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*Original*
Are algae ready to take off? GHG emission savings of algae-to-kerosene production / Prussi, M.; Weindorf, W.; Buffi, M.; Sanchez Lopez, J.; Scarlat, N.. - In: APPLIED ENERGY. - ISSN 0306-2619. - ELETTRONICO. - 304:(2021), p. 117817. [10.1016/j.apenergy.2021.117817]

*Availability:*
This version is available at: 11583/2970494 since: 2022-08-05T13:21:46Z

*Publisher:*
Elsevier Ltd

*Published*
DOI:10.1016/j.apenergy.2021.117817

Applied Energy 304 (2021) 117817

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

# Are algae ready to take off? GHG emission savings of algae-to-kerosene production

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## HIGHLIGHTS

- Sustainable aviation needs liquid fuels, and feedstock availability is crucial.
- Algae to kerosene is today one of the few certified pathway.
- An assessment of the GHG saving has been performed, using CORSIA methodology.
- GHG saving can be up to 68%, for the best case scenario.
- Nutrients and energy used for production are crucial to produce a sustainable aviation fuel.

## ARTICLE INFO

*Keywords:*
Biofuels
Aviation decarbonisation
SAF
GHG savings
Microalgae
LCA

## ABSTRACT

Aviation alternative fuels are perceived as an effective short-term mean to decarbonise our flights. Sustainable aviation fuels from algae have been recently approved for commercial flights, and here we present an assessment of their greenhouse gas (GHG) savings. Three case studies have been investigated with different plant designs and cultivation strategies. The Carbon Offsetting and Reduction Scheme for International Aviation's Life Cycle Assessment methodology is used as a guideline to assess the GHG saving potential of aviation fuels from algae. The approach here presented allows having a sound comparison with other alternative fuel production pathways. We show that the cultivation strategy based on oil maximisation does not necessarily provide significant advantages in terms of GHG savings. The assessed GHG savings fall in a wide range, being dependent on the inputs and cultivation strategy considered. In the best-case scenario, up to 68% of GHG savings can be achieved, therefore offering a substantial advantage over traditional fuels. When compared with the GHG saving of kerosene from other traditional bio-based feedstocks, like rapeseed, the results confirm algae as an interesting alternative, provided that certain conditions for their cultivation, such as high process optimisation, nutrient recycling and use of renewable energy to meet input demand, are met. The study also assessed the area potentially needed for an algae production plant able to supply large volumes of raw material to an existing commercial biorefinery. The findings confirm the potential of this feedstock to mitigate land abandonment on the coasts of the Mediterranean basin.

## 1. Introduction

Before the COVID-19 pandemic, the international civil aviation was consuming globally about 160 megatons (Mt) of fuel, corresponding to approximately 2.6% of greenhouse gas (GHG) emissions from overall fossil fuel combustion [1]. The sector was growing at a significant pace, with an increase in the projected fuel consumption from 2015 to 2045 between 2.2% and 3.1% [2]. The United Nation's International Civil Aviation Organization (ICAO) decided to implement measures to mitigate the environmental impact of air travel, and a global $CO_2$ standard had been defined to regulate fuel efficiency for new aircrafts, starting from 2020 [3]. In 2016, the ICAO Assembly agreed on the adoption of a global market-based scheme to tackle international aviation GHG emissions: the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) [4]. CORSIA requires airline operators to offset GHG emissions, expressed in $CO_{2\text{equivalent}}$, with respect to a baseline set for 2019. To achieve a carbon neutral growth, international

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https://doi.org/10.1016/j.apenergy.2021.117817
Received 29 May 2021; Received in revised form 23 August 2021; Accepted 5 September 2021

**List of acronyms**

| | |
|---|---|
| ASTM | American Society for Testing and Materials |
| CAPEX | Capital Expenditure |
| CEF | CORSIA Eligible Fuel |
| CORSIA | Carbon Offsetting and Reduction Scheme for International Aviation |
| EC | European Commisson |
| EU | European Union |
| EGD | European Green Deal |
| FFA | Free Fatty Acids |
| GHG | Greenhouse gas |
| HEFA | Hydroprocessed Esters and Fatty Acids |
| HTL | HydroThermal Liquefaction |
| HVO | Hydrotreated Vegetable Oils |
| ICAO | International Civil Aviation Organization |
| ILUC | Induced Land Use Change |
| IPCC | Intergovernmental Panel on Climate Change |
| LCA | Life-Cycle Assessment |
| LHV | Lower Heating Value |
| LUC | Land Use Change |
| LUISA | Land Use-based Integrated Sustainability Assessment |
| NEDO | New Energy and Industrial Technology Development Organization |
| NER | Net Energy Ratio |
| OPEX | Operating Expenses |
| PBR | PhotoBioreactors |
| PV | Photovoltaic energy |
| RED | Renewable Energy Directive |
| RES | Renewable Energy Sources |
| RWP | Raceway Ponds |
| SAF | Sustainable Aviation Fuels |
| TRL | Technology Readiness Level |
| UCO | Used Cooking Oil |

aviation operators can offset their emissions either through credits or by using CORSIA Eligible Fuels (CEFs) [5]. Staples et al [6] proposed six scenarios corresponding to significant emission reductions, and all of them imply offsetting more than 85% of the projected jet fuel demand with alternative fuels.

Sustainable Aviation Fuels (SAF) are defined as renewable or waste-derived aviation fuel that meets the CORSIA Sustainability Criteria. Despite SAF are identified as a suitable solution to achieve decarbonisation in the short- to medium-term, their current penetration is virtually zero. According to Chiaramonti et al [7], by 2030 aviation is not expected to be supplied with a significant amount of biofuels mainly due to the uptake of alternative fuels in the transport sector, which is currently very low.

Many of the current policy initiatives at the European scale highlight the need to produce sustainable biofuels in the transport sector, particularly in those subsectors struggling to find a suitable decarbonising strategy (e.g. aviation sector), as well as the urge for their uptake by the industry and the market. The legislative landscape at European level is relatively favourable for algae-to-fuel pathways. The European Green Deal (EGD) [8], the overarching policy framework from the European Commission released in December 2019 aims to achieve a climate neural continent by 2050 and reduce the pressure on environment by, inter alia, shifting to sustainable and smart mobility. In line with the EGD and the Clean Energy for All Europeans' package [9], the Renewable Energy Directive (REDII) [10] pursues the decarbonisation of the economy, including the transport sector. The REDII establishes an obligation on fuel suppliers to ensure a minimum mandatory share of 14% of renewable energy within the final consumption of energy in the transport sector and a sub-target of 3.5% of advanced biofuels by 2030. Although this provision mainly targets the fuels used in road and rail transport, the renewable fuels supplied to the aviation sector (except for those produced from food and feed crops) may also be considered for compliance, and their contribution would count 1.2 times their energy content. In the path towards a climate neutral EU, the 2030 Climate Target Plan [11] adopted in September 2020 also urges to scale up efforts to improve the efficiency of aircrafts and ships in their operations and increase the use of sustainably produced renewable and low-carbon fuels. At the time of the elaboration of this manuscript, the European Commission (EC) is in the process of releasing the ReFuelEU Aviation [12], following the EU's ambition to achieve climate neutrality by 2050. Among other measures, the ReFuelEU Aviation may impose a mandate for a minimum share of SAF, which would gradually increase over time.

