impact category "Biomass properties" do you find more important?
   a. Ultimate analysis of biomass
   b. Proximate analysis of biomass
   c. Both equally important
6. Which KPI of the impact category "Biocrude properties" do you find more important?
   a. Ultimate analysis of biocrude
   b. Proximate analysis of biocrude
   c. Both equally important
7. Which KPI of the impact category "Biofuel properties" do you find more important?
   a. Proximate analysis of marine biofuel
   b. Annual production of marine biofuel
   c. Physical properties of marine biofuel
8. Which KPI of the impact category "Overall process" do you find more important?

a. Overall process yield
b. Energy efficiency
c. Both equally important

9. Rank the different impact categories of the economic assessment according to priority?
   a. Feedstock processing stage
   b. HTL (biomass conversion) stage
   c. Selling price of biofuel
   d. Overall Process (CAPEX and OPEX)
10. Which KPI of the impact category "Feedstock Processing" do you find more important?
   a. Biomass pre-processing costs
   b. Feedstock transportation
   c. Both equally important
11. Which KPI of the impact category "HTL stage" do you find more important?
   a. Total investment
   b. Upgrading operational Costs
   c. Both equally important
12. For the impact category "selling price of biofuel" the KPI of "min. biofuel selling price" has been chosen. Do you agree and/or would you add an extra KPI?
13. Rank the KPIs of the impact category "Overall Process" according to priority
   a. Transportation costs
   b. Levelized costs of energy
   c. Rate of return
   d. Payback time
14. Rank the different Areas of Protection of the environmental assessment according to priority?
   a. Ecosystem Health
   b. Human Health
   c. Man Made Environment
15. Rank the different impact categories of the Area of Protection "Ecosystem Health" according to priority?
   a. Climate change
   b. Eutrophication
   c. Acidification Potential
16. Rank the KPIs of the impact category "Climate Change" according to priority?
   a. GHG emissions harvesting
   b. GHG emissions transport
   c. GHG emissions conversion
   d. GHG emissions biofuel combustion

e. Global warming potential

17. For the impact category “Eutrophication” the KPI of “Freshwater Eutrophication” has been chosen.
18. For the impact category “Acidification Potential” the KPI of “Soil Acidification” has been chosen. Do you agree and/or would you add an extra KPI?
19. Which KPI of the Area of Protection “Human Health” do you find more important?
    a. Particulate matter emission
    b. Regulated toxic gas emission
    c. Both equally important
20. For the Area of Protection “Man Made Environment” the KPI of “Soil Erosion” has been chosen. Do you agree and/or would you add an extra KPI?
21. Rank the different Areas of Impact of the social assessment according to priority
    a. Workers
    b. Local community
    c. Value chain actors
    d. Society
    e. Consumers
22. Rank the different impact categories of the Area of Impact “Workers” according to priority
    a. Working Hours
    b. Equal Opportunity
    c. Sexual harassment
23. For the impact category “Working Hours” the KPI of “Overtime worked by employees” has been chosen. Do you agree and/or would you add an extra KPI?
24. For the impact category “Equal Opportunity” the KPI of “Gender Gap Index” has been chosen. Do you agree and/or would you add an extra KPI?
25. For the impact category “Sexual Harassment” the KPI “Number of Sexual Harassment cases that have been reported” has been chosen. Do you agree and/or would you add an extra KPI?
26. Which impact category of the Area of Impact “Local Community” do you find more important?
    a. Local employment
    b. Rural development
    c. Both equally
27. For the impact category “Local Employment” the KPI of “Unemployment Statistics” has been chosen. Do you agree and/or would you add an extra KPI?
28. For the impact category “Rural Development” the KPI of “Rural Abandonment Statistics” has been chosen. Do you agree and/or would you add an extra KPI?
29. For the area of impact “Value Chain Actors” the KPI of “Gini Index (Wealth Distribution)” has been chosen. Do you agree and/or would you add an extra KPI?

30. Which impact category of the Area of Impact "Society" do you find more important?
    a. Contribution to economic development
    b. Poverty alleviation
    c. Both equally important
31. For the impact category "Contribution to Economy" the KPI "Contribution to GDP" has been chosen. Do you agree and/or would you add an extra KPI?
32. For the impact category "Poverty Alleviation" the KPI of "Multidimensional Poverty Index" has been chosen. Do you agree and/or would you add an extra KPI?
33. Which impact category of the Area of Impact "Consumers" do you find more important?
    a. Feedback Mechanism
    b. Transparency
    c. Both equally important
34. For the impact category "Feedback Mechanism" the KPI "Customer Satisfaction Score" has been chosen. Do you agree and/or would you add an extra KPI?
35. For the impact category "Transparency" the KPI "Company Rating in Sustainability Indices" has been chosen. Do you agree and/or would you add an extra KPI?
36. Did we miss some crucial KPIs for a successful sustainability analysis?

#### *7.4.2.2. Survey Namibia*

##### *7.4.2.2.1. Ranking KPIs for a potential Marine Biofuel value chain in Namibia*

As a part of CLEAN SHIPPING project, as an expert, we ask you to rank different aspects, impact categories and Key Performance Indicators (KPIs) for a potential marine biofuel value chain in Namibia based on Acacia wood chips. This survey will focus on the technical, economic and environmental aspects of the value chain. All the responses will be anonymized and no personal information will be disclosed.

