



# Carbon footprint assessment of microalgal biomass production, hydrothermal liquefaction and refining to sustainable aviation fuel (SAF) in mainland Portugal

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## ABSTRACT

Industrial liquid effluents (e.g., from fertilizer industry) and flue gas streams (e.g., CO<sub>2</sub>-rich, from cement industry) arise as an opportunity for waste valorization. Microalgae are suitable biomass for assimilating both effluents at the cultivation stage. Under a biorefinery concept, given the urge for energy transition in the aviation sector, this research explores the transformation of a microalgae consortium grown at an industrial site in Portugal and its subsequent harvesting, hydrothermal liquefaction (HTL), and bio-oil refining. A life cycle assessment (LCA) approach is undertaken with two functional units (FU): 1 kg of microalgae dry-cell weight (dw) and 1 MJ of bio-jet fuel. The latter follows an attributional approach with energy allocation for comparison with the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) guidelines. HTL is based on data from bench-scale experiments and literature, whereby the Petroleum Refinery Life Cycle Inventory Model (PRELIM) is used to mimic bio-oil refining. Following this approach, achieving Sustainable Aviation Fuel (SAF) compliance requires net-zero electricity (0 gCO<sub>2</sub>eq/kWh), with an HTL bio-oil yield of 55.6 % dw (the maximum observed), a minimum refining bio-jet fuel yield of at least 16 %. Alternatively, an HTL bio-oil yield of 36.9 % dw (the median observed) with a refining efficiency of at least 24.3 %.

## 1. Introduction

The aviation sector, responsible for the transportation of both people and goods, is one of the pillars of the modern global economy. However, since there is currently no feasible manner to electrify most commercial flights, this industry remains broadly dependent on fossil fuels, representing 2 % of global energy-related CO<sub>2</sub> emissions [1]. To meet the Paris agreement goals and achieve net-zero emissions by 2050, there is a need to replace the current fossil-based jet fuel by sustainable aviation fuel (SAF) that can simultaneously guarantee abundant supply, low price, and reduced CO<sub>2</sub> emissions.

In this context, SAF must be produced from low-cost, readily available, resources that do not compete with food production or other energy generation needs. Furthermore, both raw-material and production processes must be close to carbon neutrality.

One possible solution, which applies the principles of circular economy, and is aligned with the United Nations Sustainable Development Goal 12 (SDG 12), is to integrate waste management and energy recovery, exploring industrial waste conversion to SAF and other useful products. This integrated approach is already being explored in other bioenergy generation processes, such as the production of biogas from municipal solid waste, bioethanol from agricultural residues, or biodiesel from cooking oil waste. However, the sheer amount of jet fuel needed, coupled with the specific characteristics of this fuel, limit the number of options available to develop a truly sustainable production process.

Microalgae are photoautotrophic microorganisms that, similarly to plants, can sequester CO<sub>2</sub> in the presence of light and convert it into biomass. They have several advantages over plant-based biomasses: they can be harvested year-round, have a higher areal biomass productivity,

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are easier to process, and do not compete for fertile soil. They can also be cultivated in effluent streams, using them as a source of phosphorus, nitrogen, and other nutrients, which reduces clean water spending. Because of these characteristics, microalgae have been extensively studied for their potential application on CO<sub>2</sub> fixation from industrial exhaust streams [2–4] and wastewater treatment [5–7], with some works combining both applications [8]. Additionally, some species can accumulate high lipid content, with some works reporting >30 % dry weight, which makes them especially appealing for biofuel production.

The high water content in microalgal biomass poses a challenge for direct conversion to biofuels, requiring energy-intensive harvesting and drying processes. Hydrothermal liquefaction (HTL) emerges as an attractive alternative, resembling pyrolysis but using water as a catalyst. This enables direct conversion to bio-oil, minimizing the need for extensive drying and dewatering stages, thus reducing associated costs and emissions [9–11].

Move2LowC project ([www.move2lowc.com](http://www.move2lowc.com)) was centered on the decarbonization of transportation, and focused, amongst others, on the production of sustainable biofuel for the aviation sector. This project studied the use of HTL to convert microalgal biomass into bio-jet fuel, after bio-oil upgrading. However, the resulting bio-jet fuel, despite being a green biofuel, cannot be considered a SAF unless it follows specific criteria. In accordance with CORSIA (Carbon Offsetting and Reduction Scheme for International Aviation) guidelines [12], SAF compliance requires achieving a minimum of a 10 % reduction in greenhouse gas emissions (GHG) compared to the reference fossil fuel comparator (89 gCO<sub>2</sub>eq/MJ). This requirement is explicitly outlined in Criterion 1.1 of the guidelines, stating that “CORSIA eligible fuel will achieve net greenhouse gas emissions reductions of at least 10 % compared to the baseline life cycle emissions values for aviation fuel on a life cycle basis”. Another crucial criterion, as specified in Criterion 2.1, asserts that “CORSIA eligible fuel will not be made from biomass obtained from land converted that was primary forest, wetlands, or peat lands and/or contributes to degradation of the carbon stock in primary forests, wetlands, or peat lands as these lands all have high carbon stocks”. Consequently, a comprehensive life cycle assessment (LCA) becomes fundamental when evaluating the sustainability of any produced jet fuel. This assessment must encompass a thorough inventory of each stage of the process, considering not only the production through HTL, but also the cultivation of the microalgae, upgrading of the bio-oil, and the positioning of various infrastructure and transport needed.

Given the profusion of research and the imperative nature of these subjects, one would anticipate a proliferation of studies assessing the feasibility of deploying microalgae and HTL for SAF production. Nevertheless, an exhaustive query on Web of Science™ [Topic, ((LCA or “Life cycle a\*”) and “\*jet fuel” and “microal\*” and “HTL”)], conducted as of September 2023 yielded merely five results, thereby underscoring a pronounced knowledge gap in this domain. Notably, even the Committee on Aviation Environmental Protection in the International Civil Aviation Organization (ICAO) document “CORSIA Default Life Cycle Emissions Values” abstains from offering an evaluation of SAF derived from microalgal biomass, predominantly attributing this omission to their low risk in generating induced land-use change emissions [13]. Remarkably, the limited literature that does undertake a LCA of the microalgae-to-bio-jet fuel pathway through HTL reveals promising outcomes designating them as potential SAF sources, reporting values such as 35.2–86.5 gCO<sub>2</sub>eq/MJ [14], 27–38 gCO<sub>2</sub>eq/MJ [15] and 25 gCO<sub>2</sub>eq/MJ [16]. However, it is noteworthy that these studies employ divergent LCA criteria, allocation methodologies and system boundaries, thereby preventing direct comparisons between these studies and the CORSIA guidelines [12–15]. Fixing the differences in methods is crucial for strengthening the basis of sustainable aviation fuel.

Hence, this work focused on data collection from different sources (i.e., literature, modelling, and experimental data) to obtain an inventory of the processes explored during Move2LowC project. Then, using the inventory obtained, a characterization of the process proposed by

Move2LowC project was performed through attributional LCA, with energy allocation, to evaluate the influence of different factors on global warming potential (GWP) impact category (in 100 years) outcomes and CORSIA’s SAF compliance (i.e., location of each unit of the system, availability of industrial flue gas waste streams, HTL syngas energy recovery, utilization of net zero carbon electricity and the conversion efficiencies of the thermochemical processes).

## 2. Materials and methods

### 2.1. LCA methodology

This research follows the methodology outlined in ISO 14067, ISO 14040 and ISO 14044. ISO 14067 [17] establishes principles, requirements and guidelines for the quantification and reporting of the carbon footprint of a product (CFP), in alignment with the LCA International Standards (ISO 14040 [18] and ISO 14044 [19]). These standards focus on a single impact category: climate change, measured by the global warming potential over a 100-year timeframe (GWP100) and expressed in CO<sub>2</sub> equivalent (CO<sub>2</sub>eq). The key stages in the LCA process include goal and scope definition, life cycle inventory and results interpretation. The considerations made for this study within these stages are described below.

#### 2.1.1. Goal and scope

The goal of this study was to characterize and identify hotspots in the “microalgae to bio-jet fuel” conversion process developed within Move2LowC project in terms of GWP, and to address the following research questions (RQ):

RQ1: What is the carbon footprint of converting 1 kg (dry cell weight) of microalgae into multi-product, in gCO<sub>2</sub>eq/kg dw microalgae?

RQ2: What is the carbon footprint of obtaining 1 MJ of bio-jet fuel from microalgae, in gCO<sub>2</sub>eq/MJ bio-jet fuel, and how can it achieve SAF compliance?

After conducting an attributional LCA for the base-case scenario (Sc0), various alternative scenarios were explored. These included: (Sc1) the location of the different units; (Sc2) the absence of local industry for CO<sub>2</sub> valorization by microalgae, other than HTL and refining/upgrading, that could provide CO<sub>2</sub> within the system; (Sc3) heat recovery from recirculating HTL syngas for HTL heat generation; (Sc4) a combination of scenarios and, finally, (Sc5) establishing minimum requirements targeting SAF compliance. Table 1 summarizes the description of each scenario.

Fig. 1 depicts the flowsheet for the proposed value chain, while Fig. 2 provides an overview of the locations in mainland Portugal considered in the study, including (A) cultivation (using non-arable land), harvesting and HTL at ALGATEC Eco Business Park located in Póvoa de Santa Iria (point A, Fig. 2); (B) bio-oil refining/upgrading to bio-jet fuel at Sines oil refinery (point B, Fig. 2); (C) bio-jet fuel storage at the logistics platform in Aveiras de Cima (point C, Fig. 2) and (D) aircraft fueling at Lisbon airport (point D, Fig. 2). Transportation of bio-oil to the refining/upgrading site and bio-jet fuel to the airport were considered, accounting for actual distances and infrastructure between the sites, as illustrated in Fig. 2.

Two different boundaries were established depending on the research questions considered. For RQ1 (Fig. 1, yellow dotted line), the process was considered from microalgae cultivation to bio-oil upgrading into bio-jet fuel. For RQ2 (Fig. 1, black dashed line), the process also included the transport of bio-jet fuel to the airport and the combustion in the aircraft engines.

