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DOI
10.1016/j.ecmx.2025.101038

Publication date
2025

Document Version
Final published version

Published in
Energy Conversion and Management: X

Citation (APA)
Chandrasekaran, S., Vidal, A. M., Castro, E., Osseweijer, P., & Posada, J. (2025). 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*, *26*, Article 101038. https://doi.org/10.1016/j.ecmx.2025.101038

Energy Conversion and Management: X 26 (2025) 101038

Contents lists available at ScienceDirect

Energy Conversion and Management: X

journal homepage: www.sciencedirect.com/journal/energy-conversion-and-management-x

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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ARTICLE INFO

Keywords:
Capability Sensitive Design
Hydrothermal Liquefaction
Olive residues
Techno-economic evaluation
Co-processing
Marine biofuels

ABSTRACT

This study aims to design and evaluate the techno-economic feasibility of socially just and context-specific biohubs for producing marine biofuels based on olive residues with hydrothermal liquefaction (HTL) in Spain, using existing infrastructures. The conceptual process and biohubs design are co-designed using a multi-actor approach, involving local stakeholders through participatory methods, with the help of a Capability-sensitive design. The material and energy balances (from Aspen Plus simulations) are used to evaluate the technical and economic performance (such as capital expenses, operational costs, and minimum fuel selling price) of biohub. 21 possible scenarios are investigated to understand the impact of design aspects (such as scale, distributed configuration, and co-processing) on the minimum fuel selling price (MFSP). The MFSP of the HTL biofuels varied by a factor of 0.6–3.1 compared to the conventional fossil-based fuels. Additionally, co-processing of HTL bio-crude at existing petroleum refineries reduces equipment costs by 16%. The study also recommends that the minimum scale of the HTL facilities should be between 588–882 dry tons per day (DTPD) of crude olive pomace processing capacity, to benefit from economies of scale. Overall, the investigation shows an economically feasible way to develop context-relevant olive residue-based biohubs for marine biofuel production with existing infrastructures in Spain, while ensuring social justice near biomass production sites. We argue this approach can be replicated in the other olive-producing regions in the Mediterranean and conclude that olive residues from the Mediterranean region have a huge potential to provide alternative advanced "drop-in" biofuels for the shipping sector.

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

☆ This article is part of a special issue entitled: 'Biofuels' published in Energy Conversion and Management: X.

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https://doi.org/10.1016/j.ecmx.2025.101038
Received 19 February 2025; Received in revised form 13 April 2025; Accepted 22 April 2025
Available online 25 April 2025

Nomenclature

Glossary

AB	Advanced biofuels
BBVC	Bio-based value chain
BECCS/U	Bioenergy with carbon capture, storage, and utilisation
BtL	Biomass to Liquid
CA	Capability Approach
CAPEX	Capital Expenditure
CEPSA	Compañía Española de Petróleos, Sociedad Anónima
CHP	Combined heat and power cogeneration plant
COP	Crude olive pomace
CSD	Capability Sensitive Design
DM	Dry Matter
DTPD	Dry metric tons per day
EOP	Exhausted Olive Pomace
EU	European Union
EUR	Euro
GHG	Greenhouse gas
HTL	Hydrothermal Liquefaction
IEA	International Energy Agency
ktpa	Kilo tons per annum
LHSV	Liquid Hourly space velocity
MBF	Marine biofuel
MFSP	Minimum fuel selling price
MGO	Marine gas oil
MSW	Municipal Solid Waste
NRTL	Non-random two liquid
OMWW	Olive Mill Wastewater
OPEX	Operational Expenditure
OTPB	Olive Tree Pruning Biomass
PNNL	Pacific Northwest National Laboratory
POO	Pomace Olive Oil
PSA	Pressure Swing Adsorption unit
R&D	Research and development
RRI	Responsible Research and Innovation
SOT	State-of-the-art Technology
SRK	Soave-Redlich-Kwong
SS	Sewage Sludge
VLSFO	Very low sulphur fuel oil
VSD	Value Sensitive Design
WWT	Wastewater Treatment Plant

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 [10–12]. Over the past decade, the Pacific Northwest National Laboratory (PNNL) in the United States has investigated the economic performance of common thermo-chemical conversion pathways using diverse feedstocks across various scales (from state-of-the-art technology (SOT) to Nth kind plant) [13–15]. 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 (standalone facility vs decentralised HTL facility + central upgrading facility) and learning curve of the technology (pioneer (SOT) state-of-the-art technology or commercial "Nth" kind) on the MFSP of the product. They identified that the production cost of the Nth kind plant was almost 43 % lower than the SOT case. Also, the MFSP of the decentralised system was 26 % and 44 % less than the Nth 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 [17–20]. 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. Methodology

2.1. System and scenarios

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 Fig. 1 and Table 1, respectively.