1. Do you consent to participate in this survey?
2. Name, organization
3. Rank the different aspect of the value chain according to priority

a. Technical
b. Economical
c. Environmental
d. Social

4. Rank the different impact categories of the technical assessment according to priority
    a. Biomass (feedstock) properties
    b. Biocrude properties

c. Upgraded biofuel properties
d. Overall Process parameters

5. Which KPI of the impact category "Biomass properties" do you find more important?
   a. Ultimate analysis of biomass
   b. Proximate analysis of biomass
   c. Both equally important
6. Which KPI of the impact category "Biocrude properties" do you find more important?
   a. Ultimate analysis of biocrude
   b. Proximate analysis of biocrude
   c. Both equally important
7. Which KPI of the impact category "Biofuel properties" do you find more important?
   a. Proximate analysis of marine biofuel
   b. Annual production of marine biofuel
   c. Physical properties of marine biofuel
8. Which KPI of the impact category "Overall process" do you find more important?
   a. Overall process yield
   b. Energy efficiency
   c. Both equally important
9. Rank the different impact categories of the economic assessment according to priority?
   a. Feedstock processing stage
   b. HTL (biomass conversion) stage
   c. Selling price of biofuel
   d. Overall Process (CAPEX and OPEX)
10. Which KPI of the impact category "Feedstock Processing" do you find more important?
    a. Biomass pre-processing costs
    b. Feedstock transportation
    c. Both equally important
11. Which KPI of the impact category "HTL stage" do you find more important?
    a. Total investment
    b. Upgrading operational Costs
    c. Both equally important
12. For the impact category "selling price of biofuel" the KPI of "min. biofuel selling price" has been chosen. Do you agree and/or would you add an extra KPI?
13. Rank the KPIs of the impact category "Overall Process" according to priority
    a. Transportation costs

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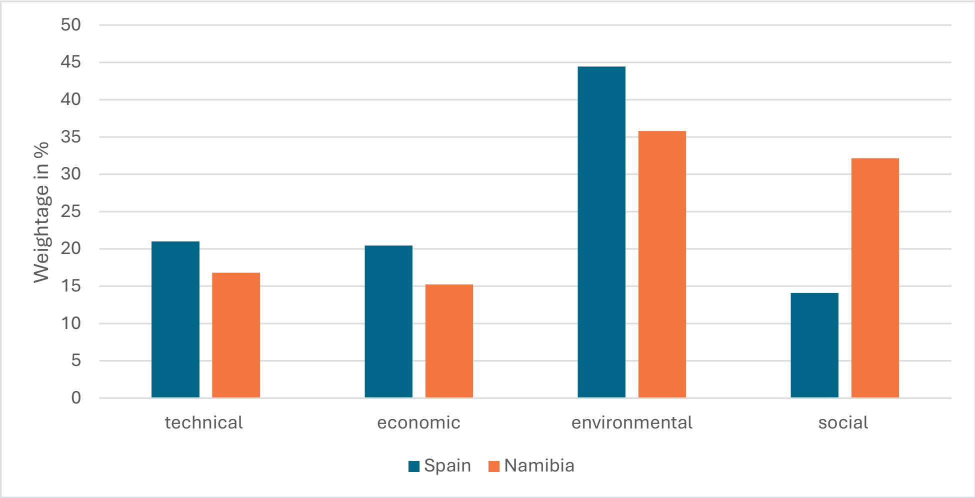
b. Levelized costs of energy
c. Rate of return
d. Payback time

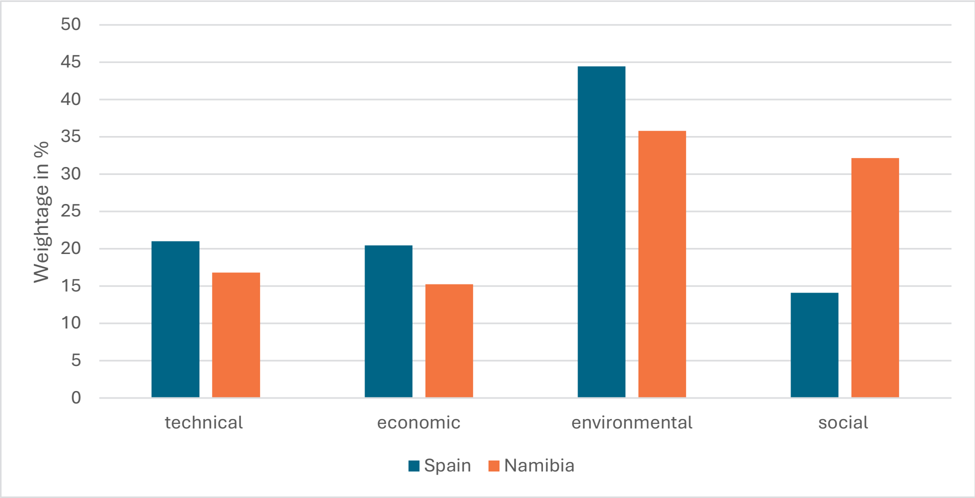
14. What Area of Protection (AoP) of the environmental assessment do you find more important?
    a. Ecosystem health
    b. Human health
    c. Both equally important
15. Rank the different impact categories of the Area of Protection "Ecosystem Health" according to priority
    a. Climate change
    b. Land degradation
    c. Fauna
16. Rank the KPIs of the impact category "Climate Change" according to priority
    a. GHG emissions harvesting
    b. GHG emissions transport
    c. GHG emissions conversion
    d. GHG emissions biofuel combustion
    e. Global warming potential
    f. Carbon sink loss
17. Rank the KPIs of the impact category "Land Degradation" according to priority
    a. Soil erosion
    b. Biodiversity
    c. Soil fertility
    d. Encroached area
18. Which KPI of the impact category "Fauna" do you find more important?
    a. Wildlife count
    b. Cattle farming capacity
19. Which KPI of the Area of Protection "Human Health" do you find more important?
    a. Particulate matter emission
    b. Regulated toxic gas emissions
    c. Both equally important
20. Did we miss some crucial KPIs for a successful sustainability analysis?