Two different functional units (FU) were also selected to answer the research questions:

For RQ1, the FU was 1 kg (dry cell weight) of microalgae biomass transformed into multi-product.

For RQ2, the FU considered was 1 MJ of produced bio-jet fuel for comparison with fossil-based jet A-1.

**Table 1**  
Description of the scenarios analyzed.

Scenarios	Description
Sc0: Base-case scenario	HTL facility is situated adjacent to the microalgae cultivation and harvesting site (point A, Fig. 2). It is physically separated from refining/upgrading location (point B, Fig. 2). The setup involves no heat recovery, and there is no recirculation of CO <sub>2</sub> . Instead, the system utilizes nearby industry CO <sub>2</sub> uptake.
Sc1: Location/Transport effect	
<u>Sub-scenarios</u>	
Sc1.1	HTL facility is situated near the refining/upgrading units, following system configuration 1.
Sc1.2	The entire system (including microalgae cultivation and harvesting) is positioned at the refining/upgrading site, following system configuration 2.
Sc2: No local industry for CO <sub>2</sub> valorization	
<u>Sub-scenarios</u>	
Sc2.1	CO <sub>2</sub> supplementation, equivalent to the amount derived from industrial exhaust gases in the base case, is achieved by using food-grade CO <sub>2</sub> produced explicitly for its application in cultivation.
Sc2.2	CO <sub>2</sub> generated during the process, specifically during HTL and refining, is recirculated, thereby minimizing or eliminating the requirement for food-grade CO <sub>2</sub> and its associated emissions.
Sc3: Heat recovery	The combustion of syngas from HTL is utilized for heat production, thereby reducing NG inputs. This approach takes into account the Sc0 configuration, where there is no heat surplus from refining/upgrading.
Sc4: Combined scenario	Combination of Sc1.2 and Sc3 to attain a reduced GWP100 value.
Sc5: SAF compliance requirements	Multi-variable optimization of Sc4 for compliance with SAF eligibility.

In both cases, emissions related to infrastructure, maintenance and cleaning chemicals, end-of-life of the aqueous fraction (effluent stream treatment plant) and biochar, were excluded from the evaluation. Energy allocation was employed to facilitate a comparison with the fossil fuel comparator defined in the CORSIA methodology [12].

2.2. Inventory

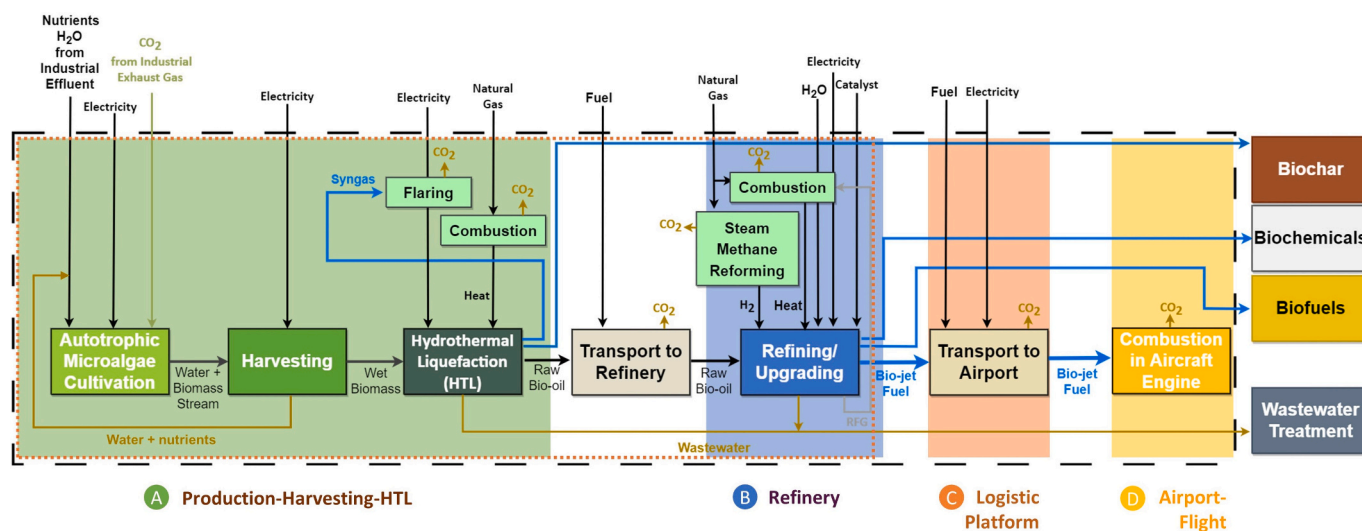
Cultivation and harvesting data were supplied by A4F (Move2LowC

project coordinator), while HTL data were sourced from both LNEG and literature. Data regarding bio-oil refining/upgrading to bio-jet fuel were obtained using PRELIM – The Petroleum Refinery Life Cycle Inventory Model [21]. In terms of the transport stages, distances between process units were calculated based on their locations and the existing transport infrastructure connecting them, namely ALGATEC Eco Business Park, the oil refinery in Sines and Lisbon airport (respectively, points A, B and D in Fig. 2).

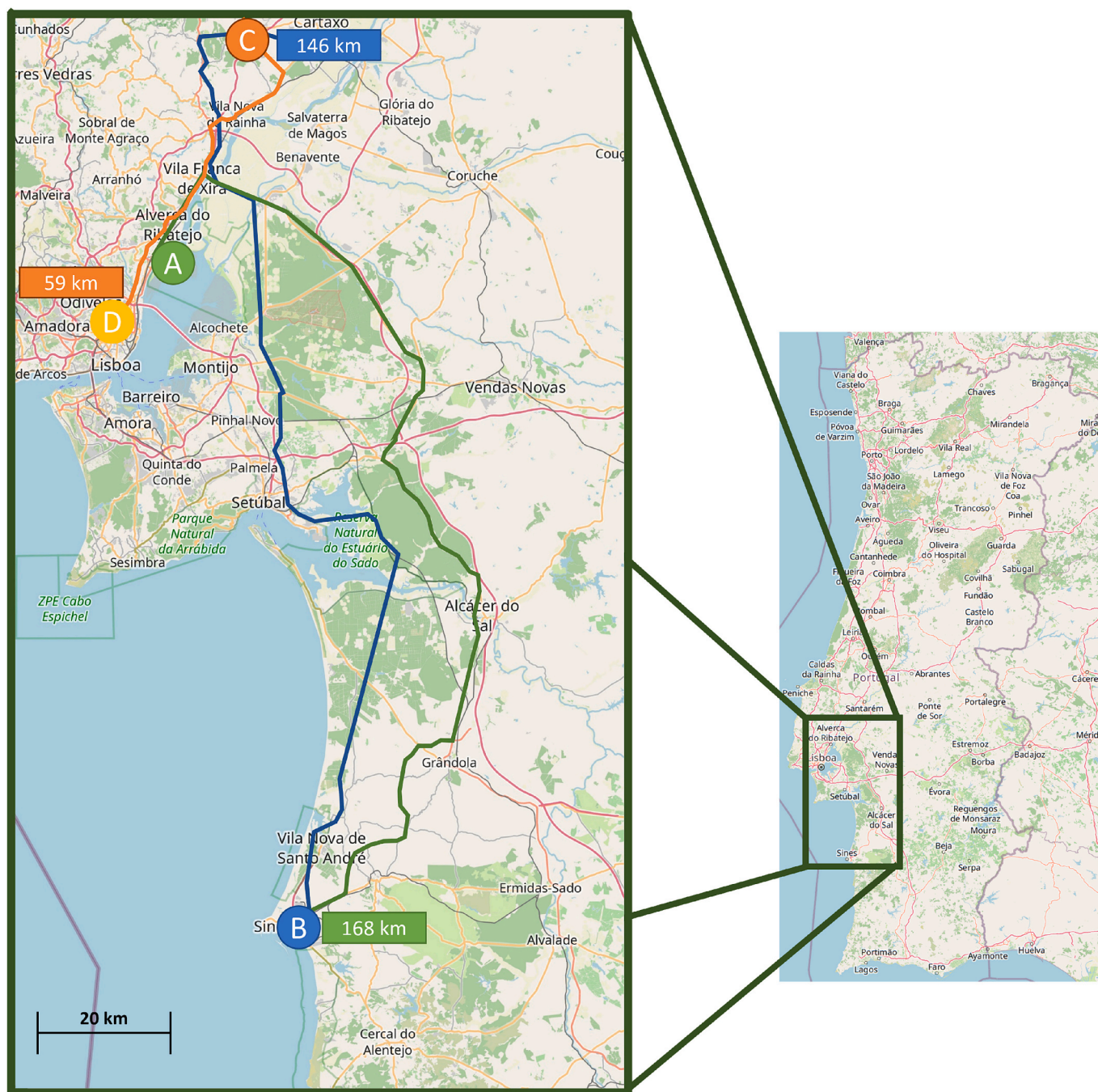
Microalgae cultivation was performed in a demonstration-scale unit (38°51'00"N, 9°04'16"W), located in a typical Mediterranean climate, using open cascade raceway ponds (OCRP) without temperature control and with a natural photoperiod without artificial lighting. The system had an implantation area of 2500 m<sup>2</sup>, an average optical path of 4 cm, and an average culture volume of 70 m<sup>3</sup>. The culture medium was supplemented with effluent from a local fertilizer production facility (ADP Fertilizantes, Póvoa de Santa Iria, Portugal), serving as the nitrogen (N) source, while phosphorous (P) and potassium (K) were added separately. Although food-grade CO<sub>2</sub> was considered, the base-case scenario also employed CO<sub>2</sub>-rich flue gas from a nearby industrial source. A mixed microalgae culture, adapted to the industrial effluent stream, was cultivated autotrophically under these conditions [22].

Following the cultivation phase, harvesting was carried out using membranes, resulting in a wet microalgae biomass with 90 % water and 10 % solids, with the composition detailed in the inventory (see below, section 3).