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 Fig. 2. The list of primary and secondary olive mills in the chosen regions of investigation is indicated in Appendix A1.

2.1.2. 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 Appendix A6. 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.

2.2. 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 h per year [17].

2.2.1. 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

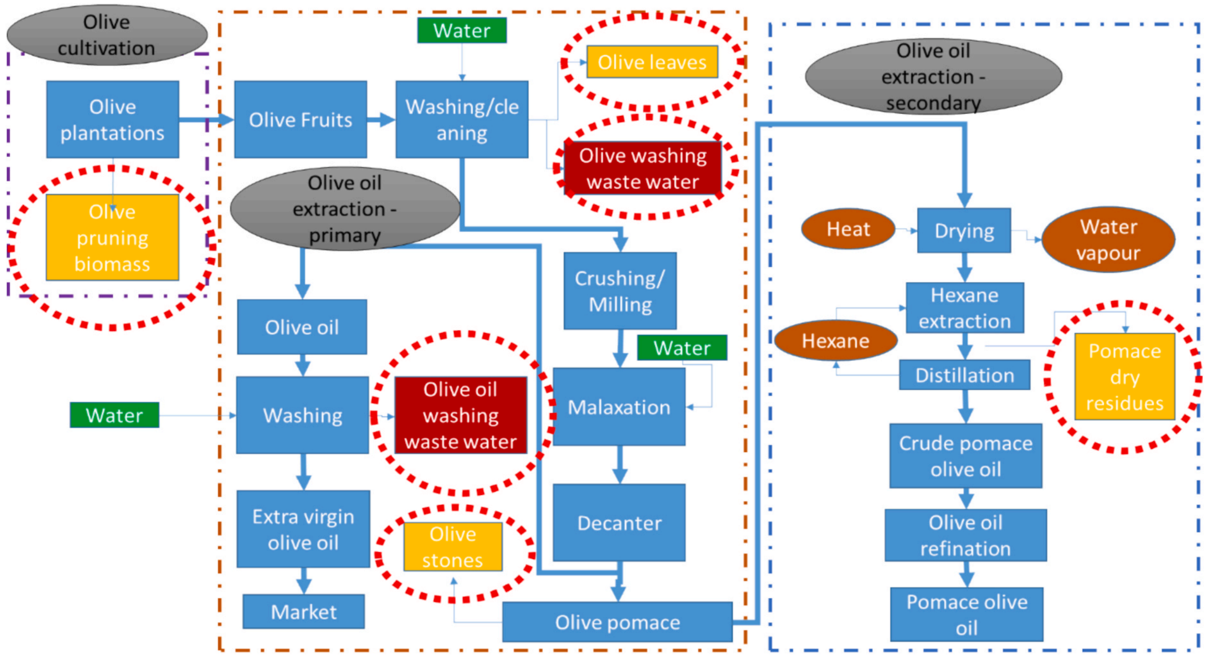

Fig. 1. Stages (purple dashed box – olive cultivation, brown dashed box – primary olive oil mill, blue dashed box – secondary extraction mill) in olive oil production with residue (highlighted in red dots) generation. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Overview of residue from the olive sector in the region of Andalusia. Sources: [7,26–29].

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

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. Fig. 3 shows the process flows for the integrated and distributed HTL biohub systems.

2.2.2. *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.