### 7.4.3. Rankings

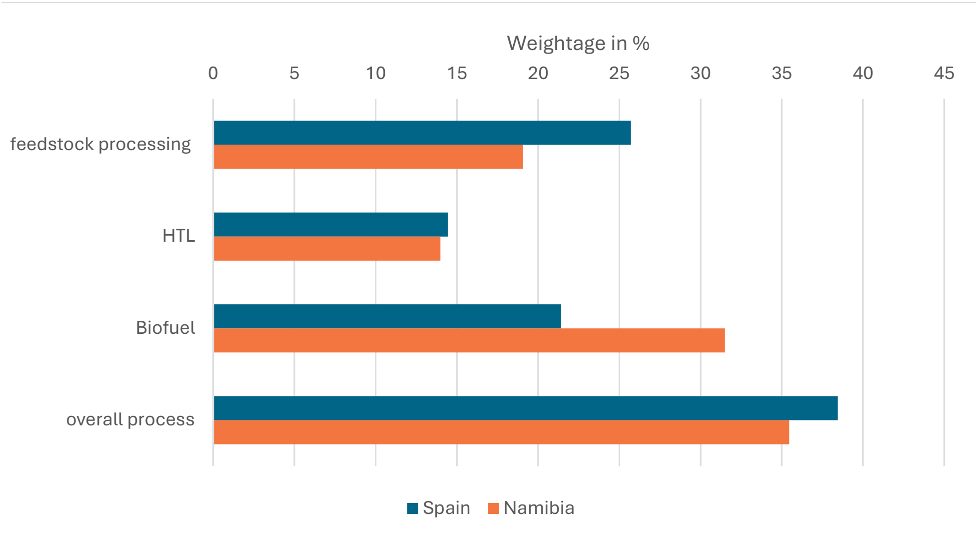
#### *7.4.3.1. Weightage on aspect level*



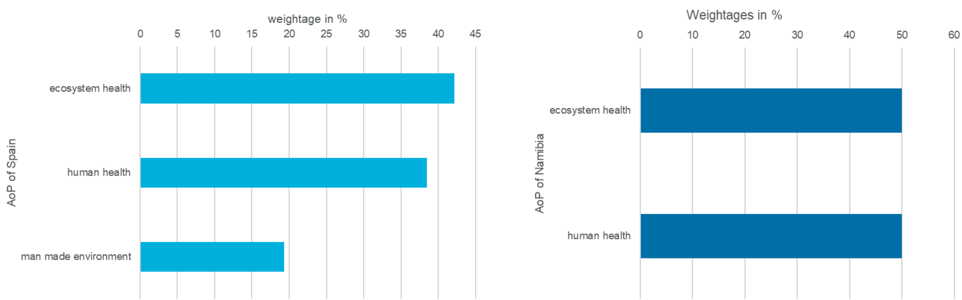

#### *7.4.3.2. Weightage on technical aspects*



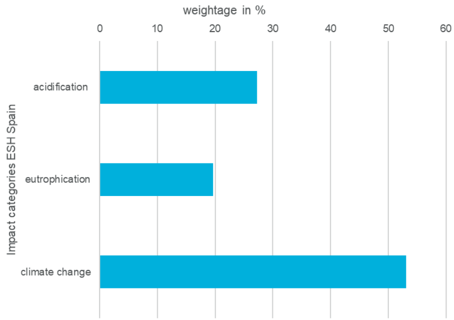
### *7.4.3.3. Weightage on economic aspects*