The microalgal biomass produced at demo-scale was characterized at LNEG through CHNS elemental analysis and used without any further processing or the introduction of additional water. HTL data were obtained from bench-scale experiments performed by LNEG in 0.16 L batch reactors, built in Hastelloy C276 by Parr Instruments, with a controller device connected to both the pressure gauge and the thermocouple. Firstly, the feedstock (biomass-to-water ratio of 1:10) was placed inside the reactor and closed, afterwards it was purged with N<sub>2</sub> to maintain an inert atmosphere inside the reactor and then pressurized with N<sub>2</sub> to guarantee that the operation pressure was within the desired range. The initial pressure was determined from preliminary tests and set at 40 bar for the reaction temperature of 325 °C [22]. The aim was to ensure that the pressure at the run temperature was within the required range (130–170 bar). The reactor was heated by an oven equipped with an oscillation system to provide agitation. The refining/upgrading of bio-oil to bio-jet fuel was modeled using the PRELIM tool [21]. The transportation between ALGATEC site (point A, Fig. 2) and the refining/upgrading site (point B, Fig. 2) was considered to be by road (tanker



**Fig. 1.** Scheme of the process boundaries, for the base case, RQ2 (black dashed line). RQ1 (orange dotted line) boundary does not consider transport to airport and combustion in jet engine (color).



**Fig. 2.** Location and distances between the considered processing units in mainland Portugal: A – Póvoa de Santa Iria (ALGATEC Eco Business Park, microalgae cultivation and harvesting); B – Sines (oil refinery, bio-oil refining/upgrading); C – Aveiras de Cima (logistic platform, bio-jet fuel storage); D – Lisbon (Humberto Delgado airport, aircraft fueling). Geographical data adapted from SNIG [20] (color).

truck- regional delivery (RD)). A segment of the transportation to the airport is conducted through a pipeline, extending from point B to point C, as depicted in Fig. 2. The remaining portion is covered by road transportation, spanning from point C to point D, as illustrated in Fig. 2. The distances outlined in Fig. 2 determine the extent of this transportation, and the electricity consumption data for the pipeline were retrieved from the 2019 report of *Companhia Logística de Combustíveis, S. A.* (CLC) [23].

The missing HTL data from Move2LowC project were modeled according to the approach described by Fortier et al. (2014) [14]. The heat requirements were determined using Eq. 1, assuming that it was solely provided by NG without considering heat recycling. The electricity

consumption for bio-oil separation was estimated using Eq. 2, with the assumption that the separation process was conducted by a cyclone. Additionally, the lower heating values (LHV) of HTL products were obtained from literature sources (see Table A1, Appendix A).

Fortier et al. (2014) [14], Nava-Bravo et al. (2021) [24] and Zhang et al. (2022) [25] have been identified as benchmark studies and supplementary data sources for this work. Their inclusion is based on being the only publications in the literature that provide comprehensive life cycle inventories covering the entire process, from microalgal biomass cultivation to bio-jet fuel production.

$$HTL\ heat [J] = \left[ \frac{4.22J}{g \cdot ^\circ C} (150^\circ C - 25^\circ C) + \frac{4.86J}{g \cdot ^\circ C} (T_{HTL}^\circ C - 150^\circ C) \right] \\ \times Wet\ microalgae, kg \times \frac{1000g}{kg} \times (1 - Fraction\ heat\ recycled)$$

Equation 1

$$Cyclone\ electricity = \frac{(130\ kW) \times Wet\ microalgae, kg}{\left( \frac{190\ m^3}{h} \right) \times \left( \frac{1000\ kg}{m^3} \right)}$$

Equation 2

The bio-oil obtained from HTL requires upgrading to be converted into bio-jet fuel. Due to the lack of Move2LowC experimental data, the inventory was developed assuming that the bio-oil would be transported to a refinery and treated as a bio-crude, subsequently refined into multiple products. The refining/upgrading processes were modeled using the Petroleum Refinery Life Cycle Inventory Model (PRELIM), developed by the University of Calgary in Canada. PRELIM is a mass and energy-based process unit-level tool designed for estimating energy use and GHG emissions associated with processing various crude oils in different refinery configurations [21]. For this work, the selected configuration in PRELIM was a coking refinery with “deep conversion FCC & GO-HC” (where FCC stands for fluid catalytic cracking and GO-HC refers to gas oil hydrocracking). The assumed input was the crude “CNRL Light Sweet Synthetic Crude” (where CNRL stands for Canadian Natural Resources Limited), chosen for its similarity to bio-crude and its suitability for maximizing jet fuel production in refineries. Additional input details are presented in Appendix A (Table A2).

The outputs obtained from PRELIM for calculations included energy use and GWP for electricity, heat (from NG, and refinery fuel gas, or RFG), and hydrogen use (from steam methane reforming, SMR, and catalytic naphtha reformer, CNR). Results for the product slate of multi-products, including jet fuel, were also utilized. This involved the fraction of jet fuel obtained and multi-products per mass of bio-oil treated, which were then converted per FU. These parameters are detailed in the life cycle inventory in section 3. The LHV for bio-jet fuel and bio-oil were also extracted from PRELIM [21] (Table A1, Appendix A).

### 2.3. Carbon footprint: Assumptions, emission characterization factors and scenarios

In the modelling of bio-oil refining/upgrading through PRELIM, the carbon footprint analysis excluded upstream releases and off-site managed waste releases. However, in the calculations for this work, the upstream effects considered were included in the emission factors (presented in sub-section 2.3.2) for NG and electricity. Only hydrogen generated from SMR is taken into account in the emissions balance (CNR generates zero emissions according to PRELIM [21]).

Since combustion in the aircraft engine was not encompassed in the boundaries for RQ1, along with the exclusion of other co-products and by-products’ end-of-life, the carbon footprint calculations incorporated CO<sub>2</sub> fixation by microalgae, and the emissions from syngas flaring emissions were included. For the calculations related to RQ2, where the analysis involves the combustion of bio-jet fuel in the aircraft engine, and the carbon footprint is allocated to this product, its CO<sub>2</sub> emissions balance out with the microalgae-allocated fixation.

The GWP100 calculations incorporated emission characterization factors detailed in Table 2. The electricity emission factor corresponds to the 2021 annual value for mainland Portugal, which no longer includes coal [26]. For the NG emission factor, both upstream and combustion releases were considered [27]. The emission factors for hydrogen production via SMR and for the RFG were determined based on the GWP values provided by PRELIM [21]. The emission factor for hydrogen production via SMR aligns with the range reported by Fortier et al. (2014) [14] for hydrogen production via different methods. Transportation was assumed to be conducted using a “9-RD” tanker truck with a capacity of 6.3 tons [28]. The emission factors for nutrients and food-

Table 2

Emission factors considered for the carbon footprint calculations.

Item	Unit	gCO <sub>2</sub> eq/unit	Ref
Electricity	kWh	151	Agência Portuguesa do Ambiente (APA, Portuguese Environmental Agency) (year of reference – 2021) [26]
Natural Gas	MJ	67.6	Joint Research Centre-Eucar-Concawe (JEC) [27]
Combustion	MJ	56.1	JEC [27]
Upstream	MJ	11.4	JEC [27]
H <sub>2</sub> via NG SMR	gH <sub>2</sub>	9.7	PRELIM [21]
RFG	MJ	57.0	PRELIM [21]
Tanker truck	tkm	110.9	European Automobile Manufacturers Association (ACEA) [28]
Diesel combustion	MJ	73.2	JEC [27]
Sodium phosphate	g	2.42	Ecoinvent [29]
Potassium chloride	g	0.49	Ecoinvent [29]
Carbon dioxide, CO <sub>2</sub>	g	1	Intergovernmental Panel on Climate Change (IPCC) [30]
Methane, CH <sub>4</sub>	g	27.9	IPCC [30]
Nitrous oxide, N <sub>2</sub> O	g	273	IPCC [30]
Propylene, C <sub>3</sub> H <sub>6</sub>	g	n.a.	IPCC [30]
Propane, C <sub>3</sub> H <sub>8</sub>	g	0.02	IPCC [30]
Isobutane, C <sub>4</sub> H <sub>10</sub>	g	n.a.	IPCC [30]
Butene, C <sub>4</sub> H <sub>8</sub>	g	n.a.	IPCC [30]
n-Butane, C <sub>4</sub> H <sub>10</sub>	g	0.006	IPCC [30]
Food-grade CO <sub>2</sub>	g	0.82	City of Winnipeg, Canada [31]

grade CO<sub>2</sub>, added during cultivation, pertain to their upstream impact at the production level.

In accordance with CORSIA methodology, “in order to allocate the emissions generated from the entire supply chain amongst all of the valuable outputs of the system, an energy allocation method for co-products is used. Under energy-based allocation, the emissions burdens are allocated to co-products in proportion to their contribution to the total energy content of all the outputs” [13]. Thus, the energy allocation factors were obtained by multiplying the amount of each fraction (in kg) by its corresponding LHV (MJ/kg) (Table A2, in annex) and dividing by the total energy amount of the stream (in MJ).

#### 2.3.1. Influence of transport – Location scenarios and different type of transport needs (scenario 1)

To assess the impact of the geographical location of process steps on overall life cycle emissions and investigate the significance of transport steps, two system configurations were examined, starting from the base-case scenario (Sc0). Scenario 1 (Sc1) includes the following configurations: (Sc1.1) system configuration 1 – HTL located next to the refining/upgrading facilities in Sines (point B in Fig. 2); (Sc1.2) system configuration 2 – cultivation, harvesting and HTL located next to the refining/upgrading facilities in Sines (point B in Fig. 2).

In Sc1.1, the transport of wet biomass, instead of bio-oil, was considered from Póvoa de Santa Iria to Sines (point A to B, Fig. 2). In Sc1.2, there is no transport to the refining/upgrading site, as all sub-processes occur at the same facilities in Sines.

The additional burden of transporting wet biomass (system configuration 1) by tanker truck to the refining/upgrading unit, instead of bio-oil in the base case, was considered and estimated, taking into account the conversion yield of wet biomass into bio-oil.