Some of the European policy frameworks specifically point to algae as a promising feedstock for the sustainable production of biofuel. Under the REDII, "algae cultivated on land in ponds or photobioreactors" are classified as a feedstock to produce advance biofuels (Annex IX Part A of the Directive). In December 2020, the European Commission launched an Inception Impact Assessment to set a roadmap – towards a strong and sustainable EU algae sector [13], which is expected to be adopted at the end of 2021. This roadmap recognises the potential of algae as feedstock for advanced biofuels and biogas and sets it as one of the expected impacts to "reduce costs for licensing (facilitated by multi use of space) and for scaling-up algae production for various applications (e.g. food, feed, pharmaceuticals, biofuels, etc.)". Algae are also more broadly covered by other EU policy initiatives as a sustainable and innovative source of bio-based feedstock for a wide range of applications. Concretely, the EU Bioeconomy Strategy [14], the European Green Deal [8] and the Farm to Fork Strategy [15] highlight the potential of algae as a new and innovative source for food (proteins) and feed products (marine feedstocks) to ensure a sustainable food system and global food security. The former will also set out well-targeted support for the algae industry.

Among the certified SAF production pathways, the American Society for Testing and Materials (ASTM) recently added the Hydroprocessed Esters and Fatty Acids (HEFA) route from algae [16]. This paper presents an analysis of the GHG saving potential of algae to kerosene pathway by means of a Life-Cycle Assessment (LCA). At the current state of play, algae to kerosene is one of the approved pathways to produce kerosene, but a clear definition of the production chain is still missing. In this work three scenarios have been designed to further enhance the available knowledge, as reported in the section on the literature review.

This paper, which is the first of its kind, makes use of the ICAO/CORSIA methodological guidelines to assess the GHG saving potential of the algae to kerosene pathway. It is worth stressing that, conversely to existing, fragmented literature, this approach allows having a unique, scientifically sound comparison with other alternative fuel production pathways. The final goal of our study is, in fact, to compare the estimated GHG savings of the HEFA technology with other existing routes for producing sustainable kerosene, and to derive some conclusions on the use of algae feedstock for aviation biofuel.

## 2. Algae based sustainable aviation fuels

The use of microalgae as feedstock for the production of bioenergy has been extensively investigated, as shown by the number of scientific publications released since 1996 (at present 6328 scientific publications according to Scopus library). When focusing specifically on algae-based kerosene, the number of related publications decrease to 25 scientific articles. On the other hand, a more extensive literature (nr. 766 scientific publications) can be found on the potential of algae as a feedstock for a series of marketable bio-based products following a Biorefining

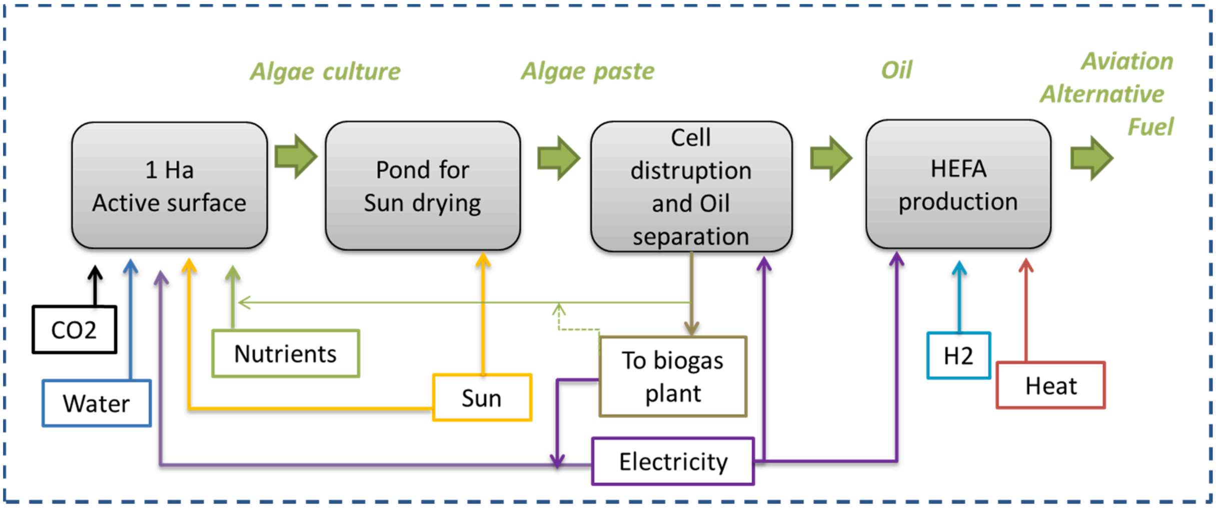


**Fig. 1.** The system boundary for core LCA of CORSIA SAFs.

approach. According to Nasir and Paulose [17] new business models can support the development of this pathway, by including technological innovations such as new strains of algae, innovative production methods, innovative logistics and synergies with existing networks and refineries of the petroleum industry.

Micro and macro algae have been largely analysed as feedstock for biofuel production. Regardless of the often claimed capacity of producing a higher quantity of oil per hectare with respect to other traditional crops, an indubitable advantage of the algae to fuel pathway lies on the possibility to grow algae on non-arable land and be fed with saline water [18]. Additionally, the rate of nutrients uptake is really high when compared to standard agriculture [19].

In terms of research projects, the CORDIS platform retrieves a list of 23 European projects dealing with microalgae and bioenergy [20], while the number of patents registered in the European Office of Patents amounts to 127 in the related field.

In spite of the widely known challenges, the algae producing industry seems to be growing in the EU. According to the latest data available on the algae industry in Europe, an increase of 150% in the number of new algae producing companies has been registered in the last decade. Currently there are around 74 enterprises producing microalgae in European countries (EU-27 + UK, Iceland and Norway). Only 3% of them dedicate their biomass to produce biofuels [21].

The microalgae production system most commonly used by European companies is photobioreactors (71%), followed by open or semi-open ponds (19%) and fermenters (10%) [21]. The species that are produced by the largest number of companies are *Chlorella* sp., followed by *Nannochloropsis* sp., both identified as interesting species due to their high lipid concentration [22,23]. Spirulina sp. (genus *Arthrospira*), a cyanobacteria also studied as a promising feedstock for biofuel is produced by 222 European companies mainly by open ponds (83%) and at a lesser extent by photobioreactors (17%) [21].

On the side of the conversion process, Yang et al [24] identified four main pathways to produce jet fuels from algae: Fischer–Tropsch, hydrotreated renewable, pyrolysis-hydrotreated and hydrothermal liquefaction-hydrotreated renewable jet fuel. They addressed the carbon distribution of microalgae lipids in 103 species, given the typical kerosene carbon distribution, ranging in $C_8 – C_{16}$. In their conclusions on the maturity of the HEFA technology, they underlined that a high lipid content in algae is required to make the process economically feasible. Bwapwa et al [25] investigated additional possibilities (e.g. fermentation, plasma gasification, etc.) arriving to similar conclusions as other authors [26]. The US Department of Energy's Argonne National Laboratory analysed biodiesel from algae in comparison with conventional diesel; the study reported a potential reduction in energy consumption of 55% and in carbon emissions of 45% through the entire life cycle [27]. Other studies reported a wide range of GHG saving potential for algae as feedstock for fuel production [28–35] (see Table A1 in Appendix 1).

The emissions calculated in these studies vary across a wide range of values. This is due to the different algae species [28–32] and cultivation strategies analysed. Moreover, methodological choices have also a significant impact on LCA results. Input sources for nutrient and energy can explain some results, such as for the case proposed by Ou et al [35], where coal fossil energy is considered. All referenced studies so far considered Hydrogenated Vegetable Oils (HVO) as final processing step, except the work of Fortier et al [34], which modelled a wastewater hydrothermal processing, resulting in 21.2 $gCO_{2eq}$/MJ for the optimized scenario.