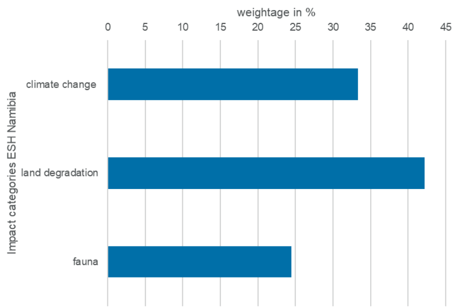



### *7.4.3.4. Weightage Environmental aspect Area of Protection*

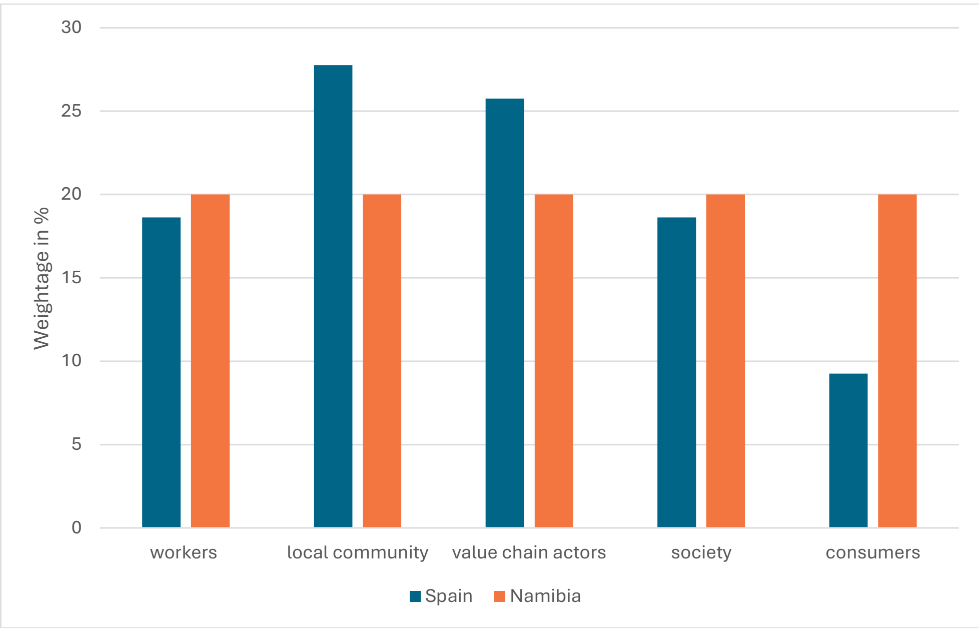


### *7.4.3.5. Weightage Environmental aspect impact category*

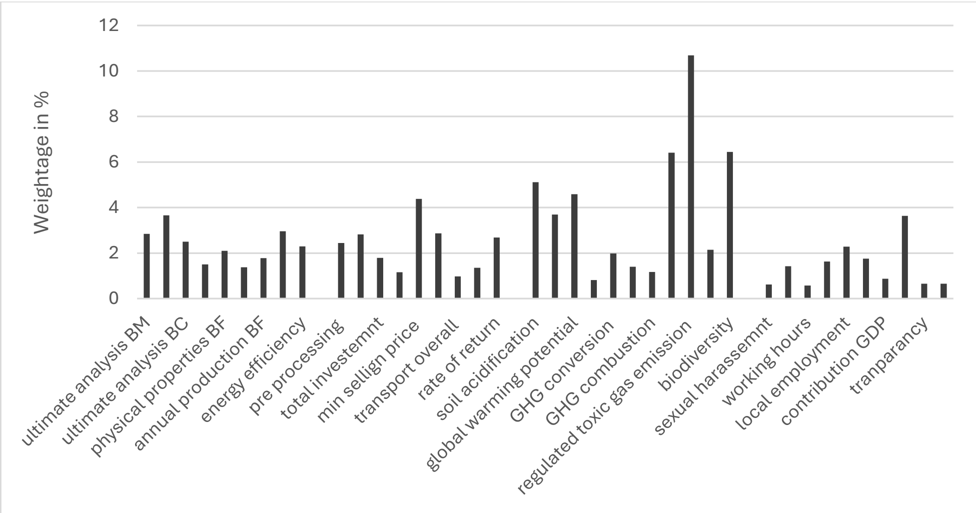


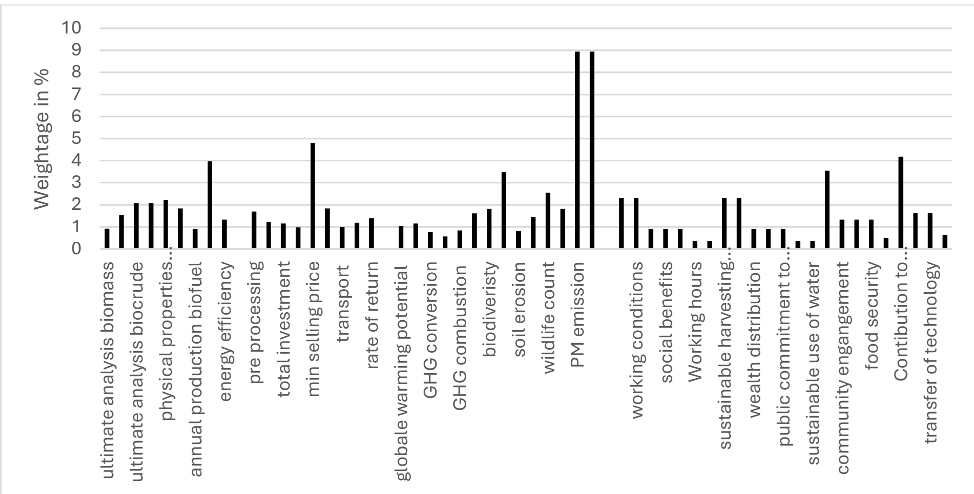

### *7.4.3.6. Weightage Social aspect*



### 7.4.3.7. KPI weightage Spain




### 7.4.3.8. KPI weightage Namibia

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# 8

# Acknowledgements

As I write this, one of the most important sections of my thesis, while looking at the lush green, misty, and hilly landscape, while listening to the songs of birds in one of the most unique national reserves of the world, I consider myself very lucky and grateful to the universe for all my previous experiences and opportunities in my life. Thank you, Universe! But who or what is the universe? For me, it is the people (in extension other life forms) who directly or indirectly influenced my life, for good or for bad! Today, I choose to focus on the good (or rather I should do that all day of my life :p). The words I hereby opt to describe may not fully justify the impact of people's effort, but I am sure they all know how much they mean to me!

First and foremost, I would like to thank the members of the **"BTS family"**. Starting with the CLEANSHIPPING supervisors, Patricia, John, and Lotte (as I call them, the "Big 3"!), I am grateful for the opportunity and trust you had in me, 5 years ago, during one of the most challenging times of the 21st century. The three of you always encouraged me to pursue my interests and new opportunities while having my back. **Patricia**, the "Meryl Streep" of BTS, I always admired your optimistic, futuristic, and never-say-never attitude. As my promotor, I greatly benefited from your ability to broaden my perspectives (especially during challenging times), much beyond my scope of vision. I truly enjoyed all our conversations over the years, especially during our B-BEST trip to Brazil, where I could witness (and be proud of) your journey and achievements. I am super glad to share and celebrate one of the important moments of our lives together. **John**, the daily supervisor whom I met in person only after 6 months into my PhD, ha-ha! This fact only highlights the rapport we had since the beginning, and I thank you for all the support for and beyond the PhD trajectory. Amongst many other things, I will always cherish the wonderful moments I (and we) had in Colombia, especially seeing you and your family in your mesmerising hometown of Manizales. Good luck with your new position and "Arepa de choclo con queso for life"! **Lotte**, although you were not my "official" supervisor, that did not stop us from interacting or sharing wonderful moments. Thank you for all the valuable insights, especially during our " intense :p" field visits to Valle del Cocora in Colombia, and the bush lands (especially in the Cheetah Conservation) in Namibia. Looking forward to creating more memories in our new journey! **Anka**, the mother of BTS, who is always