2.2.2.1. 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

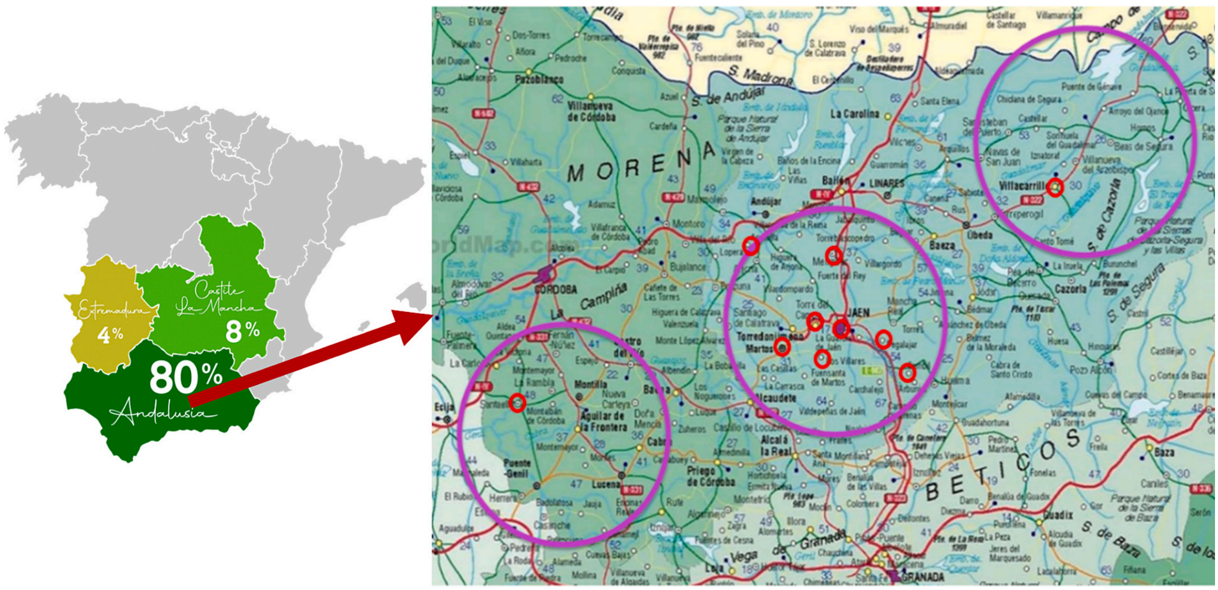

Fig. 2. Regional olive oil production contribution percentage to national output (left) in Spain and the Region of consideration of biofuel value chain (right) (adapted from [30]). Red dots indicate the places where stakeholder interviews were conducted. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

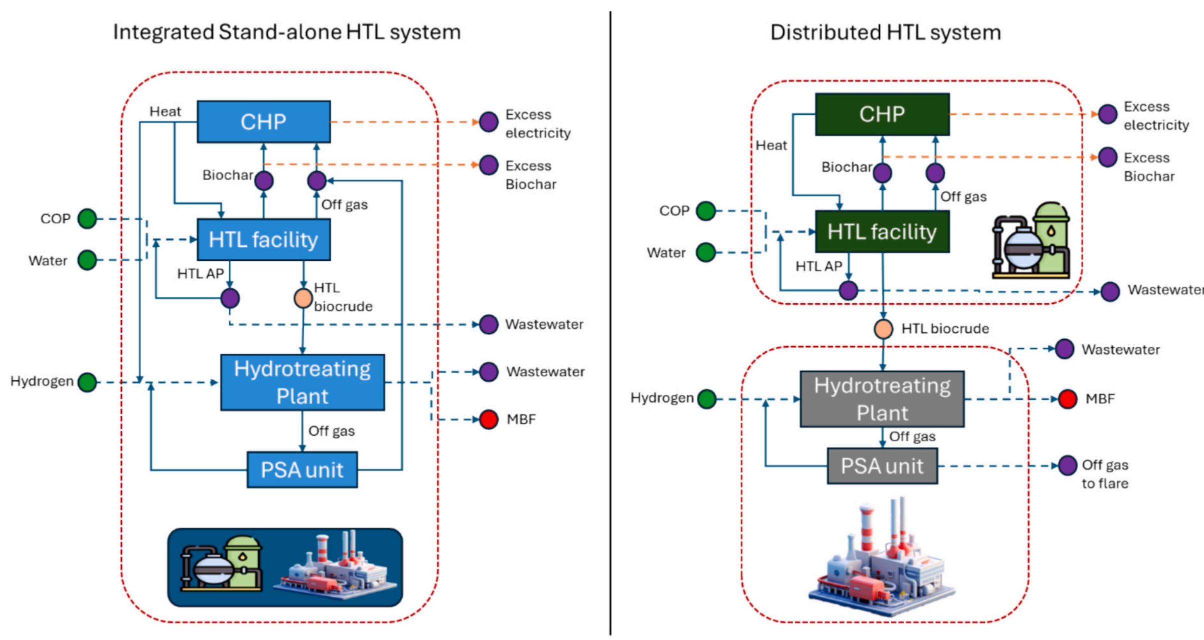

Fig. 3. Process flow diagram of biomass to biofuels conversion stage for an integrated and distributed system, where green dots represent inputs, red dots indicate the final product, orange dots indicate intermediates, and purple dots indicate by-products. Internal stream flows are described using weighted lines, and blue dotted lines indicate external flows. System boundaries are visualised using brown dashed lines. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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 bio-crude 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.

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 A4.2.

2.2.2.2. HTL. The PFD of the biomass conversion system is shown in Fig. 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

Table 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 h	
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	

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.

2.2.2.3. 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 Fig. 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 are based on bio-crude components as listed in Appendix A4.2. 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.

2.3. 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 Tables 3 and 4. The rates are normalised to 2023 Euros using the Chemical Engineering Plant Cost Index (CEPCI), and the conversion rates are mentioned in Appendix A7.