To define the process analysed in this paper, some recent pilot initiatives have been considered. For example, IHI Corporation [36] together with the New Energy and Industrial Technology Development Organization (NEDO), developed a process based on a special strain of *Botryococcus braunii* (Hyper-Growth *Botryococcus Braunii*), which claimed being able to reach an oil content above 50% on dry basis, rich in hydrocarbons. Ranga Rao et al [37] investigated *B. braunii* (N-836) cultivation in open ponds. After 25 days of cultivation the authors reported a biomass yield up to 1 g/l and hydrocarbon content of 27%. Supplementation of 0.1% $NaHCO_3$ in the medium resulted in biomass yield of 1.5 g/l and hydrocarbon content of 30%, with a fat content around 24% (w/w) mainly constituted by palmitic and oleic acids. NEDO claimed to have developed a low energy harvesting process, including a biomass drying step in open air and a recycling of nutrients and culture water. The IHI 1.5 ha pilot plant in Thailand allowed demonstrating the progression in algal cultivation, as well as the production of bio-jet fuel using microalgae as a raw material. This synthesized paraffinic kerosene was approved under the ASTM D7566 standard in 2020 through the fast track process, as a variation of HEFA pathway under the ASTM D7566; however, conversely to standard HEFA, the blending limit is 10% [38]. Lipids from a *B. braunii* algae are converted by hydrocracking/hydroisomerization to remove all oxygen and saturate double bonds, resulting in a iso-alkanes rich product.

## 3. Material and method

### 3.1. LCA methodological framework

Our study applies the guidelines set in the Core-LCA methodology, as defined by ICAO/CORSIA technical group, to perform the estimation of the GHG saving potential of this alternative fuel pathway [39,40].

E3database is used as a software to calculate GHG emissions. CORSIA allows the use of Sustainable Aviation Fuels (i.e., drop-in fuels derived from biomass or waste streams that fulfil a set of sustainability criteria) to meet the airlines' carbon offsetting requirements. The emission reductions of a specific SAF pathway are calculated using a LCA approach [5]. It is worth noticing that the CORSIA LCA is the first method adopted internationally for the calculation of life-cycle GHG emissions of aviation fuels. The CORSIA LCA method encompasses (1) the life-cycle accounting for GHG emissions, (2) the inclusion of emissions from Induced Land Use Change (ILUC), (3) the prevention of indirect environmental impacts, and (4) crediting of practices that mitigate the risk of Land Use Change (LUC).

In line with the CORSIA methodology [41], the current emissions associated with the algae-to-kerosene pathways have been evaluated in accordance with a process-based attributional LCA approach [42], accounting for mass and energy flows along the whole fuel supply chain. The system boundaries include all processes of the algae-to-fuel production supply chain with significant GHG emissions. Fig. 1 presents the flow chart and the system boundary of the core LCA. For the electricity demand, the EU energy mix is considered.

The assessment considers the energy (in MJ) of fuel produced as the functional unit, expressed on the basis of its Lower Heating Value (LHV). The emissions are therefore expressed in grams of $CO_2$ equivalent per MJ of fuel ($gCO_2eq/MJ$) combusted in the aircraft. The GHG emissions resulting from the use of energy and chemicals for the cultivation of feedstocks are included. Therefore, other GHG emissions resulting from the various stages of fuel production (e.g. $N_2O$, and $CH_4$) are expressed in terms of $CO_2eq$ using their 100-year global warming potentials, according to the Fifth Assessment Report (AR5) of Intergovernmental Panel on Climate Change (IPCC) [43]. Emissions associated to the construction of the plant or manufacturing facilities are not included as their contribution to the LCA results of fuel products is usually very limited [44].

As this production pathway generates several outputs in addition to the main product, the application of an appropriate method ensures emissions are allocated to their respective outputs. In line with many relevant legislative acts, such as CORSIA, European RED II [45], etc., co-products emissions are allocated based on their energy content. Other allocation options could have been considered, in line with ISO guidelines, however using the same approach taken in REDII and ICAO/CORSIA allows removing methodological inconsistencies, when comparing the results. In spite of the methodological agreement, some differences still remain between CORSIA and REDII mainly in the input used for calculations and the absence of terms for emissions for Carbon Capture and Storage ($e_{ccs}$) and emissions from soil carbon accumulation via improved agricultural management ($e_{sca}$). In this study, where an energy based allocation has been preferred, the energy generated by recovering the co-product has been added in a second stage of the calculation, and for this reason has been treated as a credit. The rationale for this accounting procedure is to be able to present the energy demands of the investigated cases in a more transparent manner. The co-product could, in fact, be in other approaches and studies valorised elsewhere (e.g. for fish feeding, etc.), so not necessarily contribute to lower the energy input of the investigated process. The proposed approach allows for presenting the data of the energy demand and related emissions to be comparable with other studies, and in a second stage considering the contribution from the energy valorisation of the co-product.

A final fuel transportation phase is also considered, which includes GHG emissions from the transportation of algae SAF from the fuel production facilities to end-use sites (i.e. aircraft refuelling points). The emissions generated during the combustion of biomass-derived alternative fuels are usually not accounted [46] since for biomass-derived fuels the biogenic $CO_2$ emissions are assumed to be offset by the biomass carbon uptake occurred during the biomass growth.

For the specific case of the algae production, it is considered that the $CO_2$ used to supply the algae comes from the exhausts of a coal-fired power plant. Due to the fossil origin of the carbon, an emission occur when the fuel is burned in the engine. However, a "carbon-neutral" approach has been here considered. The justification for this approach, in line with CORSIA methodology [41], is that the previous fate of the carbon atoms does not differ with the net emission of $CO_2$ from airplane (it would have occurred from the coal plant), nor the process production is influenced by diverting the gases for fuel production (no energy recovery from gases). With this approach, no emissions are accounted for the combustion of the engine.

It is important to stress that in CORSIA, the default life-cycle emission values are calculated as the sum of the "core LCA" values and the estimated "ILUC" emission values. For algae-based feedstocks, ILUC has been considered irrelevant, when fuel output from algae is produced on barren, saline or degraded land. On the contrary, a negative impact in terms of ILUC (i.e., net $CO_2$ absorption) could be assumed in this case. In the current study, we adopted a conservative approach, and potential positive impacts on ILUC were not taken into account.

The described methodology is summarized in Eq. (1):

$$e_{fuel} = e_{ae\_c} + e_{ae\_hc} + e_{ae\_p} + e_{ae\_t} + e_{afu\_p} + e_{fu\_t} \tag{1}$$

$\mathbf{e_{ae\_c}}$: emissions from algae inoculum production and cultivation;

$\mathbf{e_{ae\_hc}}$: emissions from algae harvesting;

$\mathbf{e_{ae\_p}}$: emissions from algae processing;

$\mathbf{e_{ae\_t}}$: emissions from algae transportation to processing and fuel production facilities;

$\mathbf{e_{afu\_p}}$: emissions from algae-to-fuel conversion processes;

$\mathbf{e_{fu\_t}}$: emissions from fuel transportation and distribution.

Along with the GHG balance, an energy balance is proposed in the form of a Net Energy Ratio (NER). Since the energy consumed at various stages in the process varies for each individual case, the resulting NER is calculated as the ratio between the energy output and input.

### 3.2. *Production plant and data description*

The first choice to make when modelling an algae production site refers to the definition of a proper size for the plant, so the results on the analysis are relevant for commercial operation. The production plant has to be large enough to potentially expand into a larger commercial plant while remaining representative of the sector. A typical reference dimension for industrial-scale algae production plants in the EU is around one hectare, as this has been the scale of several EU demonstration projects, such as BIOFAT EC-FP7 [47], and CO2algaefix EC-LIFE project [48]. Additionally, the chosen scale allows for a direct comparison of the results with other production plants based on more traditional agricultural feedstocks. We acknowledge that in the future, after the take-off of the use of algae for aviation fuels, the size of an algae plant might be larger than one hectare.