looking out for the welfare of the group and its members, thank you for all your patience and efforts in making my life easier and comfortable, both in terms of administration and moral support. I always find some reason to stop by your office for a quick chat, albeit they are never short. To my fellow ex-colleagues, **Eefje**, thanks for all the kind, warm chats and especially for being the first one to welcome me to BTS. **Philipp**, the fellow foodie of BTS, I learned a lot from our short and sporadic discussions over different occasions. **Britte**, the fellow Gemini whose office space I inherited, thanks for all the intense positive vibes and the chats. Looking forward to having more. **Haneef**, the ODBP fellow, office-mate, and a

person with whom I can always have a chat or discussion. Thanks for all the moments over the years in and out of the office. I thoroughly enjoyed them all. **Eduardo**, the man who says "Maaannnn", the other Gemini, and ODBP fellow with whom I had lots of fun (and some serious) talks over the years, thanks for all the encouragement. **Gabriela**, the "Dancing Queen of BTS", thanks for being a wonderful colleague with all the positive energy. I am glad I met you on this journey, and it was sure a lot of fun. **Amalia**, thanks for being my office-mate, even for a short time, having an ever-smiling, calm energy coupled with deep knowledge, which I always admired. **Rafael**, it was great seeing you in person after so many years and thanks for all the words of support. **Pablo**, although short, it was a pleasure knowing you and good luck with your new position. And **Mar**, our interaction started even before my PhD journey with an online call, and now I am glad you are part of my committee. Thanks for all the amazing and memorable interactions over the years on different occasions. I am grateful to all of you for all the wonderful memories we shared during various interactions, such as in the office, coffee/lunch breaks, BTS meetings and retreats. I am also extending my thanks to other members of the BTS family (over the years) for their efforts, which inspired and helped me through my journey at BTS. Finally, to the new and future generation of BTS and BTV, **Gijs, Luiz, Akemi, Juan, Ali, Bob, Miriam, Nynke, Natalia**, and **Dario**, I wish you all a wonderful journey and all success in your future endeavours.

Secondly, as much as the journey, the destination is also important. Therefore, I would like to appreciate and thank the **"committee members"** for their consideration, interest, willingness, and efforts in evaluating my work critically, despite their busy schedules, to enable me to achieve this academic milestone. **Prof. Wiebren de Jong, Prof. Eulogio Castro, Prof. Lorie Hamelin, Dr. Mar Palmeros Parada, Dr. Felippe Ferrari,** and **Prof. Luuk van der Wielen**, thank you for your valuable feedback and for accepting to be part of my committee. I would also like to thank all the **project partners of the CLEANSHIPPING consortium**, whose valuable feedback and guidance led to the final quality of the dissertation.