2.3.1. Capital investment

Based on Sieder *et al.* (2017)**,** the CAPEX is calculated using the cost of equipment, using the estimation formula in Table 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

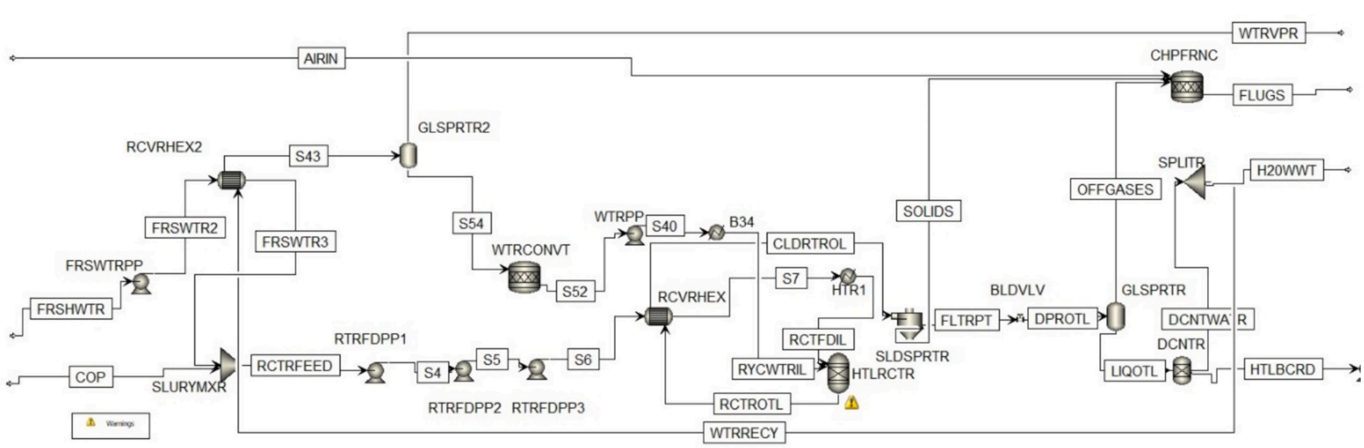

Fig. 4. Aspen Plus process flowsheet of HTL system.