#### 2.3.2. No local industry for CO<sub>2</sub> valorization (scenario 2)

In Scenario 2 (Sc2), where there is no local industry for CO<sub>2</sub> valorization through microalgal CO<sub>2</sub> intake, and assuming system

configuration 2 where all process units are located in Sines facilities, two sub-scenarios were considered:

- Sc2.1: CO<sub>2</sub> supplementation (in the same amount as CO<sub>2</sub> from industrial exhaust gases in the base case) could be performed via bottled CO<sub>2</sub> produced specifically for its application in cultivation (Fig. 3a). In this scenario, additional emissions related to CO<sub>2</sub> production were accounted for, along with CO<sub>2</sub> that is not sequestered by microalgae and, therefore, is released to the atmosphere.
- Sc2.2: The CO<sub>2</sub> generated in the process (i.e., during HTL and refining) is recirculated, minimizing/avoiding the need for bottled CO<sub>2</sub> and its associated emissions (Fig. 3b).

In Sc2.2 (Fig. 3b), it was assumed that all CO<sub>2</sub> released from the combustion of NG and RFG, which is required for the heat supply of HTL and refining/upgrading, as well as NG for SMR, is reintroduced into microalgae cultivation and sequestered to reduce the need for external CO<sub>2</sub> and its associated emissions.

The available CO<sub>2</sub> from combustion, suitable for recirculation, was determined by applying the NG combustion emission factor (56.1

gCO<sub>2</sub>eq/MJ, Table 2) to the NG requirements for the heat of HTL and refining/upgrading units, considering a combustion efficiency of 90%. The CO<sub>2</sub> available from RFG combustion was directly obtained from PRELIM [21]. For NG used in hydrogen production via SMR, the released CO<sub>2</sub> available for recirculation was estimated using PRELIM values: NG feed consumption of 80.13 MJ/bbl bio-oil; NG LHV of 36.63 MJ/m<sup>3</sup>; and a SMR emission factor of 0.663 kgCO<sub>2</sub>/m<sup>3</sup> of NG [21]. For simplification, it was considered that both the NG and RFG combustion released 100% of CO<sub>2</sub>.

### 2.3.3. Heat recovery (scenario 3)

Since HTL can be one of the most energy-intensive sub-processes in this jet fuel production system [14,32], especially in terms of heat, it may be advantageous to consider heat recovery or reintegration to reduce the emissions associated with NG combustion for heat generation. In this scenario, starting from Sc0, heat generated from the combustion of syngas (a byproduct of HTL) is reintroduced in the HTL, thereby decreasing the need for external heat generated from NG (Fig. 3c).

The available heat for recirculation generated from syngas combus-

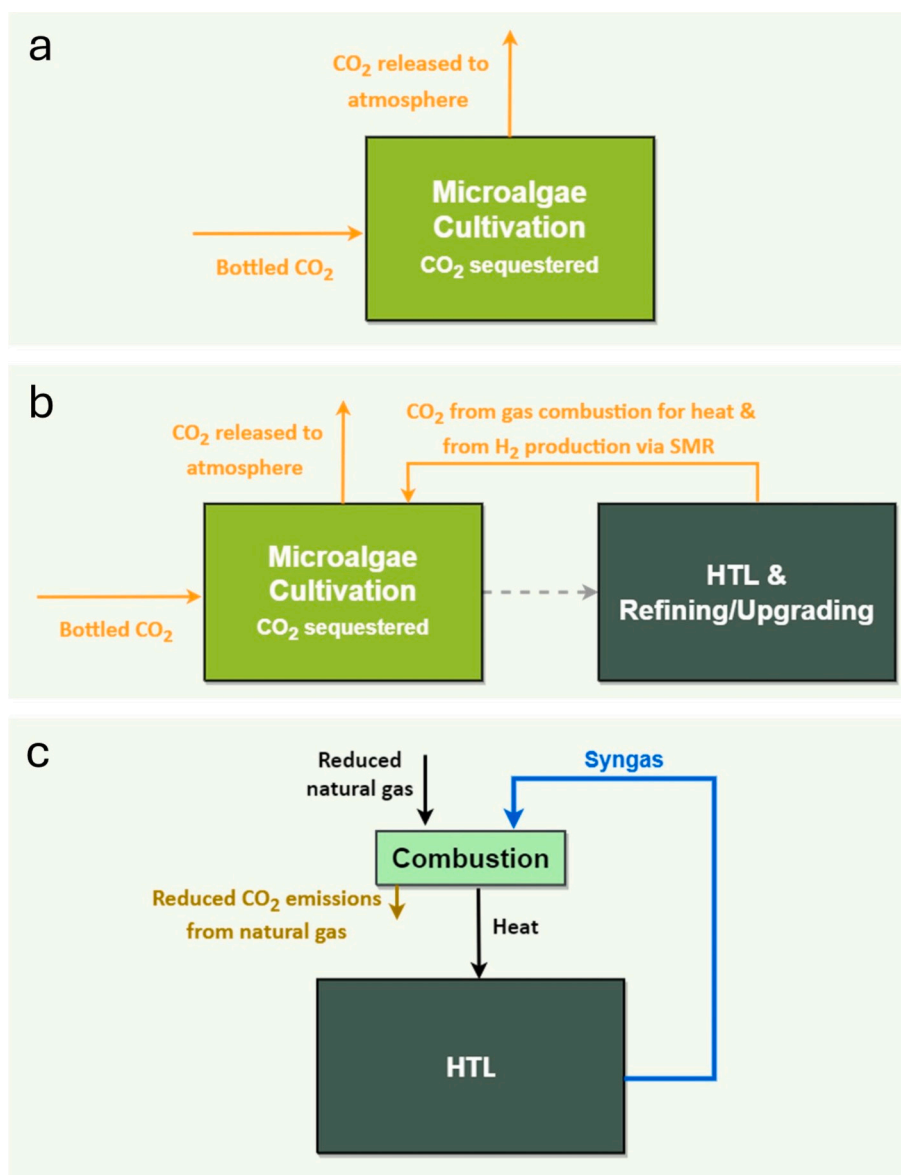


Fig. 3. Scheme of the CO<sub>2</sub> balance in cultivation for Sc2.1 (a) and Sc2.2 (b); Scheme for heat recovery from syngas combustion (c).

tion was calculated based on the syngas mass balance obtained from HTL (as presented in the life cycle inventory, section 3) and its estimated LHV (46.2 MJ/kg), considering a combustion efficiency of 90 %. The LHV was estimated based on the syngas composition (Table A3, Appendix A) and Eq. 3 from Hosokai et al. (2016) [33].

$$LHV \left[ \frac{MJ}{kg} \right] = 38.2m_c + 84.9(m_H - m_O/8) \quad \text{Equation 3}$$

#### 2.3.4. Combination of scenarios for SAF compliance (scenario 4)

To further minimize the carbon footprint of the process, a combination of options from the three tested scenarios was considered. Scenario 4 (Sc4) involves a combination of Sc1.2 and Sc3, i.e., system configuration 2 with heat recovery, and assuming local industrial CO<sub>2</sub> capturing and wastewater.

#### 2.3.5. Multi-variable optimization for SAF compliance (scenario 5)

Using Scenario 4 as a baseline – where the HTL facility is located adjacent to the microalgae cultivation and harvesting site, and near the upgrading/refining facility, with reduced natural gas consumption – various parameters were adjusted to determine the necessary conditions for achieving 80.1 gCO<sub>2</sub>eq/MJ threshold required by CORSIA for Sustainable Aviation Fuel (SAF) compliance [12]. The parameter optimization process involved varying the following, as illustrated in Fig. 4: (a) HTL bio-oil conversion yields, (b) the electricity emission factor, and (c) refinery mass conversion efficiency to jet fuel.

For parameter (a), two HTL bio-oil yields were considered: (a1) the yield from the Move2LowC project (55.6 % dw, based on bench-scale experiments) and (a2) the median yield from benchmark studies (36.9 % dw), as observed in the no-catalyst case by Zhang et al. (2022) [25].

Fig. 4 illustrates the flowchart of the optimization procedure. For each case (a1 and a2), a set of conditions for a combination of parameters (b) and (c) were determined using the Solver tool in Microsoft™ Excel for non-linear optimization. The objective was to achieve a Global Warming Potential (GWP) of 80.1 gCO<sub>2</sub>eq/MJ for bio-jet fuel in response to Research Question 2 (RQ2).

Several conditions were set during the optimization process:

- Condition I: Optimization without constraints
- Condition II: Fixed electricity emission factor of 151 gCO<sub>2</sub>eq/kWh for the year of reference – 2021 (Table 2)
- Condition III: 100 % renewable electricity mix (electricity emission factor of 0 gCO<sub>2</sub>eq/kWh).

### 3. Results and discussion

#### 3.1. Life cycle inventory, energy and mass balance

Table 3 shows the life cycle inventory to produce bio-jet fuel from microalgae biomass through HTL for the Move2LowC project. Results are presented considering two FU, 1 kg dw of microalgae converted into multi-products and 1 MJ of bio-jet fuel produced, which was the starting point for the carbon footprint calculations.

In Move2LowC, CO<sub>2</sub> supplementation is achieved by utilizing industrial exhaust gas, with only 17.7 % of the emitted CO<sub>2</sub> being sequestered by microalgae, as determined through elemental analysis. In contrast, Zhang et al. (2022) [25] supplements CO<sub>2</sub> through the recirculation of carbon in flue gas and the gas released from HTL.

Considering the HTL of the microalgal biomass, results obtained for Move2LowC revealed a greater need for energy for heating. However, this occurred because the base-case scenario did not account for heat recycling. Fortier et al. (2014) [14] and Nava-Bravo et al. (2021) [24], considered 80 % of heat recycling, reducing the need for external heat. Move2LowC resulted in the highest bio-oil yield, above what would be expected, which may have been due to HTL being performed at small-scale. Regarding refining/upgrading process, other studies only consider hydrotreating reactions for bio-oil refining/upgrading, however, the bio-oil resulting from the HTL is closer to a biocrude, and as such it needs several refining steps to reach a fuel with the characteristics of a jet fuel. Therefore, in this work the process was modeled as a conventional oil refinery with PRELIM, in which additional conversion processes, other than hydrotreatment, are carried out. Fortier et al. (2014) [14] and Nava-Bravo et al. (2021) [24] have assumed a jet fuel conversion of 90 %, however, in conventional refineries this conversion is lower [21,34].