Thirdly, going beyond the confines of the BTS section, I would like to thank some of the wonderful people at TU Delft, with whom I had the opportunity to connect during various activities. Chronologically, I would like to start by thanking the **members of the 2021, 2022, and 2023 "ODBP teaching committee"** for all the wonderful moments and experiences, especially the opportunity to explore the teaching aspect and the student culture of TU Delft. Followed by the **members of the 2021 and 2022 "Faculty PhD Council of Applied Sciences"**, who helped me to understand the culture of TU Delft and allowed me to contribute to addressing some of the important issues regarding the welfare of PhDs in the faculty. This enabled me to develop a social life at TU Delft during the ongoing COVID pandemic, which was very crucial for a newly joined expat. A special mention to **Ans van Schaik**, with whom I had the pleasure of working for two years in the FGS team, who was very receptive and encouraging about the new ideas, and I am happy to see that, amidst other things, the new "on-boarding" module is happening successfully. Subsequently, I would like to thank all the members of the **"BT PhD committee"** cohort 2022 and 2023, **Marieke, Lemin, Aster, Lars, Denzel, Maritt, Allison,** and **Héctor**, where I had the opportunity to represent BTS and learn more about the other sections of the department while actively organising different social activities, especially the annual BT symposium, which was truly a unique and fun-filled experience. In 2023, I became part of one of the most amazing, energetic, and global teams (or a family!) of the TU Delft, the **"Delft Global Initiative"**! As a proud Delft Global Fellow, I would like to recognise the efforts and thank the ever-inspiring DGI team. Much like my BTS supervisors, the DGI team always provided me with the support and opportunity to pursue my interest to expand my skillset beyond the borders, literally. Thank you, **Claire**, for shortlisting me for the AMBITION program, during which I greatly benefited from professional and personal development, in addition to the international trips to wonderful places. It was a great time in Kenya and Ghana, and I am looking forward to having more impactful adventures together in future. **Roel**, a BTS alumnus, I always learned new aspects of creating social impact during our conversations and thanks for all your support in valorising the DGI impact fund for our follow-up activities. Looking forward to our joint efforts in South Africa in the future. Last but not least, the DGI team was never complete without the wonderful vibes of **Rezi, Robèrt, Lys-Anne**, and **Fey**. I wish good luck to **Lys-Anne** and **Fey** in their new roles. Welcome to the DGI family, **Danielle**. Finally, I would like to thank my fellow **TU Delft AMBITION ambassadors, Iris, Yizhao, Vincent**, and **Ravi,** for all the unique and wonderful experiences during the AMBITION program across three different countries.

Fourthly, **<u>going global</u>**, I would also like to thank all the local partners in Spain (**Eulogio** and **Alfonso**), Colombia (**Diana** and **Daniel**), and Namibia (**Epafras, Julian, Detlef, Evert** and **Progress**) for their help and guidance during field visits. All of you went above and beyond to make the field trip more comfortable, valuable, and eventful. I would also like to acknowledge all the wonderful people I met on these trips, who provided a memorable experience for life. I would like to take a moment to extend my acknowledgements to AMBITION ambassadors and organisers from other universities for enriching the overall experience of the program. Thanks to all of them, I had one of the most adventurous, informative, and culture-rich PhD journeys, which otherwise would not have been possible.

Fifthly, I would like to extend my gratitude to all the **<u>Master's and Bachelor's students</u>** with whom I had the opportunity to interact. Thank you, **Nora, Eveline, Cedric, Puck, Roy, Henriette, Elisabeth, Sophie, Kelly, Nadia, Fiona, Miguel, Wouter, Casper,** and **Sam** for bringing a lot of fun vibes to my PhD with your intriguing questions while also broadening my knowledge, especially about Dutch culture. I wish a lot of success in your future professional and personal life.

Sixthly, I would like to go back to the time period before my PhD and appreciate the impact of certain people who were **<u>mentors</u>** to me and made me believe that I could take on and complete this journey. Thank you, **Prof. Prasanna Ramani, Prof. Amit Arora, Dr. Bart De Waele, Prof. Pedro Fardim,** and **Dr. Rita Caiado Gaspar**, for all your insights and guidance. All of you will always be an inspiration for me for your own specific reasons.

The part where I thank people for whom I can write an entire book, for their support!

> *"A man who doesn't spend time with his family can never be a real man"* - Don Corleone, Godfather

To the **<u>"Family, I gained"</u>**! A journey of an expat is filled with a lot of stories and adventures (the good, the bad, and the ugly!). One of the most valuable of them is the meaningful relationships one develops, which provide the warmth, happiness, comfort, and growth, similar to that of family by blood. I was lucky and thankful for all the amazing souls whom I could call family here in Delft (and abroad). Thank you, **Monica, Javi, Virginia, Giriprasath Ramanathan, Sneha Giriprasath, Nethra Giriprasath, Sahasra Giriprasath, Inna, Karthik, Becca, Hugo, Melle, Sivamuthuprakash**, and **Abhilash**.