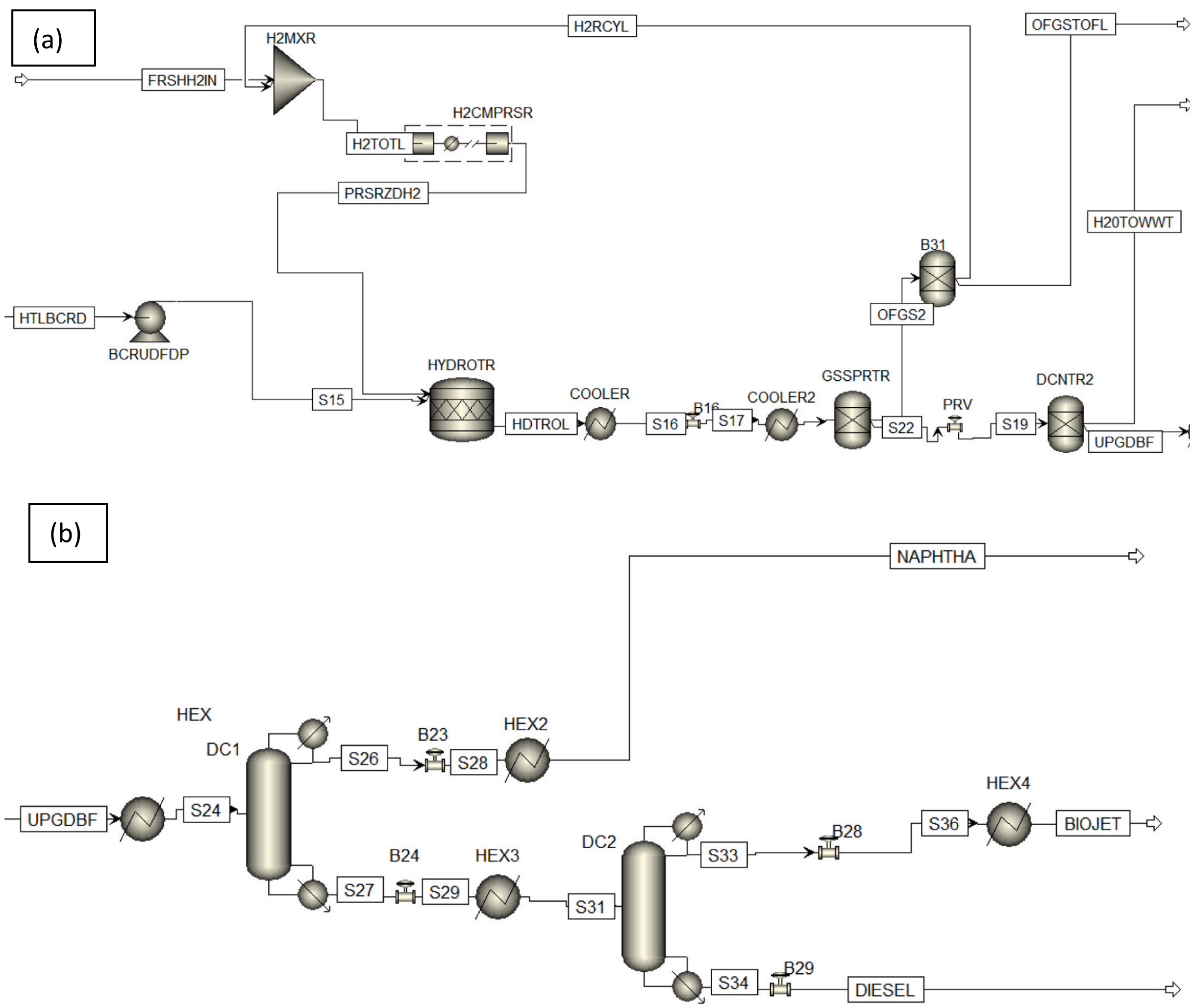

Fig. 5. Aspen Plus process flowsheet of HTL bio-crude upgrading system. a) Hydrotreating section, b) Fractionation section.

Table 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)**

the non-commercialisation of biorefineries and minimal construction experience, a 50 % contingency factor is assumed, against a conventional 15–20 %, for an Nth 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.

2.3.2. 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 Appendix A7.3. 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 4 shows the methodology for calculating operational expenses.

Table 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 Electricity = 28.6 EUR/GJ	[39–41]
t	Transport	Truck Transport, fixed = 12 EUR/ton Truck transport, variable = 0.27 EUR/ton-km	This study
wt	Waste treatment	waste processing: gas = 6.00 EUR/ton waste processing: water, black = 0.60 EUR/ton 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).

2.3.3. 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.

$$MFSP = \frac{Operatingexpenses - SalesRevenuesfrombiochar, electricity, naphtha, andbiojet}{Biofuelproductioncapacity} \quad (1)$$

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].

3. Results

3.1. Design propositions and scenarios

Table 5 highlights the design characteristics and choices preferred by the potential stakeholders of the new value chain.

Table 6 shows some examples of how the stakeholders' preferences in terms of design propositions were translated into technical design choices.

Based on the design propositions, four biohubs design scenarios have been created (SC1-4) with 21 variations as shown in Table 7 and Fig. 6 respectively.

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.

3.2. Technical performance

The Aspen Plus simulation model represents a steady-state processing condition with fixed operating parameters. Table 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

Table 5
Design Proposition for olive residues-based biohubs in Andalusia.

Biohub elements	Design variable	desired characteristics	Design proposition
Biomass extraction	- Type of biomass - Biomass transport - Biomass storage	- Large availability, easy accessibility, good compatibility with technology, and less competition - Existing knowledge and infrastructure of biomass, transport, and storage. - 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. - Use olive pruning biomass if the feedstock price can be greater than the current economic value (65 EUR/ton)
Biorefinery	- Technology - Location - Capacity	- Less dependent on natural gas imports - Benefit from economies of scale - Less stress on water resources	- Implement biomass conversion that can be managed by current mill operators. - Use existing infrastructure for biomass handling and conversion. - Biomass conversion to take place near plantations or mills. - Technology with minimal water consumption - Use byproducts for electricity/heat generation and as soil amendment.
Final Products	- Bulk chemicals - Specialty chemicals - Fine chemicals	- Products should be matched with feedstock quality and quantity. - Product with access to an existing regional market	- COP and OMWW for bioenergy; OTPB, EOP, and OL for bio-based chemicals - 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. - With reduced environmental (less CO_2 emissions, reduced water consumption, etc.) footprint - Byproducts valorisation for self-sufficient processes and the sustainable olive sector
End-user market segment	- Technical - Economic - Environmental - Social	- New fuels should have similar physio-chemical properties in comparison to fossil fuels - The price of the new alternative fuels should be less than twice that of conventional fuels. - Feedstock should not compete with food crops. - A secure and continuous feedstock supply guarantee is needed	- Drop-in biofuels are preferred - The selling price ratio of HTL marine biofuels: fossils should be less than 2. - Lignocellulosic non-edible feedstocks are preferred. - Diverse feedstock providers (small-scale and large-scale) - Combination of both processing and field residues.

Table 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.