Based on the life cycle inventory above, Fig. 5 represents the energy (electricity, heat and fuel) consumption of the process, where it is evident that cultivation is the most energy intensive step, amounting to 78 % of total energy consumption, which suggests this will be the greatest source of emissions of the process. In this sense, it may be beneficial to further investigate the optimization of the raceway's mixing system. HTL has also a significant heat consumption, making it important to consider heat recovery and recirculation, and different heat sources to NG, as a way of minimizing associated emissions. For instance, Fortier et al. (2014) [14] makes use, partially, of biomethane. Transport, namely through pipeline, did not have a substantial impact on the overall energy use, even though there is still a considerable distance between the locations.

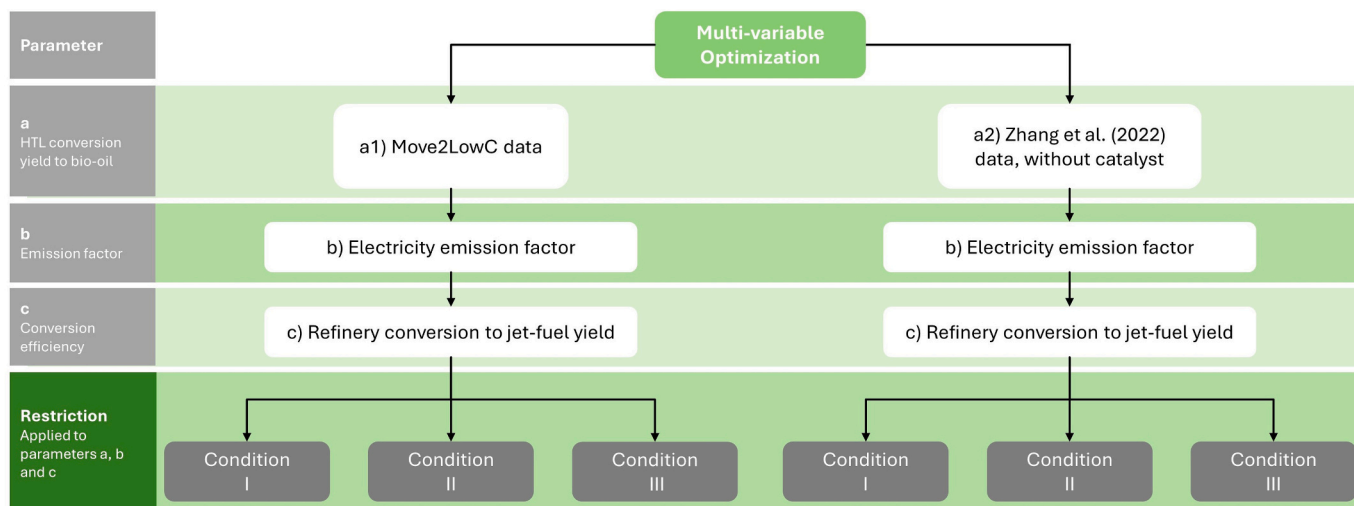


Fig. 4. Schematic representation of the best-case scenario optimization process (six outcomes) (color).

**Table 3**

Life cycle inventories for Move2LowC concept. Values per kg of dry cell weight microalgae, and per MJ of bio-jet fuel without allocation.

Parameter	Units	Functional Unit (FU)	
		kg dw microalgae	MJ bio-jet fuel
<i>Values per FU</i>			
<b>Cultivation</b>			
<u>Input</u>			
Water	L	1168	216
Nitrogen (N)	g	123.7	22.8
Sodium phosphate (NaH <sub>2</sub> PO <sub>4</sub> )	g	115.1	21.3
Corresponding P	g	25.8	4.8
Potassium chloride (KCl)	g	62.4	11.5
Corresponding K	g	32.6	6.0
Supplemented CO <sub>2</sub>	kg	6.6	1.2
Sequestered CO <sub>2</sub>	kg	1.17	0.22
Electricity	kWh	16.2	2.99
<u>Output</u>			
Water + biomass stream	kg	n.a.	n.a.
Microalgae (dw)	kg	1	0.18
Ash	kg	0.25	0.05
Carbon, C	kg	0.32	0.06
Hydrogen, H	kg	0.03	0.01
Nitrogen, N	kg	0.06	0.01
Oxygen, O	kg	0.34	0.06
Water	kg	n.a.	n.a.
<b>Harvesting</b>			
<u>Input</u>			
Water + biomass stream	(see Cultivation)		
Electricity	kWh	0.25	0.05
<u>Output</u>			
Wet microalgae	kg	10	1.84
Microalgae (dw)	kg	1	0.18
Water	kg or L	9	1.66
<b>HTL</b>			
<u>Input</u>			
Wet microalgae	(see Harvesting)		
Heat	MJ	13.8	2.55
Electricity	kWh	0.007	0.0013
<u>Output</u>			
Bio-oil	kg	0.556	0.10
Biochar	kg	0.097	0.02
Syngas	kg	0.004	0.001
Methane	g	0.14	0.03
Propylene	g	0.29	0.05
Propane	g	1.94	0.36
Isobutane	g	0.91	0.17
Butene	g	0.47	0.09
n-Butane	g	0.38	0.07
Effluent stream	kg, L	9.34	1.73
Aqueous fraction	kg	0.343	0.06
<b>Transport to Refinery</b>			
Road (bio-oil)	tkm	0.09	0.017
<b>Refining/Upgrading</b>			
<u>Input</u>			
Bio-oil	(see HTL)		
Electricity	kWh	0.025	0.005
Heat	MJ	1.46	0.27
from RFG	MJ	0.98	0.18
from NG	MJ	0.48	0.09
Hydrogen	g	4.1	0.8
from SMR	g	2.4	0.5
from CNR	g	1.7	0.3
<u>Output</u>			
Multi-product	kg	0.536	0.10
Bio-jet fuel	MJ (kg)	5.4 (0.125)	1.0 (0.02)
Others	kg	0.411	0.08
<b>Transport to Airport</b>			
Pipeline (bio-jet fuel)	kWh	0.0002	4E-05
Road (bio-jet fuel)	tkm	0.007	1E-03

### 3.2. Base-case scenario (Sc0)

The carbon footprint of Sc0, for RQ1 and RQ2, is summarized in Table 4 and Table 5, respectively, in which are also shown the GHG emissions balance, considering system boundaries and assumptions

mentioned in section 2.

The carbon footprint of the conversion of microalgae into multi-products (RQ1), from cultivation to bio-oil refining/upgrading, resulted in 2.7 kgCO<sub>2</sub>eq/kg dw microalgae (Table 4), which is nearly three times the mass of dry cell weight microalgae cultivated. This value is primarily influenced by the utilization of electricity for cultivation in the mixing system and the heat generated from NG combustion for HTL. However, the impact of the latter is almost offset by the emissions avoided through algal CO<sub>2</sub> fixation. Fig. 6 offers a visual representation of the emissions balance for RQ1.

Considering RQ2, the carbon footprint of 1 MJ of bio-jet fuel obtained for Sc0 was 161.45 gCO<sub>2</sub>eq/MJ bio-jet fuel (Table 5), which is 81 % higher than the reference value determined by CORSIA for conventional aviation fuel (89 gCO<sub>2</sub>eq/MJ), being 102 % above the standards for SAF compliance (80.1 gCO<sub>2</sub>eq/MJ). Therefore, there is the need for further optimization of the Move2LowC concept. There are several viable possibilities to do it: 1) increase the biomass productivity by lowering the degree of effluent toxicity to the microalgae growth; 2) change all the energy inputs of the process to renewable energy, since the electricity usage in the raceway mixing system is what contributes the most for these emissions (Fig. 7) – this would reduce the total GHG emissions by ca. 64 %; 3) increase the biomass conversion efficiencies in particular the HTL yield for bio-oil; 4) increase the scale of production. It is important to highlight that the technology readiness level of this case study is still low in comparison with the current established technologies used as benchmark. Therefore, an increase in scale would allow to obtain data for a more representative comparison with the selected references.

### 3.3. Scenario analysis

The carbon footprint results for the alternative scenarios studied (Sc1.1, Sc1.2, Sc2.1, Sc2.2, Sc3 and Sc4) are presented in Table 6. The most negative scenario is Sc2.1 (bottled CO<sub>2</sub> without recirculation), which resulted in the highest carbon footprint, considering both direct (5.43 kgCO<sub>2</sub>eq/kg dw microalgae) and indirect (5.41 kgCO<sub>2</sub>eq/kg dw microalgae) emissions, as depicted in Fig. 3. The differences between Sc2.1 and Sc0 balances are the additional emissions of 10.84 kgCO<sub>2</sub>eq/kg dw microalgae for RQ1 and of 447.9 gCO<sub>2</sub>eq/MJ bio-jet fuel for RQ2, minus the emissions from transport to the refinery. This CO<sub>2</sub> source for cultivation is not sustainable, thereby exacerbating the overall impact of the process compared to the base case (Sc0), in which CO<sub>2</sub> is sourced from local industrial exhaust gas streams. When considering the recirculation of CO<sub>2</sub> (Table 7), the carbon footprint diminishes, as the demand for bottled CO<sub>2</sub> decreases. Consequently, the associated emissions also decrease, as illustrated in Fig. 4 in Section 2. The emissions resulting from the released CO<sub>2</sub> stand at 9942 gCO<sub>2</sub>eq/kg dw microalgae and 410.9 gCO<sub>2</sub>eq/MJ bio-jet fuel for RQ1 and RQ2, respectively. Despite a roughly 7 % and 6 % reduction in carbon footprint values for the respective RQ1 and RQ2 of Sc2.1 (as outlined in Table 6), this improvement falls short of being deemed a promising approach. The impact still exceeds that of Sc0 and surpasses what would be considered sustainable aviation fuel (SAF).

In the context of different location scenarios, specifically Sc1.1 and Sc1.2, it is evident that the former resulted in a higher carbon footprint than that of Sc0, while the latter resulted in a slightly lower one.