*"Home is where somebody notices when you are no longer there." - Aleksandar Hemon*

To the **"Family, I was kind of adopted"**! Over the period of my life, I have been blessed with some truly awesome people who consider me part of their family and notice when I am not present. No words can do justice in describing the impact and effect of these people on my life, and all I can say is thank you for all the love. I am deeply thankful to the **parents and family members** of my "brothers from another mother", **Diwakar, Arun, Shashank, Vaishnav,** and **Anton**, along with their respective partners (**Sayujya, Surya, Nithya,** and **Claudia**), for all your unconditional love and affection, which gives me strength and happiness.

To the **"Family, I was born into"**! Thank you, **Appa, Amma, Balaji, Thathas** and **Pattis**. I will always remember your sacrifices, efforts, care, love, and affection, which shaped me into the person I am today. Thanks to all my cousins, aunts, and uncles for their support, love, and care, all my life. I will continue to grow and carry on the values as much as possible within my human power. Finally, welcome to the family, **Kristina, Hassan, Zahir,** and **Priya.** It's going to be lots of fun!

*" In life, it's not where you go, it's who you travel with" – Charles Schulz*

Last but certainly not least, I want to thank the two people who shaped me into who I am today, both personally and professionally, since I arrived in the EU in 2018. They listened to and supported all my rambling, understood my thought process and body language during every low and high moment, and were never hesitant to teach or scold me. We travelled the world together for incredible adventures and moments, some of which involved near-death experiences :p. Given these qualities, you two are the most suitable paranymphs I could ever ask for, **Susan** and **Marfa**, because I know I can face any challenge with either of you by my side (or rather, nothing is scarier than you, just like any sister to a brother!). Although I could write a separate dissertation on the impact you both have had on me, I'd rather simply say that no other two people deserve to stand on stage while I defend my thesis and accept that certificate, as you invested in my PhD more than I did. This is my way of thanking you. Also, Marfa, I hope the debt I owe you for one PhD defence is now fully repaid!

Finally, I would also like to thank all the people (and other life-forms) who indirectly enabled me in the above experiences to complete my PhD trajectory successfully. Now, looking forward to the next adventure of life!

**Sivaramakrishnan Chandrasekaran**
**KwaZulu-Natal, September 2025**

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# 9

# List of Publications

## 9.1.JOURNAL ARTICLES AND CHAPTERS IN BOOKS (PERTAINING TO THIS THESIS)

- **S. Chandrasekaran**, A. M. Vidal, E. Castro, P. Osseweijer, J. Posada, Techno-economic feasibility of olive residue-based biohubs for marine biofuel production: A capability-sensitive and context-specific approach in the Mediterranean region, Energy Conversion and Management: X, Volume 26, 2025, 101038, ISSN 2590-1745, https://doi.org/10.1016/j.ecmx.2025.101038.
- **S. Chandrasekaran**, P. Osseweijer, J. Posada, (under review) Agrarian Biohubs for drop-in marine biofuels: A Techno-economic and environmental assessment of inclusive, context-specific, and capability sensitive Biohubs in Spain, Colombia, and Namibia using field residues
- **S. Chandrasekaran**, S. van der Veen, A. M. Vidal, E. Castro, D. C. Meza-Sepúlveda, E. Andreas, P. Kashandula, L. Asveld, P. Osseweijer, and J. Posada, (submitted to peer-review journal) Biohubs for Emerging Bioeconomy: Factualization of early-stage inclusion of stakeholders to conceptual design through empirical studies in Spain, Colombia, and Namibia
- **S. Chandrasekaran**, P. Wammes, J. A. Posada, Life-cycle assessment of marine biofuels from thermochemical liquefaction of different olive residues in Spain, Editor(s): A. C. Kokossis, M. C. Georgiadis, E. Pistikopoulos, Computer Aided Chemical Engineering, Elsevier, Volume 52, 2023, Pages 3393-3398, ISSN 1570-7946, ISBN 9780443152740, https://doi.org/10.1016/B978-0-443-15274-0.50541-2.

## 9.2. PRESENTATION AT CONFERENCES (PERTAINING TO THIS THESIS)

- **S. Chandrasekaran**, P. Wammes, and J.A. Posada (2023). Life-cycle assessment of marine biofuels from thermochemical liquefaction of different olive residues in Spain. 33rd European Symposium on Computer-Aided Process Engineering (ESCAPE 33), 18-21 June 2023, Athens, Greece [Oral Presentation]
- S. van der Veen, **S. Chandrasekaran**, L. Asveld, J. Posada, and P. Osseweijer (2023). Inclusive decision-making for new sustainable value chains for marine biofuels. Second International Conference on New Pathways for a Just and Inclusive Energy Transition: Connecting Multiple Stakeholders and Levels, 21-22 June 2023, Groningen, the Netherlands. [Oral Presentation]
- **S. Chandrasekaran**, S. van der Veen, L. Asveld, P. Osseweijer, and J. Posada (2024). Inclusive design of context-specific biohubs for sustainable marine biofuels production: An approach guided by value-sensitive design (VSD). Brazilian Bioenergy

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Science and Technology –International Energy Agency Bioenergy 2024 Conference, 22-24 October 2024, São Paulo, Brazil. [Oral Presentation]