In the proposed algae-to-kerosene pathway, the main stages are:

1. Algae inoculum production (Photo Bio Reactors (PBR) – 1/10 ha).
2. Massive cultivation in ponds array (Raceway Ponds (RWP) – 9/10 ha).
3. Harvesting/pumping of the algae to downstream processes.
4. Bio-flocculation and sun drying (algae wet paste preparation: still pumpable).
5. Cell disruption.

6a. Liquid phase centrifugation from which an oily and a water-rich phases are obtained. The oil is moved along the process while the watery phase is used for nutrient recycle.

6b. Solid phase solvent extraction from which additional oil is recovered, together with a solid protein cake (co-product).

7. Oil conversion to HEFA bio-kerosene.

The plant flow chart and the LCA system boundaries are reported in Fig. 1. The layout has been defined on the basis of existing literature in order to allow for an optimisation between algae yield, energy input and production costs. For the current assessment we assumed the plant is ideally located in a region characterised by a high radiation level: 22 GWh/ha per year incident global [49] (e.g. southern Europe or north-western coast of Africa), close to a coal-fired power station. An additional requirement is the location of the site near the seashore to have access to saline water (for medium preparation, compensation of evaporation in the open ponds, and photobioreactor cooling). The cultivation steps are: sea seawater supply, $CO_2$ supply, culture inoculum in photobioreactor, culture growth in open ponds, followed by harvesting.

The algae production begins with an inoculum section, usually made with PhotoBioReactors (PBR), to ensure a good control of the culture and prevent potential contamination by biological pollutants. The area equipped with PBR is usually limited, mainly due to their high energy demand [50] and high capital expenditures (CAPEX) and operating expenses (OPEX). In the current analysis, one-tenth of the photosynthetic active areas is covered with PBRs. The energy demand for this section has been calculated according to values reported by Tredici et al [51]. After several days, the inoculum is moved to the open ponds, which could be structure in arrays, made of several parallel lines of ponds. Due to the time needed for cultivation, these clusters of production ponds are managed with a time shifting as to achieve a well-balanced and almost constant biomass harvesting. An example of this structure has been provided, among others, by Prussi et al [52]. Paddle wheels are used for culture movement in Raceway Ponds (RWPs). The specific power of the electrical engines has been defined based on literature data [53]. Paddle wheels work with two settings: during daylight these are operated at full power, while during night-time (non-productive periods) power is reduced to 30% of the design rate, in order to avoid sedimentation and achieve a significant energy saving.

Several pre-treatment sections are needed to control the quality of the plant input streams, such as seawater filtering and sanitisation, and $CO_2$ cooling and filtration. $CO_2$ supply is needed to guarantee proper biomass and lipids yields, as reported in many studies [54]. The flue gas from a coal-fired power plant has been considered as a suitable source of $CO_2$ [55]. The energy expenditure for gas cooling and filtering has been taken into account as pressure losses, and considered in the blower energy demand. $CO_2$ from the exhaust is the main source of carbon for the microorganisms. $CO_2$ concentration in the pond is controlled by the pH sensor: once the pH increases over the threshold, the automatic $CO_2$ valve is opened. The share of $CO_2$ in the flue gas is 12% v/v; the distribution is operated by submerged diffusers. Since up to 1.8 kg of $CO_2$ is required per kilogram of biomass produced, the nominal average volume flow rate required is thus 642.9 $Nm^3/h$ (considering 8 h of work, $CO_2$ feeding is switched off at night-time), given the mentioned daily productivity and assuming a carbonation efficiency of 20%. The blower needs to have 7.5 kW of average operational demand to be able to process a flow rate of about 9.6 $m^3/min$ and ensure a $\Delta P$ of 400 mbar.

Two 2.5 kW centrifuge pumps are used to transfer the culture between the different sections of the plant, as well as for ponds replenishment (either for ponds filling after culture transfer or for make-up water feeding, compensating the daily evaporation). Open raceway ponds need daily water replenishment to counteract evaporation. The rate of integration is a function of the local climatic conditions; in this work a 1 cm/d is considered as average input for the integration of the evaporation losses [56].

Once the density reaches the target value, algae culture is moved to ponds for bio-flocculation and sun drying. The goal of this stage is to increase the density of the culture, up to the requirements of the cell disruption step, with a very low energy demand. Values reported by Bheda et al [57] have been used to derive culture densities and time required for this phase.

Cell disruption is then used to open the cell structure, allowing for oil recovery; input data have been taken from literature [27]. The output of the cell disruption stage is separated into a water phase, partly recycled for nutrient recovery and partly discharged, i.e. a lipid phase and a solid phase. The solid phase is sent to solvent extraction to maximise oil recovery. Data for solvent extraction have been derived from literature [27].

**Table 1**
List of the main input used for calculations.

| Parameter | U.M. | Case 1 | Case 2 | Case 3 | Note |
|---|---|---|---|---|---|
| **Composition of algae biomass** | | | | | |
| *Composition* | *Oil content* | 30% | 30% | 50% | |
| | *Protein content* | 43% | 43% | 21% | |
| | *Carbohydrate content* | 17% | 17% | 15% | |
| | *Ash content* | 10% | 10% | 14% | |
| | *N content* | 7.0% | 7.0% | 3.5% | N depends on the protein content |
| | *P content* | 0.7% | 0.7% | 0.7% | |
| Biomass yield | $g/(m^2*d)$ | 14.1 | 10.4 | 8.5 | |
| | t/(ha*yr) | 47 | 34 | 28 | |
| Oil yield | t/(ha*yr) | 14 | 10 | 14 | |
| Water depth | cm | 15 | 5 | 15 | |
| $P_e$ (paddle wheel) | $W/m^2$ | 1.00 | 0.47 | 1.10 | |
| N fertilizer | $t_N/(ha*yr)$ | 3.26 | 2.41 | 0.98 | Based on the N content |
| P fertilizer | $t_P/(ha*yr)$ | 0.33 | 0.24 | 0.20 | Based on the P content |
| LHV (algae biomass) | $MJ/kg_{dry}$ | 24.2 | 24.2 | 26.4 | Based on the algae composition |
| LHV (algae oil) | MJ/kg | 38.3 | 38.3 | 38.3 | |

The resulting solid cake could theoretically be valorised as feed for livestock and/or aquaculture production. However, the quality of the cake as feed may be low, in terms of protein content when nutrient starvation occurs. Consequently, the economic viability of its valorisation for the feed market should be carefully assessed. Additionally, in order to meet the high energy demand for the production of algae-based oil, the solid residue from solvent extraction is used to generate biogas for electricity production. This approach, substantially based on the energy content of the co-product, results in line with the provisions from both REDII and CORSIA. At the same time, the biogas residue (digestate) from anaerobic digestion is used for nutrients recovery. New options are offered by the HydroThermal Liquefaction (HTL) to bio-crude, which is an adequate technology for processing high moisture content biomass. In the results, this energy and nutrient recovery step is represented as specific credit.

Algae-based oil has been considered as the feedstock for the HEFA process. This is a conversion technology commercially available with a high maturity level (Technology Readiness Level - TRL9), which consists in the hydroprocessing of lipid feedstocks and their upgrading to drop-in jet fuels. The HEFA technology is suitable for processing several types of feedstocks, such as oil crops and residual oil (e.g. used cooking oil or tallow oil), as well as co-products from the oil processing industry. The process consists of various catalytic reaction mechanisms in the presence of hydrogen [58]. Hydrogen use in the catalytic reactor allows removing the carbonyl group after hydrogenation and, simultaneously, break the glycerol compound with the release of propane and Free Fatty Acids (FFA). Downstream processes such as isomerisation, cracking or cyclisation are required to improve the fuel properties.