Sc1.1 involves the transportation of wet biomass, rather than bio-oil, from cultivation site to HTL in Sines. Due to the higher mass of wet biomass per kilogram of dry cell weight microalgae (10 kg/kg dw microalgae) compared to bio-oil (0.556 kg/kg dw microalgae), the burden by tanker truck to Sines in this scenario is expected to be eighteen times higher than in Sc0. This results in an increase in the emissions of the transport to refinery fraction from 10 gCO<sub>2</sub>eq/kg dw microalgae to 186 gCO<sub>2</sub>eq/kg dw microalgae for RQ1 and from 0.4 gCO<sub>2</sub>eq/MJ bio-jet fuel to 7.7 gCO<sub>2</sub>eq/MJ bio-jet fuel for RQ2.

On the other hand, Sc1.2, where all sub-processes are located at the

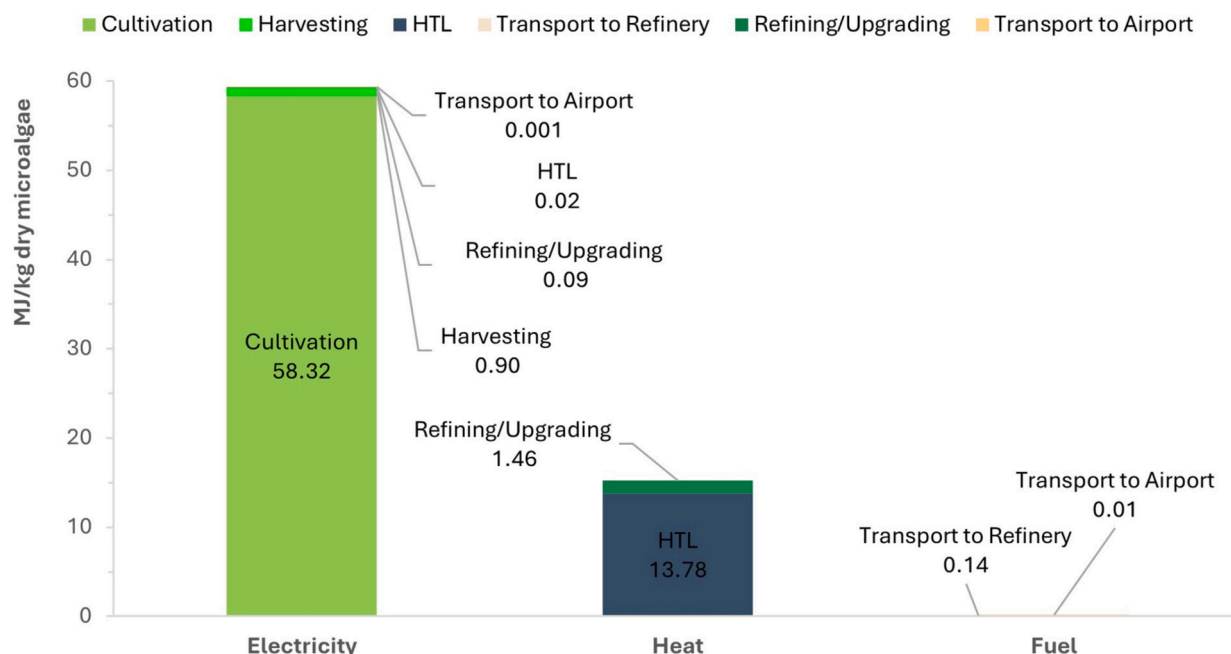


Fig. 5. Energy consumption (electricity, heat, and fuel) of Move2LowC system (Sc0) (color).

Table 4  
GHG emissions per kg of dw microalgae (FU), for Sc0, considering RQ1.

GHG Emissions Balance (Sc0, RQ1)	
Parameter	GWP (gCO <sub>2</sub> eq/kg dw microalgae)
<b>Cultivation</b>	
Electricity (mixing system)	2446.2
CO <sub>2</sub> sequestered by microalgae	-1173.8
Sodium phosphate (NaH <sub>2</sub> PO <sub>4</sub> ), P source	278.6
Potassium chloride (KCl), K source	30.7
<b>Harvesting</b>	
Electricity (membrane)	37.8
<b>HTL</b>	
Heat (from NG)	1034.3
Electricity (bio-oil separation)	1.0
Syngas flaring:	
Methane	3.5
Propane	0.035
n-Butane	0.002
<b>Transport to Refinery</b>	
Road Transport (bio-oil)	10.4
<b>Refining/Upgrading</b>	
Electricity	3.7
Heat (from RFG)	0.06
Heat (from NG)	36.3
Hydrogen (from SMR)	23.7
<b>Total</b>	<b>2732.4</b>

same facilities, eliminates the need for transport to the refinery, making it more convenient and efficient. Consequently, there are no associated emissions. While Sc1.1 is not sustainably viable due to the exacerbation of the carbon footprint, Sc1.2 is much more attractive and promising than even the current configuration. However, it still falls short of enabling the production of SAF. Nevertheless, it represents a positive step in the right direction.

The implementation of heat recovery (Sc3) resulted in a lower carbon footprint compared to the base value in both Sc0 and all previously discussed scenarios (Table 6). Even though the available heat for recirculation, generated from syngas combustion (as calculated in Section 2), is significantly smaller (0.17 MJ/kg dw microalgae) than the heat required for HTL (13.8 MJ/kg dw microalgae), its utilization resulted in a significant reduction in emissions. This reduction amounted to

Table 5  
GHG emissions per MJ of bio-jet fuel (FU), for Sc0, considering RQ2 and energy allocation.

GHG Emissions Balance (Sc0, RQ2)	
Parameter	GWP (gCO <sub>2</sub> eq/MJ bio-jet fuel)
<b>Cultivation</b>	
Electricity (mixing system)	101.10
Sodium phosphate (NaH <sub>2</sub> PO <sub>4</sub> ), P source	11.52
Potassium chloride (KCl), K source	1.27
<b>Harvesting</b>	
Electricity (membrane)	1.56
<b>HTL</b>	
Heat (from NG)	42.75
Electricity (bio-oil separation)	0.04
<b>Transport to Refinery</b>	
Road Transport (bio-oil)	0.43
<b>Refining/Upgrading</b>	
Electricity	0.15
Heat (from RFG)	0.002
Heat (from NG)	1.50
Hydrogen (from SMR)	0.98
<b>Transport to Airport</b>	
Pipeline (jet fuel)	0.006
Road Transport (jet fuel)	0.15
<b>Total</b>	<b>161.45</b>

approximately 12.9 gCO<sub>2</sub>eq/kg dw microalgae for RQ1 and 0.5 gCO<sub>2</sub>eq/MJ bio-jet fuel for RQ2.

In this scenario, the emissions from HTL heat are solely attributed to the 13.6 MJ/kg dw microalgae still provided by external NG. While this pathway remains distant from achieving SAF standards, it has demonstrated promise. It is worth noting that even though the mass of syngas obtained in HTL is currently low (as indicated in Table 3), if a higher percentage of gas can be obtained, the available heat for recirculation derived from its combustion would increase, facilitating a more substantial reduction in emissions.

Scenario 4 (Sc4) yielded the lowest GWP, a result of the combined effects of Sc1.2 and Sc3. This is attributed to the absence of transport emissions to refining/upgrading and a reduction in emissions from HTL heat. This scenario, while promising, is still a considerable distance away from meeting SAF standards, and its carbon footprint exceeds that

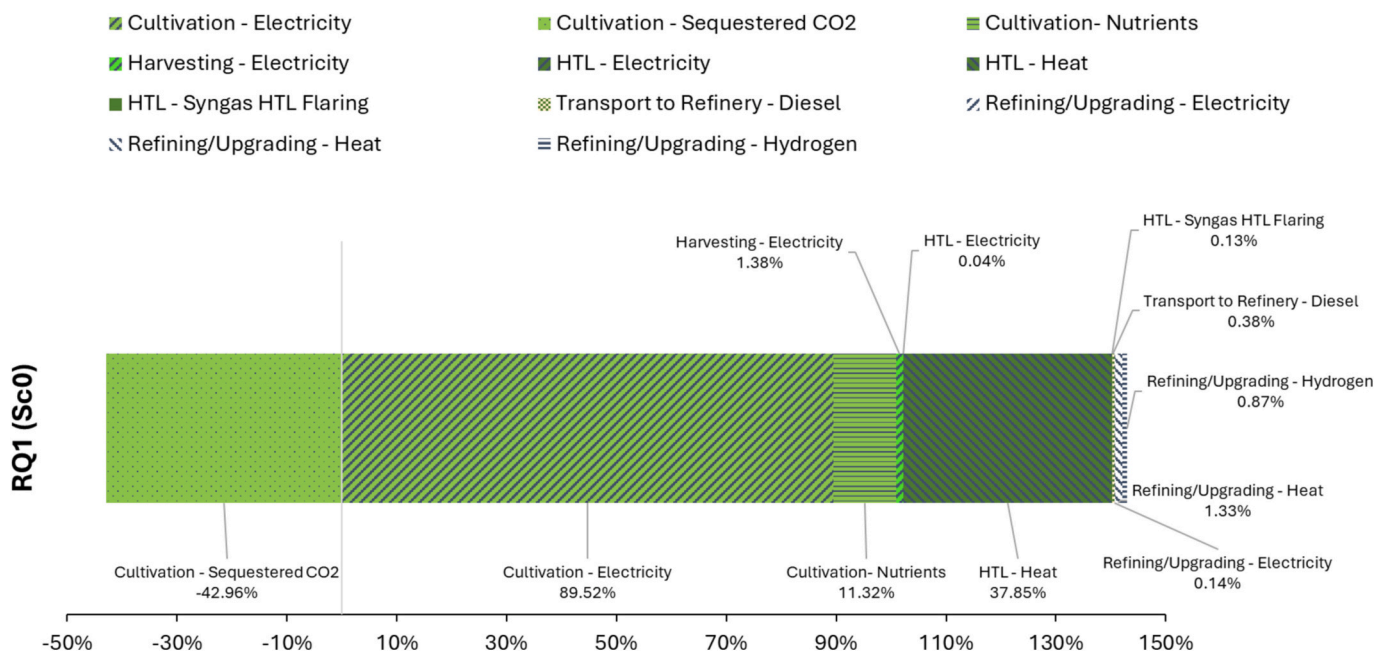


Fig. 6. GHG emissions balance (contributions in %) for Sc0 considering RQ1 system boundaries (color).