- **S. Chandrasekaran**, A. Vidal, E. Castro, P. Osseweijer, and J. Posada (2024). Olive residues for maritime biofuels: Techno-economics of Hydrothermal Liquefaction of pruning biomass in Spain. Brazilian Bioenergy Science and Technology –International Energy Agency Bioenergy 2024 Conference, 22-24 October 2024, São Paulo, Brazil. [Poster presentation]

## 9.3. JOURNAL ARTICLES AND CHAPTERS IN BOOKS (NOT PERTAINING TO THIS THESIS)

- S. van der Veen, E. van Rechteren Limpurg, L. Asveld, and **S. Chandrasekaran**, "Strengthening Social Life Cycle Assessment for a just bioeconomy: Insights from Namibia's bush-based value chains," Sustain Prod Consum, vol. 57, pp. 198–212, Jul. 2025, doi: 10.1016/j.spc.2025.05.003.
- **S. Chandrasekaran**, N. B. Salah, J. A. Posada, European Union's biomass availability for Sustainable Aviation Fuel production and potential GHG emissions reduction in the aviation sector: An analysis using GIS tools for 2030, Editor(s): A. C. Kokossis, M. C. Georgiadis, E. Pistikopoulos, Computer Aided Chemical Engineering, Elsevier, Volume 52, 2023, Pages 3055-3060, ISSN 1570-7946, ISBN 9780443152740, https://doi.org/10.1016/B978-0-443-15274-0.50487-X.


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# Curriculum Vitae

Sivaramakrishnan Chandrasekaran was born in the historic city of Calcutta (now Kolkata), known as the City of Joy, in the eastern part of India, on June 14th, 1995. He grew up in the suburbs of Chennai (then Madras) in South India, often referred to as the Detroit of South Asia. His childhood across the culturally rich cities of India provided him with a perspective that appreciated diversity and cultural values. In 2012, he graduated from high school with a centum in chemistry and biology, becoming the first student from his school to achieve this feat. With a merit scholarship, he chose to pursue a B.Tech in Chemical Engineering at Amrita Vishwa Vidyapeetham in Coimbatore. During the four-year programme, to broaden and define his trajectory, Siva gained experience through his first research project (under his mentor, Prof. Dr. Prasanna Ramani) and various industrial internships. For his bachelor's thesis, driven by a fascination for the field of biochemical engineering (especially lignocelluloses), Siva secured a scholarship to conduct research on the topic of "Extraction of Valuable Components from food processing waste" under Prof. Dr. Amita Arora at the Centre of Technology Alternatives for Rural Areas (CTARA) at the Indian Institute of Technology, Bombay. During his research tenure, he encountered many passionate researchers dedicated to using science to enhance the welfare of rural communities. Following this valuable and transformative research experience, he graduated with distinction in 2016, securing the silver medal.

To gain relevant practical experience, in 2016, Siva joined Southern Petrochemical Industries Corporation, a fertiliser company in the Coastal city of Tuticorin, as a graduate trainee. Over two years, he gained experience in the commercial production methods of ammonia, urea, and NPK fertilisers. As the assistant manager, he managed teams for daily production, which included cross-department communication, promoting safe practices, and achieving planned targets. Furthermore, the experience revealed to him the true identity of the chemical sector, a backbone to the nation's economy.

In 2018, to further deepen and specialise in his core discipline, he moved abroad to pursue a Master's in Chemical Engineering at KU Leuven, Belgium, with a specialisation in Chemical and Biochemical process engineering. In summer 2019, as an adventure beyond his comfort zone, Siva did his internship at Huntsman Corporation, Everberg, in the team of strategic upstream purchasing, where he was mentored by Dr. ir. Bart De Waele. During his internship, Siva gained experience with techno-commercial analysis of alternative technologies and an understanding of the global supply chain dynamics of petrochemical commodities. For his end master's thesis, due to COVID-19, Siva modified his research topic to Simulation of liquid hot water pretreatment of birchwood for production of platform chemicals using Aspen Plus, under the supervision of Prof. dr. Pedro Fardim. In 2020, he graduated *cum laude*. The experiences during his Master's triggered a curiosity within him to ask the question, "Why is there a significant gap between academic innovation and societal implementation?".

In 2021, he commenced a PhD focused on the development of sustainable and inclusive value chains for marine biofuels within the section of Biotechnology and Society, led by Prof. Patricia Osseweijer at Delft University of Technology. In addition to his research, he served as a teaching assistant, supervised bachelor's and master's thesis students, and was a member of the Faculty PhD Council and the Department PhD Committee, where he represented his fellow PhD candidates. Since January 2023, Siva has also held the position of Delft Global Fellow. In 2024, Siva received the Delft Impact Booster Fund to conduct follow-up activities related to his PhD research for societal implementation. Following the successful completion of the joint-honours AMBITION programme (EU-funded), Siva has been a scientific ambassador for sustainable transitions in Europe and Africa since June 2025. As of May 2025, he has been a postdoctoral researcher working on the Recyclable Woody Thermoplastic Composites and Coatings (ReWoody) project, funded by NWO, in the section of Biotechnology and Society at Delft University of Technology.