To define the energy and GHG balances, the overall plant output needs to be estimated, both in terms of mass and energy content. The number of working days was set to 330 days of operation per year, taking into account the ordinary and extraordinary algae plant maintenance. The annual average productivity is considered together with the average oil content. These two parameters are related to many

**Table 2**
Emission factors for electricity at medium voltage level.

| Source | Emission factor ($gCO_{2eq}/kWh$) |
|---|---|
| **EU-mix 2016** | **383** |
| Wind | 11 (on-shore) |
| Solar PV | 39 |
| **50/50 Wind/PV** | **25** |

factors such as algae strain, cultivation strategy, nutrient management, weather conditions, and other operative aspects. In order to define the impact of the cultivation strategy on, inter alia, the oil content and biomass composition, the following three cases are presented:

- **Case 1**: standard RWP - 15 cm water depth - average yield is 14.1 g/$m^2$d (42 t/ha yr) and the average oil content of 30% (14 t/yr ha).
- **Case 2**: low head RWP - 5 cm water depth - average yield is 10.4 g/$m^2$d and the average oil content of 30% (10 t/ha yr).
- **Case 3**: standard RWP - 15 cm water depth. Due to nutrient reduction, the average yield is 8.5 g/$m^2$d (28 t/ha yr) and the average oil content of 50% (14 t/ha yr).

The main inputs considered for each study case are listed in Table 1.

We run various sets of simulations using electricity from these two sources, i.e. wind-derived (50%) and photovoltaic (PV) (50%). In many studies wind and PV electricity are considered as zero GHG emissions, as the energy for plant building and end-of-life are neglected. However, conversely from standard large fuel productions, these aspects can have a significant impact on PV, hydro and wind power, as well as the indirect effects associated with plant construction, etc. In the case of wind power, the GHG emissions have been derived from Nugent et al. [59]. Wind turbines with a rated power of 2 MW (average current capacity of wind turbines) and above have been taken into account, resulting in an average GHG emission factor of 11 g CO2eq/kWh (including electricity transport and distribution). For PV solar energy, the GHG emissions indicated in Nugent et al., and Muteri et al., [59,60] have been used. Only crystalline silicon cells, the most common type of PV plants in the EU, have been considered, resulting in an average emission factor of 39 $gCO_2$eq/kWh (including electricity transport and distribution) as detailed in Table 2.

### 3.3. Software used for the simulations

Developed by the Ludwig-Bölkow-Systemtechnik (LBST), the E3database has been used [61] to perform the calculations of the GHG emissions. The E3database is a tool for life-cycle analyses of energy supply (e.g. electricity, heat, transportation fuel), products (e.g. steel, aluminium), and services. The tool comprises the calculation of energy and material flows, GHG emissions and emissions of air pollutants.

### 3.4. First order estimation of the scale-up potential

Large algae production facilities based on open ponds should be located in areas where water and sunlight are abundant and, possibly, where average temperatures are fairly constant all over the year. Therefore, the suitable locations for an integrated biorefinery, including the microalgae farm, are usually considered in proximity of the sea, and the Mediterranean basin thus represents a suitable area. In this zone the climate conditions are optimal for microalgae growth, with temperatures ranging from 15 to 30 °C, with limited rainfall all over the year. On the other hand, microalgae farms require large areas which should not compete with or replace other economically feasible land uses such as touristic shorelines, agricultural lands and/or urban areas.

In order to identify some suitable areas where a modern microalgae biorefinery could be located, we used a recent study of JRC [62] which mapped EU territories under high potential risk of abandonment due to factors related to biophysical land suitability, farm structure and agricultural viability, population and other regional variables. According to the JRC study, the area of abandoned agricultural land (4.8 million ha gross in the EU area) is likely to remain unused within 2015–2030, and large part of these territories are close to the Mediterranean coasts. Some of these areas under risk of abandonment are also in the proximity of existing petroleum refineries (as reported in the online available map of Concawe [63]), which already provide infrastructures for managing large quantities of feedstock and a consolidated fuel distribution network.

**Table 3**
Simulation results for the analysed cases: energy demand and output.

| Plant section | Case 1 | Case 2 | Case 3 |
|---|---|---|---|
| | RWP 15 cm<br>Yield 14.1 g/$m^2$d<br>30% oil | RWP 5 cm<br>Yield 10.4 g/$m^2$d<br>30% oil | RWP 15 cm<br>Yield 8.5 g/$m^2$d<br>50% oil |
| | kWh/ha yr | | |
| Photo Bio Reactors (PBR) | 17,734 | 17,734 | 17,734 |
| RaceWay Ponds (RWP) | 53,724 | 36,234 | 57,024 |
| Harvesting and Pumping | 1,320 | 1,320 | 1,320 |
| Flocculation and Sun drying | 561 | 415 | 338 |
| **Total Input** | **73,339** | **55,703** | **76,416** |
| **Energy Output** | **312,397** | **231,307** | **206,027** |
| **Net Energy Ratio** | **4.3** | **4.2** | **2.7** |

## 4. Results

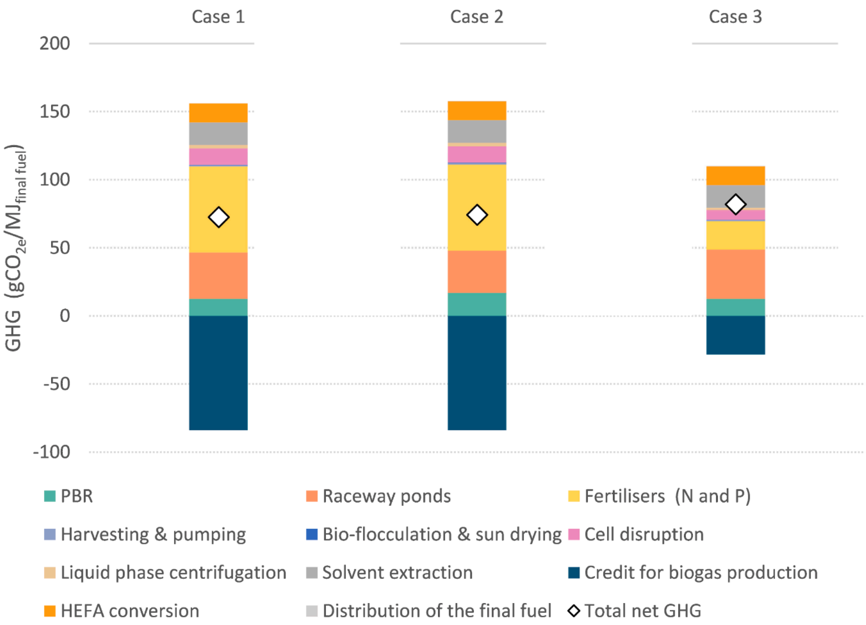
The algae-to-fuel production plant has been designed as a one-hectare energy-optimised industrial facility with process integration to maximise the energy output and the GHG savings associated to the production of the Sustainable Aviation Fuel. The results for the three study cases analysed according to the parameters described in the methodology are presented hereafter.