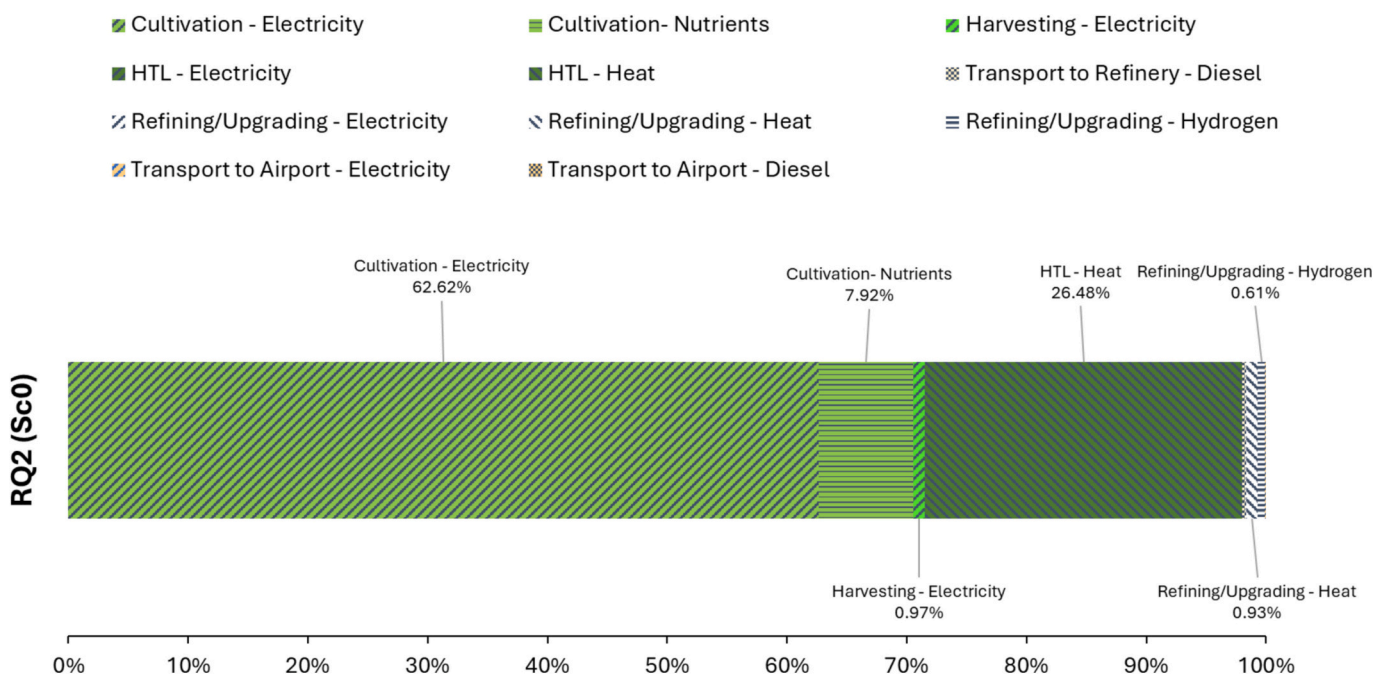


Fig. 7. GHG emissions balance (contributions in %) for Sc0 considering RQ2 system boundaries and energy allocation (color).

of conventional jet fuel.

It is crucial to emphasize that the percentage variation in the GWP of the scenarios concerning Sc0 (Table 6) differs between RQ1 and RQ2, as RQ2 incorporates allocation to jet fuel, leading to a distinct weight in the variation of the impact.

### 3.4. Sensitivity analysis and comparison with literature

In examining the “best” scenario, Sc.4, the key process steps include Cultivation, HTL, Upgrading/Refining and Transport to the airport. Electricity consumption during cultivation, particularly for mixing, varies due to factors like reactor configuration, displaced volume, and

others. Normalizing this energy consumption per 1 kg of dry weight microalgae (0 % moisture) introduces additional variability, influenced by factors such as microalgae species, nutrient load, CO<sub>2</sub> capture efficiency.

Pérez-López et al. (2017) [35] reported electricity usage values for a 25 m<sup>2</sup> open raceway pond (ORP) ranging from 89 to 619 kWh/kg dw. Pechsiri et al. (2023) [36] provided figures of 6.6 kWh/kg dw for ORP and 8.5 kWh/kg dw for a 100 m<sup>2</sup> thin-layer cascade open pond. Herrera et al. (2020) [37] reported 0.57 kWh/kg dw for a 1000 m<sup>2</sup> ORP. The work by Pérez-López et al. (2017) [35] specifically reports that, for their experimental setup, temperature control system was the main contributor to environmental impacts, this is not the case in the open cascade

**Table 6**

GHG emissions results for all scenarios, comparison with Sc0 and with SAF (for RQ2).

Scenario	GWP (kgCO <sub>2</sub> eq/kg dw microalgae)	Variation * (%)	GWP (gCO <sub>2</sub> eq/MJ bio-jet fuel)	Variation * (%)	SAF compliance (%)
Sc0: Base-case scenario	2.73	n.a.	161.45	n.a.	+102
Sc1: Transport effect					
Sc1.1: System configuration 1	2.91	+6	168.72	+5	+111
Sc1.2: System configuration 2	2.72	-0.38	161.02	-0.27	+101
Sc2: Fuel grade CO <sub>2</sub>					
Sc2.1: W/ recirculation	13.56	+396	608.96	+277	+660
Sc2.2: W/o recirculation	12.66	+363	571.93	+254	+614
Sc3: Heat recovery	2.72	-0.47	160.92	-0.33	+101
Sc4: Sc1.2 + Sc3	2.71	-0.85	160.49	-0.60	+100

\* Variation in % in relation to Sc0 GWP value.

**Table 7**Gas combustion (for HTL and refining/upgrading heat) emissions, and CO<sub>2</sub> emissions from hydrogen production via SMR, available for recirculation. Only direct emissions related to combustion and no upstream effects.

Source of CO <sub>2</sub> emissions	gCO <sub>2</sub> eq %/kg dw microalgae
<i>HTL</i>	
NG combustion for heat	859.0
<i>Refining/Upgrading</i>	
NG combustion for heat	30.1
RFG combustion for heat	0.1
NG for H <sub>2</sub> via SMR	6.7
<b>Total</b>	<b>895.8</b>

\* assumed 100 % of CO<sub>2</sub> released.

raceway ponds analyzed in this work, as no temperature control is used. Consequently, the high electricity usage values likely result from lower productivity due to the toxicity of the wastewaters used and the option for lack of temperature and lighting control. These results emphasize the impact of system design and medium composition on microalgae cultivation, underscoring the importance of evaluating various conditions to accurately assess the optimal operating parameters.

Given that ALGATEC Eco Business Park is installing a nearby photovoltaic system to supply the electricity for cultivation, this effectively reduces electricity consumption to zero in terms of GWP100 impact category. Running a net-zero electricity scenario (0 gCO<sub>2</sub>eq/kWh) in the sensitivity analysis would simulate this condition. Furthermore, the Portuguese electricity emission factor is steadily declining, targeting net-zero emissions by 2050 (see supplementary material, Fig. A1).

Heat consumption for HTL, bio-oil yield, and the conversion efficiency of upgrading/refining to jet-fuel were reviewed from the literature (see supplementary material, Table A4 and Fig. A2). For the sensitivity analysis, the nominal values were adjusted to their minimum and maximum bounds for each selected parameter. Table 8 presents the minimum, nominal, and maximum values considered for each parameter, allowing observation of the variation in GWP100 results.

The sensitivity analysis results (Fig. 8) indicate that the most influential parameters are the electricity emission factor, HTL bio-oil yield, and the upgrading/refining conversion efficiency to jet-fuel. One significant perturbation is the use of a 100 % renewable electricity generation mix, which enables SAF compliance (58.1 gCO<sub>2</sub>eq/MJ, below the 80.1 gCO<sub>2</sub>eq/MJ threshold). In contrast, despite the disparity between minimum and maximum bounds for truck transport electrification (Table 8), this is not reflected in the sensitivity analysis. Additionally, HTL heat is also not critical for reducing CO<sub>2</sub>eq emissions, being expected to rely on biomethane as part of the ongoing energy transition.

The conversion efficiency of upgrading/refining bio-oil to jet-fuel also plays a key role in determining whether the bio-jet fuel meets SAF compliance. For instance, doubling the nominal conversion

**Table 8**

Minimum, nominal and maximum values of HTL heat consumption, bio-oil yield, and refining efficiency, used to assess the variation in GWP100 results during the sensitivity analysis.

Parameter	Minimum Bound	Nominal value	Maximum Bound
Electricity emission factor (gCO <sub>2</sub> eq/kWh)	0	151	198
Truck transport emission factor (gCO <sub>2</sub> eq/tkm)	0	110.6	235
HTL bio-oil yield	36.9	55.6	55.6
HTL heat	0.5	13.8	33
Upgrading/Refining jet-fuel efficiency	15	22.4	90

efficiency from 22.4 % to 50 % would result in emissions of 72 gCO<sub>2</sub>eq/MJ, below the CORSIA SAF compliance limit of 80.1 gCO<sub>2</sub>eq/MJ. Literature review (Fig. A2, supplementary material) shows conversion efficiencies exceeding 70 %, although this process has not been experimentally tested or simulated by the authors. Instead, inventories from other studies are typically used [38], or efficiency values assumed from literature [39,40], which leads to variability in results.