Table 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

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 1/4th of the reported values, which can be attributed to the stoichiometric reactions of compounds present in HTL bio-crude obtained from olive residues

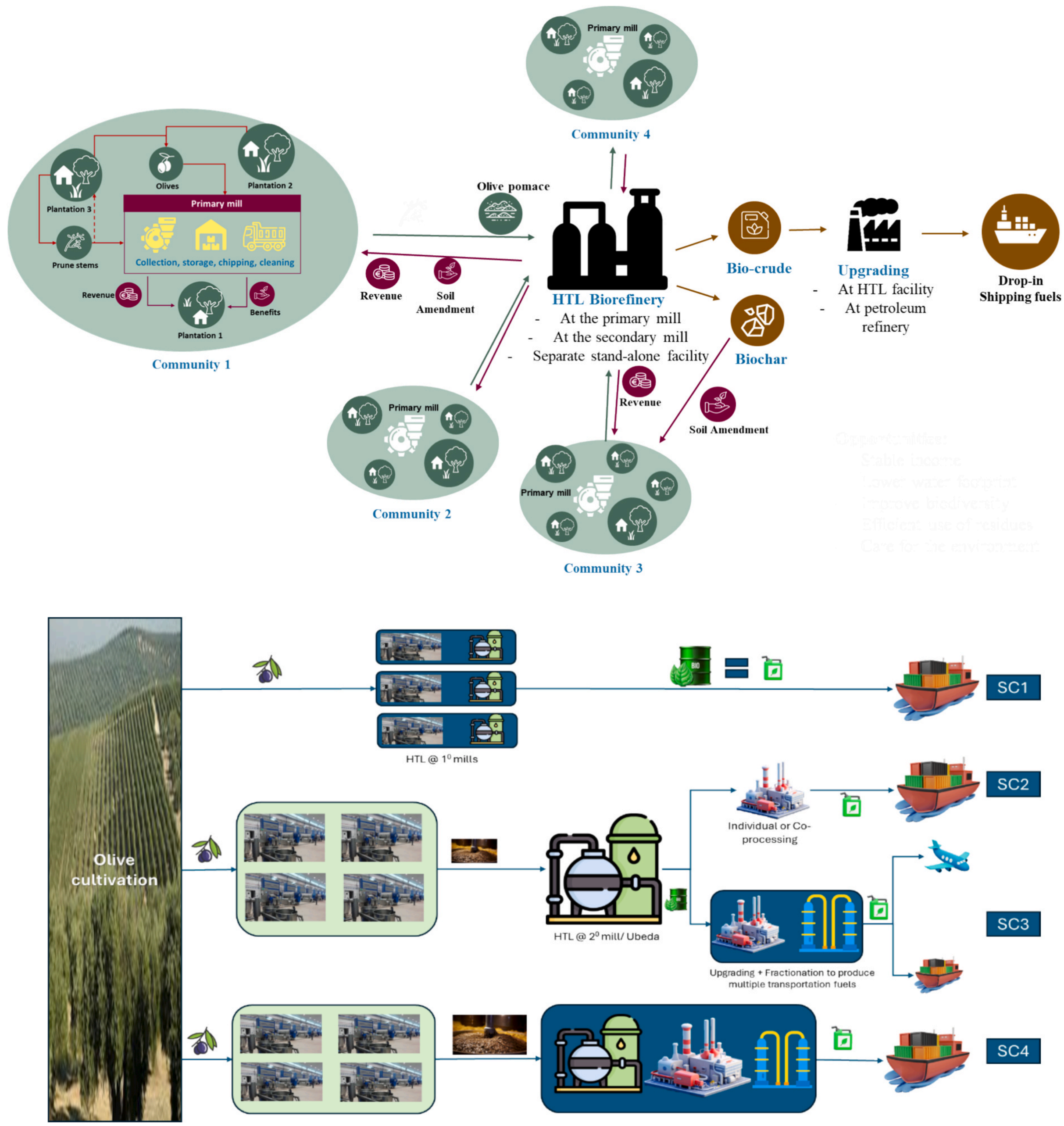

Fig. 6. Possible biohub design based on crude olive pomace in Jaén (top) and biohubs scenario variations (bottom).

[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. Fig. 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.

3.3. Economical performance

The economic performance of the 588 DTPD HTL biofuel system is shown in Table 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

Table 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

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 Fig. 8.

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.