### 4.1. Energy consumption

The results for the energy consumption of the three case studies are presented in Table 3. For the cases studied, NER values ranged from 2.7 to 4.3. The NER has only been calculated up to the raw biomass

**Table 4**
GHG emissions ($gCO_2eq/MJ_{final\ fuel}$) for the different production steps, for the three case studies.

| Primary energy source | Electricity mix EU | | | | | |
|---|---|---|---|---|---|---|
| Plant section | Case 1 | | Case 2 | | Case 3 | |
| PhotoBioreactors | 12.5 | 8% | 16.9 | 11% | 12.5 | 11% |
| Raceway ponds | 34.1 | 22% | 31.0 | 20% | 36.2 | 33% |
| Fertilisers (N and P) | 63.1 | 40% | 63.1 | 40% | 20.8 | 19% |
| Harvesting & pumping | 0.8 | 1% | 1.1 | 1% | 0.8 | 1% |
| Bio-flocculation & sun drying | 0.4 | 0% | 0.4 | 0% | 0.2 | 0% |
| Cell disruption | 12.0 | 8% | 12.0 | 8% | 7.2 | 7% |
| Liquid phase centrifugation | 2.6 | 2% | 2.6 | 2% | 1.6 | 1% |
| Solvent extraction | 16.6 | 11% | 16.6 | 11% | 16.6 | 15% |
| HEFA conversion | 13.9 | 9% | 13.9 | 9% | 13.9 | 13% |
| Distribution of the final fuel | 0.2 | 0% | 0.2 | 0% | 0.2 | 0% |
| **GHG emissions** | 156.2 | | 157.8 | | 110.0 | |
| Credit for biogas production | −83.9 | | −83.9 | | −28.5 | |
| **Total net GHG emissions** | **72.3** | | **73.9** | | **81.5** | |
| **GHG saving** | **19%** | | **17%** | | **8%** | |



Note: this assessment considers the use of grid electricity (2016 EU electricity mix)

**Fig. 2.** Contribution to the GHG emissions of the different stages, for the three case studies. Note: this assessment considers the use of grid electricity (2016 EU electricity mix).

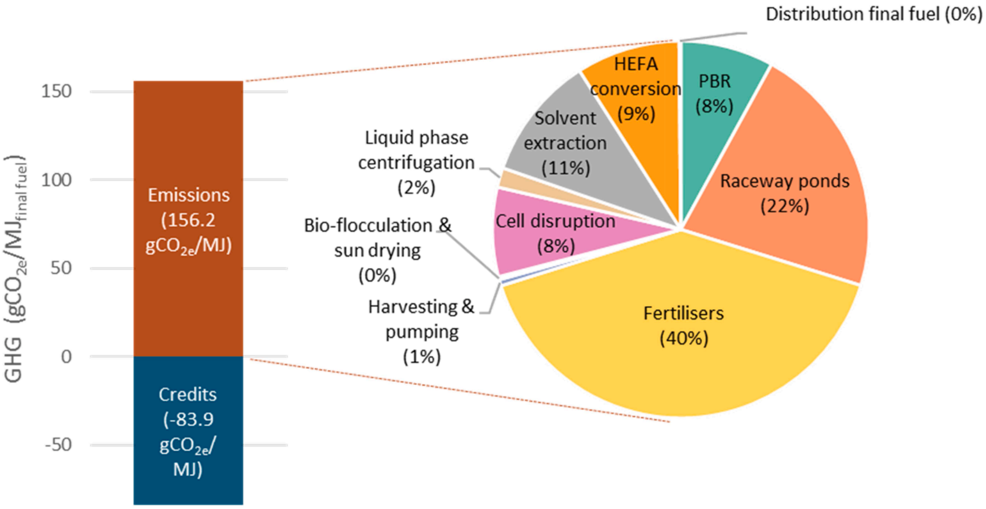


**Fig. 3.** Emissions and credits (in $gCO_2eq$ per unit of fuel MJ) for the reference scenario and the breakdown (in %) of the different stages generating GHG emissions.

production stage, in order to compare the results with other studies, regardless of the final goal of the production (i.e. by-products, fuels, pharmaceutical, etc.). The values obtained are in line with other studies; for instance, the extensive literature review conducted by the NRC [64] reported an energy return on investment of pond-based algae ranging from 0.13 to 7.0. The reduction of the energy losses (often referred as water head) investigated in Case 2, allows for a total energy input reduction. However, due to the modelled reduction in average productivity (related to a higher algae concentration and consequent difficulties with cooling and mixing) the NER in Case 2 is similar to the one obtained in Case 1. Any increase in productivity could immediately result in a considerable reduction in energy consumption, which is worth investigating further. Interestingly, Case 3 (oil maximisation) presents the lowest NER, mainly due to the lower areal productivity, only partially mitigated by the increase in oil content, i.e. the overall lower energy output.

### 4.2. Assessment of GHG emission savings

The GHG emissions assessed for the three case studies are reported in Table 4 and represented in Fig. 1. ICAO/CORSIA baseline for fossil derived kerosene (89 $gCO_{2eq}/MJ$) is used to define the emission savings for kerosene. Total net GHG emissions for the three case studies amount to 72.3, 73.9 and 81.7 $gCO_2eq/MJ_{fuel}$, respectively, representing an estimated GHG savings, compared to the fossil-based equivalent, of 19%, 17% and 8%, for cases 1, 2 and 3, respectively.

As shown in Fig. 2 and Fig. 3, in Cases 1 and 2 fertilisers represent the item with the highest contribution to the GHG emissions by MJ of final fuel (40% in both cases), followed by RWP demand (22% and 20%, respectively). In Case 3, the contribution of these items to the total GHG

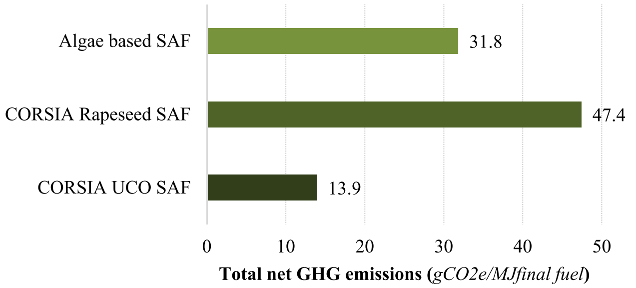


**Fig. 4.** Comparison of core LCA GHG emissions (no iLCU) of alternative fuels options for the aviation sector. UCO: Used Cooking Oil.

**Table 5**
Results for renewable energy (RES) cases: impact of assuming GHG emission for electricity produced from RES.

| **Primary energy source**<br>**Plant section** | **RES with no GHGs** | | | **RES with GHGs** | | |
|---|---|---|---|---|---|---|
| | **Case 1** | **Case 2** | **Case 3** | **Case 1** | **Case 2** | **Case 3** |
| | $gCO_2eq/MJ_{final\ fuel}$ | | | $gCO_2eq/MJ_{final\ fuel}$ | | |
| PhotoBioReactors (PBR) | 0.8 | 1.1 | 0.8 | 0.0 | 0.0 | 0.0 |
| Raceway ponds (RWP) | 2.2 | 2.0 | 2.4 | 0.0 | 0.0 | 0.0 |
| Fertilisers (N and P) | 63.1 | 63.1 | 20.8 | 63.1 | 63.1 | 20.8 |
| Harvesting & pumping | 0.1 | 0.1 | 0.1 | 0.0 | 0.0 | 0.0 |
| Bio-flocculation & sun drying | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Cell disruption | 0.8 | 0.8 | 0.5 | 0.0 | 0.0 | 0.0 |
| Liquid phase centrifugation | 0.2 | 0.2 | 0.1 | 0.0 | 0.0 | 0.0 |
| Solvent extraction | 11.7 | 11.7 | 11.7 | 11.3 | 11.3 | 11.3 |
| HEFA conversion | 12.5 | 12.5 | 12.5 | 12.4 | 12.4 | 12.4 |
| Distribution of the final fuel | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 |
| **GHG emissions** | 91.6 | 91.7 | 49.1 | 87.0 | 87.0 | 44.7 |
| Credit for biogas production | −52.6 | −52.6 | −17.3 | −50.5 | −50.5 | −16.5 |
| **Total net GHG emissions** | **39.0** | **39.1** | **31.8** | **36.5** | **36.5** | **28.2** |
| **GHG saving** | **56%** | **56%** | **64%** | **59%** | **59%** | **68%** |

emissions is quite the opposite (19% from fertilisers; 33% from RWP demand). It is worth highlighting the fundamental role of the energy recovery stage in the biogas plant: in terms of energy input, it could represent from the 17% (case 3) to the 46% (case 1) of the energy demand. Likewise, for other crop based alternative fuels, the cultivation phase is significant. In terms of GHG savings, the base case allows obtaining a CORSIA eligible fuel, with GHG emission savings higher than 10% (Fig. 4).