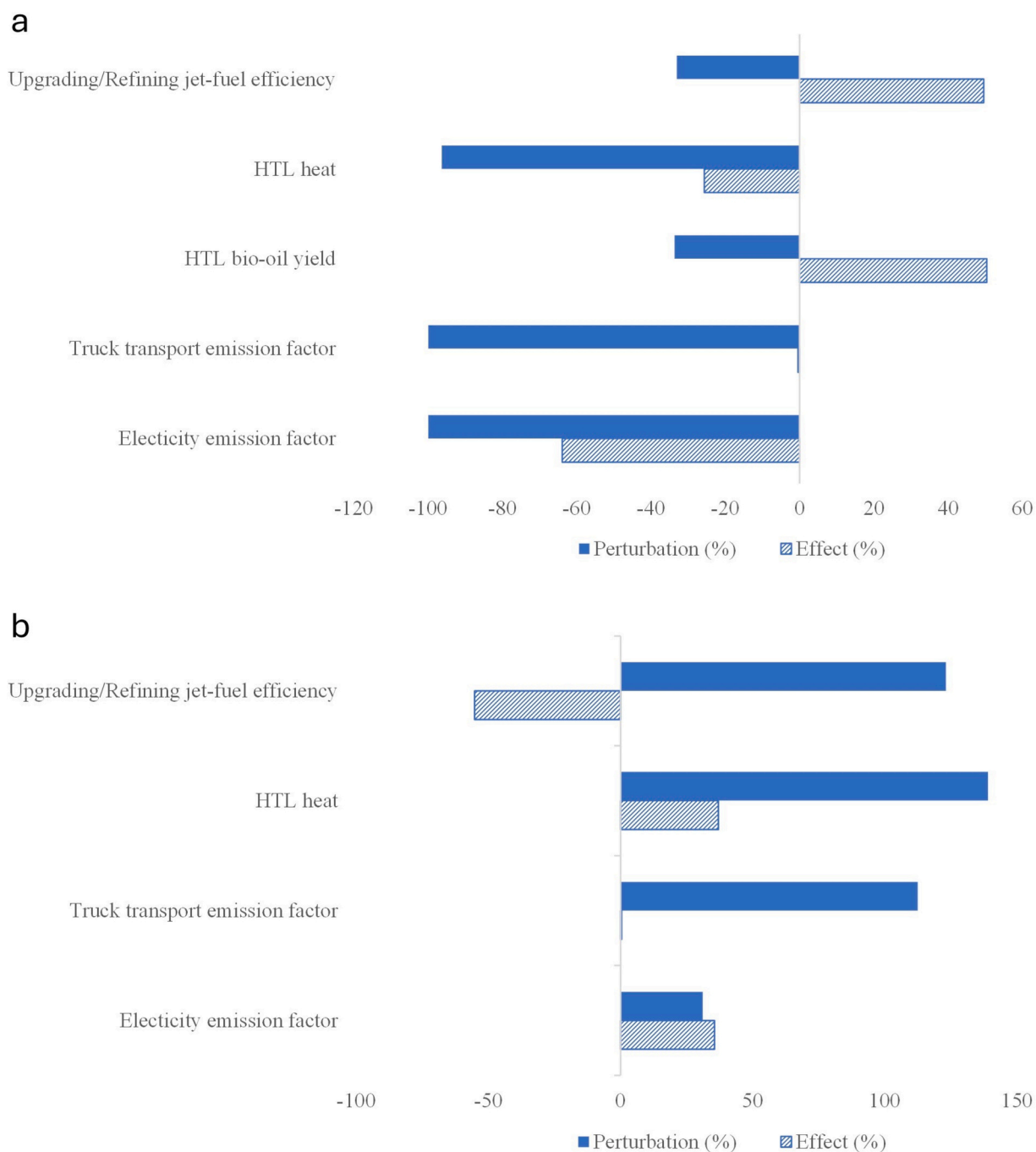
In this study, the industrial-scale PRELIM model was employed for a process unit with “deep conversion for fluid catalytic cracking and gas oil hydrocracking”, resulting in a much lower conversion efficiency to jet-fuel. This highlights the need for experimental testing of HTL bio-oil upgrading and proper characterization of the produced jet-fuel, particularly in terms of technical specifications. For example, Jet A-1 kerosene – commonly used in turbine engines – must meet ASTM D1655 standards, which require a minimum flash point of 38 °C and a maximum freeze point of -47 °C.

### 3.5. Multi-variable optimization for SAF compliance

Table 9 outlines six critical conditions for streamlining SAF production in accordance with the CORSIA 10 % GHG reduction rule, which stipulates a maximum carbon footprint of 80.1 gCO<sub>2</sub>eq/MJ.

Case a1), for a current bio-oil yield of 55.6 % dw, entails the optimization of both the electricity emission factor and the refinery jet-fuel yield. Ideally, the electricity emission factor must decrease from 0.151 to 0.033 kgCO<sub>2</sub>eq/kWh, while the jet-fuel yield requires only a minor increase of 0.006 %. If the electricity emission factor remains at its 2021 value, the jet-fuel yield must rise to 45 %, approximately double the current value. Conversely, with an electricity emission factor of 0 kgCO<sub>2</sub>eq/kWh, the jet fuel yield would only need to be 16 %.

For a HTL bio-oil yield of 36.9 % dw, unrestricted parameters resulted in a complete reduction of the electricity emission factor to 0 kgCO<sub>2</sub>eq/kWh, requiring a jet-fuel yield of 24.3 %. This scenario is only feasible with a fully decarbonized electricity mix, comparable to case (a1) under Condition III.



**Fig. 8.** Sensitivity analysis illustrating the effects of minimum (a) and maximum (b) bound perturbations on the nominal values of key parameters. (color).

With a HTL bio-oil yield of 36.9 % dw and the 2021 electricity emission factor, the jet-fuel yield should be at least 68 %, significantly higher than the typical yield in refineries. Previous studies [14,24] suggest an unrealistic 90 % upgrading conversion efficiency, while the fraction of jet-fuel produced through PRELIM modelling, and in typical refineries, is considerably lower [21,34]. As anticipated, for a bio-oil yield of 36.9 % dw, Condition III reflects the parameter values obtained in Condition I.

It is noteworthy that GHG savings requirements for other transportation systems are more stringent than the CORSIA aviation threshold of 10 %. For instance, the GHG savings threshold is at least 50 % for biofuels and biogas produced in facilities that were in operational before October 5th, 2015, and it increases to 70 % when using renewable fuels of non-biological origin or recycled carbon fuels.

For aviation fuel to meet these stringent thresholds, insights from Table 8 indicate that achieving this is only feasible with 100 % renewable utilities (both electricity and heat) and bio-jet yields exceeding 50 %. This underscores the necessity for experimental testing of HTL bio-oil upgrading and the characterize of the resulting jet-fuel in terms technical specifications, i.e., in accordance to ASTM D1655 specifications.

#### 4. Conclusions

This study conducted a global warming impact assessment of converting microalgae consortia into bio-jet fuel, guided by the following research questions:

**Table 9**

Optimized outcomes for parameters (b) electricity emission factor and (c) refinery conversion efficiency, for both cases (a1) and (a2), that achieve a carbon footprint of 80.1 gCO<sub>2</sub>eq/MJ for bio-jet fuel.

Outcomes *	Case a1) HTL bio-oil yield of 55.6 % dw			Case a2) HTL bio-oil yield of 36.9 % dw		
	I	II	III	I	II	III
b) Electricity emission factor (kgCO <sub>2</sub> eq/kWh)	0.033	0.151	0	0	0.151	0
c) Refinery conversion to jet fuel yield (%)	22.45	45.02	16.14	24.33	67.88	24.33

\* I – Non-restricted optimization; II – Electricity emission factor fixed to the current value (2021); III – 100 % renewable electricity.

- RQ1: What is the carbon footprint of converting 1 kg (dry cell weight) of microalgae into multi-product, in gCO<sub>2</sub>eq/kg dw microalgae?
- RQ2: What is the carbon footprint of obtaining 1 MJ of bio-jet fuel from microalgae, in gCO<sub>2</sub>eq/MJ bio-jet fuel, and how can it achieve SAF compliance?

The analysis, which included nominal values for cultivation, HTL, and upgrading/refining units, along with an exploration of different scenarios – such as the impact of location, CO<sub>2</sub> supplementation origin, and heat reintegration – aimed to construct a best-case scenario. The findings revealed that the project could achieve a GWP of 2709 gCO<sub>2</sub>eq/kg dw microalgae (RQ1) and 160.49 gCO<sub>2</sub>eq/MJ bio-jet fuel (RQ2).

Electricity consumption emerged as the most significant challenge, primarily due to the electricity mix considered in 2021 (151 gCO<sub>2</sub>eq/kWh). However, these values could be significantly reduced (by at least 64 %) with a transition to 100 % renewable energy sources, such as the photovoltaic plant currently being installed at the ALGATEC Eco Business Park.

Achieving SAF compliance according to CORSIA (threshold of 80.1 gCO<sub>2</sub>eq/MJ) is only feasible with a complete energy transition (100 % renewable electricity) and/or bio-jet yields exceeding 50 %.

Furthermore, it was identified a lack of realistic experimental studies on upgrading/refining microalgae HTL bio-oil. Previous studies suggest unrealistic conversion efficiencies 70 % or higher, while the jet fuel production fractions estimated through PRELIM modelling and typical refinery operations are considerably lower. This highlights the critical need for experimental testing of HTL bio-oil upgrading/refining at pilot-scale and the characterization of the produced jet fuel according to technical specifications. (i.e. Jet A-1 kerosene grade standards suitable for most turbine-engine aircraft, with a minimum flash point of 38 °C and a maximum freeze point of –47 °C, in accordance with ASTM D1655 specifications).

#### CRediT authorship contribution statement

**Renata Pires:** Writing – original draft, Software, Methodology. **Tiago P. Silva:** Writing – original draft, Validation, Methodology. **Cláudia Ribeiro:** Writing – review & editing, Formal analysis, Data curation. **Luís Costa:** Writing – review & editing, Funding acquisition, Formal analysis, Data curation. **Cristina T. Matos:** Writing – review & editing, Funding acquisition, Formal analysis, Data curation. **Paula Costa:** Writing – review & editing, Formal analysis, Data curation. **Tiago F. Lopes:** Writing – original draft, Validation, Supervision, Conceptualization. **Francisco Gírio:** Writing – review & editing, Funding acquisition, Formal analysis. **Carla Silva:** Writing – original draft, Validation, Supervision, Funding acquisition, 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.

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#### Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.algal.2024.103799>.

#### Data availability

Data will be made available on request.

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