3.4. Sensitivity analysis

3.4.1. 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

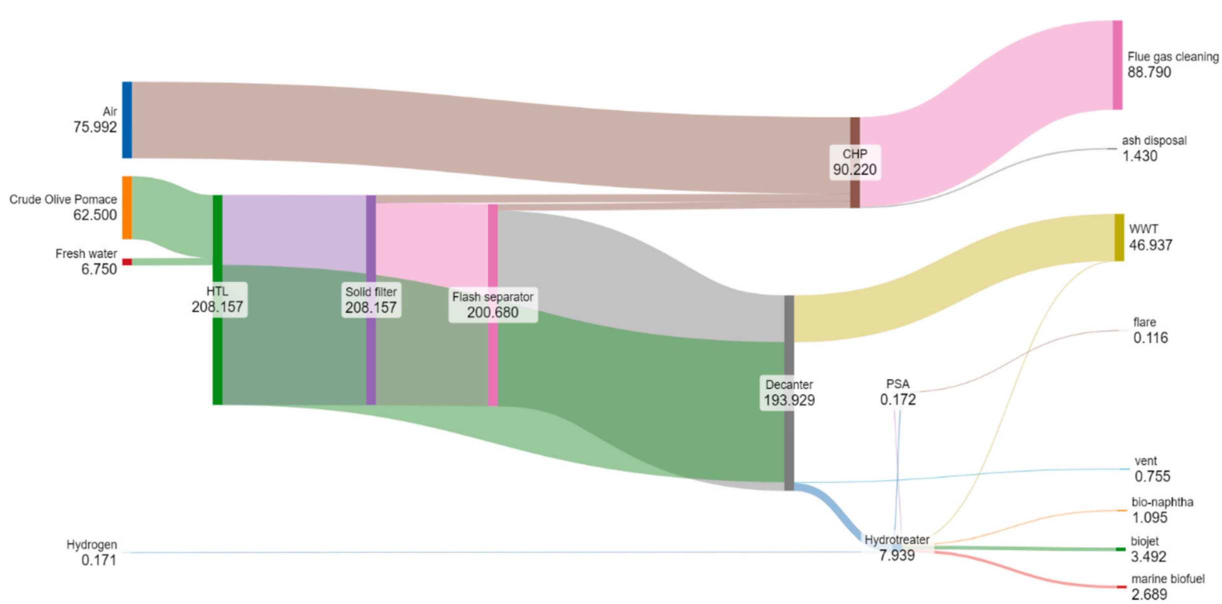

Fig. 7. Stream mass balance (in tons per hour) in a 588DTPD HTL marine biofuel system.

Table 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.

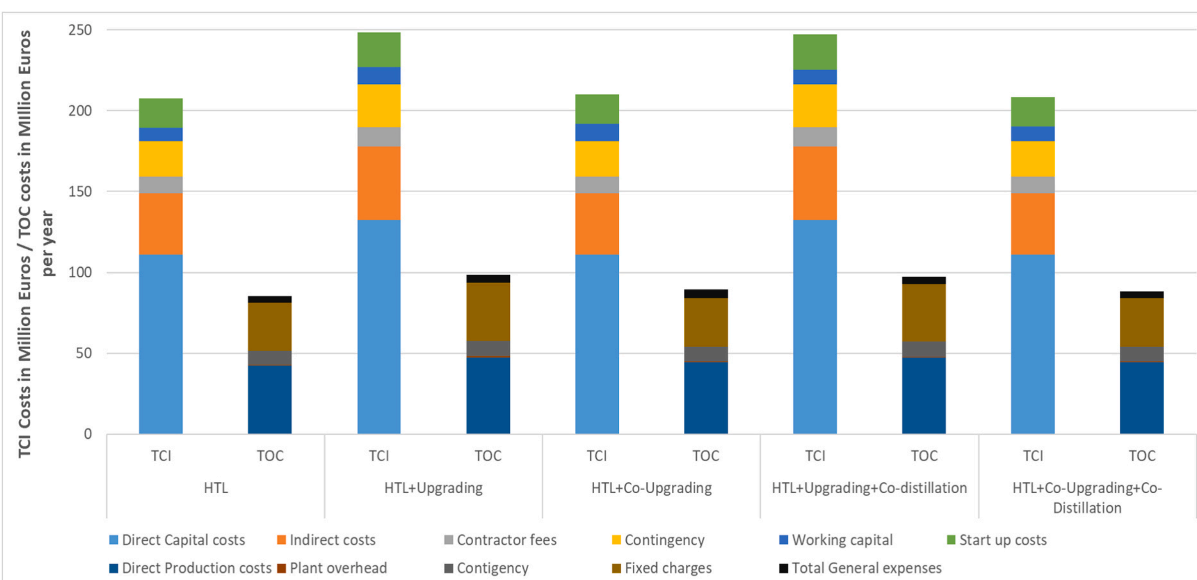

Fig. 8. Detailed total capital investment (TCI) and total operating cost (TOC) of studied HTL biofuel scenarios.

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 Fig. 9. With COP biomass processing varying from 60 to 1494 DTPD, the MBF: fossil