Case 2 shows the effect of lowering the water head, which was investigated to reduce the energy input at the most energy demanding stage. From an energy point of view, the RWPs represent almost 70% of the energy input needed for algae production. In spite of this optimisation, the reduction in productivity considered in the present analysis tends to limit the potential benefits while the GHG savings potential resulted close to the one of the reference scenario. Case 1 and Case 2 performed similarly in terms of potential GHG savings, as lower productivity can be correlated to lower energy demand. When the current electricity mix for EU is considered as the source of primary energy, Case 3 (oil maximisation) results show the lowest GHG savings, mainly due to the higher specific impact of the emissions associated to the energy input per unit of product.

### 4.3. Effect of the energy input GHG emission factor

In order to evaluate potential strategies to reduce the GHG emissions in the case studies, the substitution in the source of energy to meet plant demand was also assessed. When renewable energy is inset into the current grid mix, the results change drastically. As shown in Table 5, under this assumption the specific contribution of the energy input is less significant and Case 3 shows the best performance with GHG savings amounting to 68% compared to the fossil-based equivalent fuel. Results also show the minor impact of considering GHG emissions associated with the renewable energy supply. The choice of this approach is based on the assumption that plants located on marginal lands close to the seashore could be effectively powered by wind and solar energies. Moreover, in light of the recent ambitious decarbonisation targets, set by European Commission in the new EU Green Deal [8], the future mix will be largely sourced from renewables.

In all the simulations proposed, the role of the fertiliser appears to be a key factor in the GHG balance of the system. This conclusion suggests the need to find alternative sources for such nutrients (i.e. waste water treatment residual sludge) and implement, at plant level, effective recycle strategies. It is also worth highlighting the reduction, for Case 3, in the role of biogas energy recovery step, suggesting the possibility to consider other options for the resulting residual cake.

### 4.4. Comparison with other biomass to jet pathways

As the modelled plant targets aviation fuel market, it is worth comparing the results with the default values proposed in the ICAO/CORSIA documentation [5]. CORSIA reports values of net GHG emissions for HEFA alternative fuels from rapeseed produced in Europe of 47.4 $CO_2$eq/MJ. This value is in line with the results presented under the high renewable input scenario in our study. In the same ICAO/CORSIA documentation, the HEFA produced from Used Cooking Oil is evaluated with a resulting GHG emission of 13.9 $CO_2$eq/MJ (Fig. 4).

It is important to emphasise that the algae-to-fuel pathway could offer higher GHG savings than traditional biomass feedstocks, such as rapeseed, through process optimisation, nutrient recycling and renewable energy.

### 4.5. Potential for large scale algae deployment in Mediterranean basin

Scaling-up is a required step to lower the production costs of the algae-to-kerosene pathway and demonstrate its potential.

Four potential sites have been identified, where microalgae farms could be located (Fig. 5), using the data and maps from the Land Use-based Integrated Sustainability Assessment (LUISA) project [65] made available by the JRC. Moreover, the selected potential sites are at the same time high-suitability areas for solar power installations as shown in other maps [66], which makes feasible the use of renewable energy to provide electrical power for microalgae cultivation. The potential implementation of an integrated biorefinery concept, including lipids production from microalgae in a target area, requires the availability of a large extension of land. Considering a modern biorefinery based on HVO technology such as the ENI's refinery in Gela (Sicily, Italy) [67], with an overall capacity of 750,000 tonnes of lipids per year, the demand of land to dedicate to open ponds to grow microalgae is about 53,600 ha (based on the data reported in Table 1, for Case 3). As reported in the LUISA project dataset [65], the target countries identified as suitable to build the bio-jet plants in the Mediterranean area have a large amount of agriculture abandoned land. Thus, the installation of the identified plants would turn into production between 3 and 24% of the national abandoned area (as shown in Table 6) offering an alternative economic activity for such areas while minimising the competition with other land uses.

Considering the same capacity as the Gela plant, and assuming a HVO process oriented to maximise the jet-fuel output [68], the potential

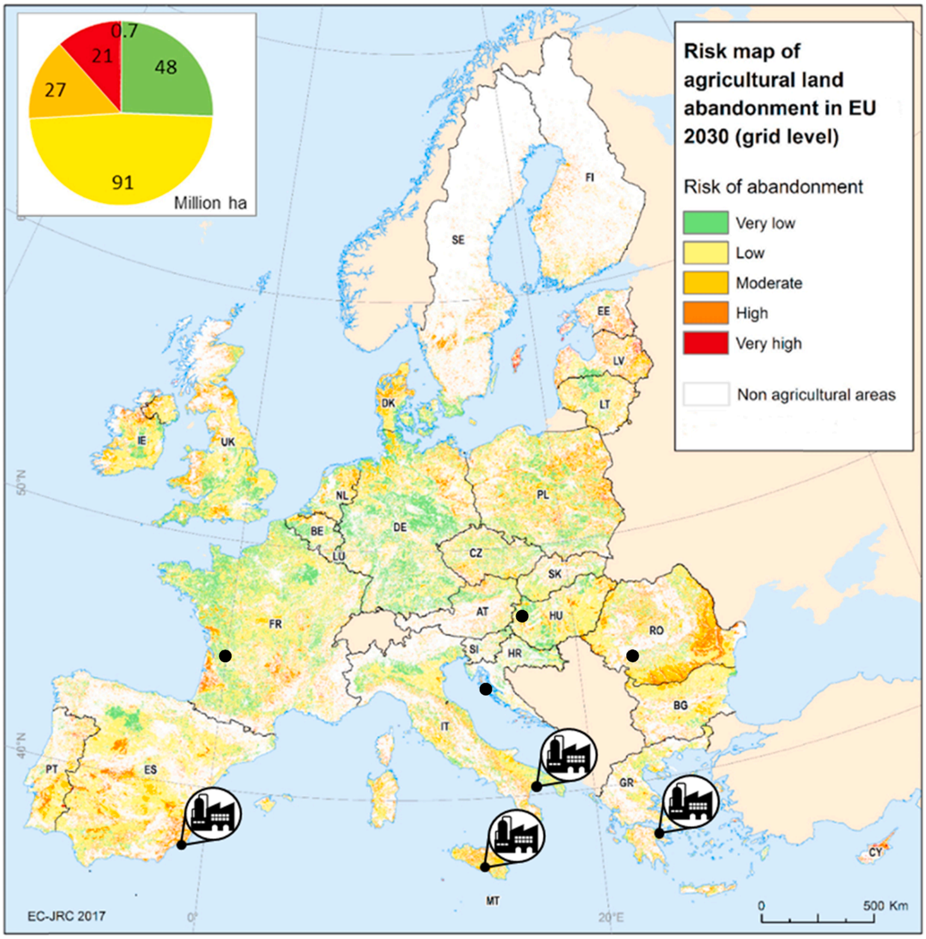


**Fig. 5.** Map of risk of agriculture land abandonment in EU-28 in 2030 (source LUISA project [65]) and the identified potential sites for microalgae farms.

**Table 6**
Abandoned agricultural land in the EU Mediterranean countries potentially turned into production by the identified microalgae farms (estimated area: 53,600 ha per algae production plant).

| Country | Estimated agricultural land abandonment (as identified in Perpiña et al., 2021 [65]) | Biojet plants | Area required by the plant(s) over the total estimated abandoned land |
|---|---|---|---|
| – | [thousands of hectares] | Nr. | |
| Spain | 1096.5 | 1 | 4.9% |
| Italy | 456.3 | 2 | 23.5% |
| Greece | 179.2 | 1 | 3% |

alterative kerosene production would result in 575,000 tonnes per year. Assuming 55 Mt/yr as the overall demand of jet A-1 in EU-28 (plus Iceland, Liechtenstein, Norway and Switzerland) during 2018 [69], an integrated biorefinery, including a microalgae farm, could cover more than 1% of the overall demand. This could significantly contribute to the development of the sector, as foreseen by the different policy frameworks, and to provide new opportunities for employment and economic growth, while reducing depopulation in rural and coastal areas. Moreover, the overall GHGs savings for the sector would be 1.5 Mtoe of $CO_2$ per year for the scenario assuming renewable electricity and low fertilizer as inputs (Table 5, Case 3).

## 5. Conclusions

Our study presents an assessment of the energy demand and the associated GHG emissions from the production of algae-based kerosene. The analysis covers the production of algae biomass in raceway ponds, the processing of the resulting biomass (including cultivation, harvesting, drying, cell disruption, liquid phase centrifugation and solvent extraction) and the conversion of the obtained lipids into bio-based kerosene by the Hydroprocessed Esters and Fatty Acids (HEFA) technological process. For the latter step, our study used the latest publicly available data related to such technology.

The potential benefits from the use of algae as a feedstock for alternative fuels have been reported in many studies, but the negative energy and economic balances of pilot initiatives hindered the deployment of such technology at commercial scale. Recently, a new initiative, which resulted in the American Society for Testing and Materials (ASTM) fuel certification, provided new momentum to this pathway.

The scenario proposed aimed to highlight the impact of the emissions related to energy sources and process strategies. In spite of the interesting Net Energy Ratio proposed for the cultivation stage, the results drastically change when different hypothesis are applied to the source of the primary energy considered, stressing the fact that algae production is energy-intense. These findings suggest that any research on this topic should carefully consider the energy demand and supply of the system in order to present valuable results.

The values of GHG savings resulting from our analysis vary significantly depending on the inputs and cultivation strategy considered. In the best-case scenario, 68% of GHG emissions reduction compared with the reference fossil-based kerosene could be achieved. According to Recast of the Renewable Energy Directive II [10], biofuels are required to fulfil the GHG emissions minimum saving criteria (in addition to the additional sustainability criteria) and thus kerosene from microalgae biomass must achieve a reduction of GHG emissions of at least 65% in

**Table A1**
Greenhouse gases assessment for renewable jet fuel from microalgae.

| Microalgae strain | Cultivation technology | Conversion technology | GHG Saving Potential | Calculation models, tools, system boundaries and allocation strategy | Refs |
|---|---|---|---|---|---|
| Species | – | – | *$gCO_2eq/MJ$* | – | – |
| *Nannochloropsis sp.* | RWPs* | HVO** | 27 (system expansion), 38 (economic allocation) | LCA including economic allocation and system expansion by Simapro software V7.3.3. | [28] |
| *Nannochloropsis sp.* | RWPs | HVO | 33.7 | Beihang-AF3E model with GREET-modified database according to Chinese government inventory. System boundary “well to wheel”. Mass allocation for materials for inputs and outputs, and energy allocation for electricity. | [29] |
| *Botryoc. sp.*, *Chlorella sp.*, *Chlamyd sp.* | RWPs | HVO | 40.1 (base case),<br>29 (with alter. co-products allocation) | Attributional life cycle GHG model (ALCEmB – Assessment of Life Cycle Emissions of Biofuels). Mass-based allocation for co-products. | [30] |
| *Chrorella sp.* | RWPs | HVO | 31.3 | LCA model with GREET1_2011 inventory. Simulation tool based on system optimization from photobioreactors to open ponds. Hybrid allocation approach (combination of market and energy allocations). | [31] |
| *Chlorella sp.*, *Isochrysis sp.*, *Nannoch sp.* | PBRs*** | HVO | 17.2 – 51.0 | GREET 1_2014-modified database according to Chinese government inventory. APD_v1.1 (algae process description) tool for processes. The system boundary does not consider the contribution of infrastructure and aircraft. | [32] |
| Oil-rich microalgae strain (not specified) | LDPE plastic-layer PBR | HVO, HTL | 45 (HVO),<br>33 (HTL) | GHGs impact calculated by energy allocation. Calculations done using Ecoinvent version 3.5 (IPCC 2013, GWP 100a). | [33] |
| Oil-rich microalgae strain (not specified) | Open ponds for waste-water | HTL**** | 21.2 (optimized), 131.9 (base case) | LCA model considering “well-to-wake” approach with SimaPro 7.3.3 software. System boundary excludes labour, construction, infrastructure impact and no benefit from wastewater treatments. | [34] |
| Oil-rich microalgae strain (not specified) | RWPs | HVO | 216.3 (with no credits),<br>159.2 (with credits from Anaerobic Digestion). | Well-to-Wake (WTW) analysis by Tsinghua China LCA Model (TLCAM). Energy allocation for co-products. The paper contains a very detailed environmental and energy assessment (reported for each plant section). | [35] |

[*] PhotoBioreactors (PBRs).
[**] Hydrotreated Vegetable Oils (HVO).
[***] Raceway Ponds (RWP).
[****] HydroThermal Liquefaction (HTL).

comparison to the reference values, if produced in installations starting operation from 1 January 2021.

When compared with the GHG saving potential offered by more traditional feedstocks, the results from our assessment confirm algae as an interesting alternative, if appropriate conditions for their cultivation are present, inter alia, high process optimisation, nutrient recycling and use of renewable energy to meet input demand. Indeed, the current evaluation has been performed using conservative assumptions for a 1 ha plant. In commercial, optimised-scale plants, the production of kerosene may exhibit better GHG emissions performance, resulting from real operational data.

Optimisation is expected to be fundamental also to limit costs, which have not been considered in this study but are usually recognised as a limiting factor for the scale-up of such plants [70]. As of today, an economic analysis based on large-scale plants is still missing, and the potential of algae has not been fully investigated yet. It is worth highlighting that in terms of productivity, algae can deliver 10 tonnes of oil per year and a significant amount of proteins, which is remarkable when compared to other oil crops such as palm oil.

Moreover, the possibility to use algae to biologically fix $CO_2$ is a great advantage for the medium term since it can grow using air as a main source of $CO_2$, as it occurs in nature. While the energy costs involved in this process have to be carefully assessed, at the current stage of knowledge it seems a promising possibility, considering that other “air-capture” based options are energy demanding [71].

Scaling-up algae production is a crucial step to see this promising feedstock taking off. The analysis carried out on suitable production and conversion sites in the Mediterranean basin confirm the potential of this pathway to support the decarbonisation of the aviation sector.

## CRediT authorship contribution statement

**M. Prussi:** Conceptualization, Methodology, Investigation, Writing – original draft. **W. Weindorf:** Software, Formal analysis, Data curation. **M. Buffi:** Investigation, Validation. **J. Sánchez López:** Writing – original draft. **N. Scarlat:** Validation, Supervision.

## 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.

### *Acknowledgment*

The authors express their gratitude to Carolina Perpiña Castillo, Carlo Lavalle and the other colleagues of the unit B3 of the European Commission Joint Research Centre working on project “LUISA Territorial Modelling Platform” for their precious support on the maps on European abandoned lands and related data.

### *Disclaimer*

The views expressed are purely those of the authors and may not, under any circumstances, be regarded as an official position of the European Commission.

## Appendix A

See Table A1.

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