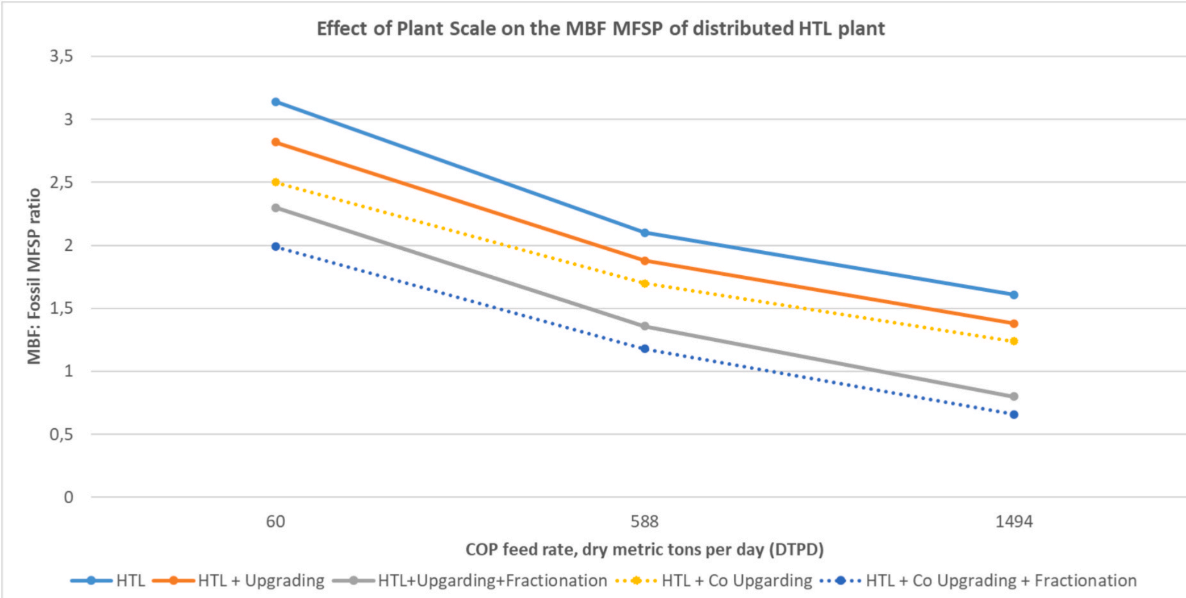

Fig. 9. Effects of plant scale on the MBF: fossil MFSP ratio of the distributed HTL plant.

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.

3.4.2. 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 Fig. 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

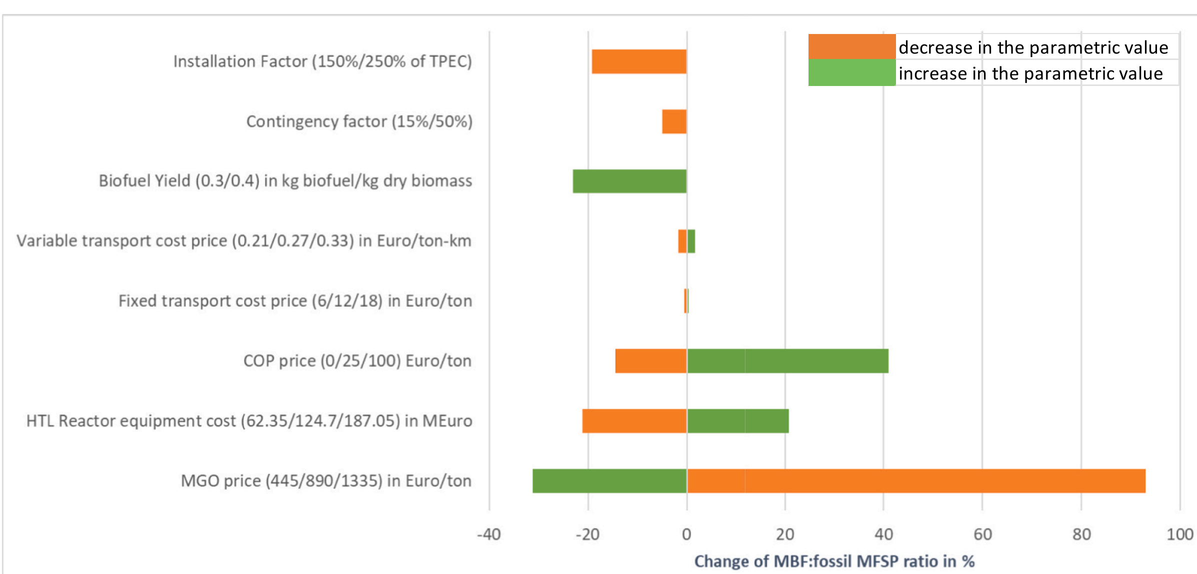

Fig. 10. Sensitivity analysis of the MBF: fossil MFSP ratio of HTL biofuels, Green (increase of parametric value from the base case), Orange (decrease of parametric value from the base case). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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.

4. 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.

CRediT authorship contribution statement

Sivaramakrishnan Chandrasekaran: Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Alfonso M. Vidal:** Writing – review & editing, Investigation. **Eulogio Castro:** Writing – review & editing, Resources, Methodology, Investigation. **Patricia Osseweijer:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization. **John Posada:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

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

Acknowledgments

The authors would like to thank all interview and workshop participants and staff from the Universidad de Jaén, for their support in the field studies. This study is carried out in the context of the 'Value from Biomass' program of the Dutch Research Council (NWO), the institute that granted funding for this study, with grant number Biom.2019.002.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecmx.2025.101038.

Data availability

Data will be made available on request.

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