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Life cycle assessment of novel thermochemical – biochemical biomass-to-liquid pathways for sustainable aviation and maritime fuel production

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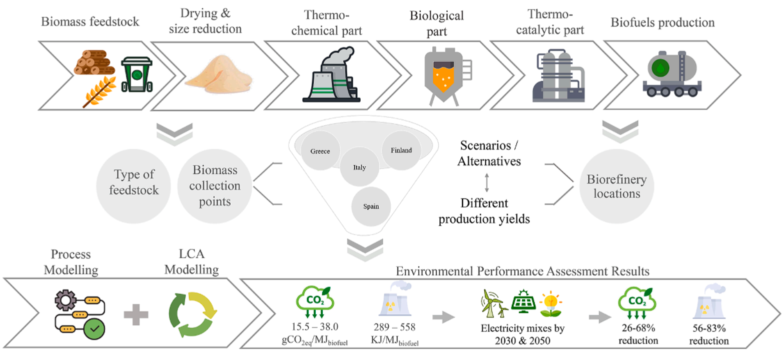
HIGHLIGHTS

- Sustainability of a thermochemical-biochemical pathway for biofuel production.
- Different types of biomass feedstock in potential biorefinery locations included.
- Greenhouse Gas emissions reduction in the range of 60–86%.
- Up to 68% Greenhouse Gas emissions reduction in 2050 compared to 2022.
- Up to 83% decrease in non-renewables consumption in 2050 compared to 2022.

GRAPHICAL ABSTRACT



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ABSTRACT

This paper aims to carry out an integrated Life Cycle Assessment (LCA) to evaluate the environmental performance of a novel thermochemical-biochemical biomass-to-liquid pathway for sustainable aviation and maritime biofuel production. Five scenarios are defined, considering different types of biomass feedstock and biorefinery locations, in different geographically dispersed European countries. The results indicate that the replacement of conventional aviation and maritime fuels with sustainable biofuels could reduce Greenhouse Gases (GHG) by 60–86%, based on feedstock type. When the renewable share in the electricity mix reaches 100% (in 2050), the GHG emissions will experience a great decrease (26% – 68%), compared to 2022 levels. The non-renewable energy consumption will also decrease (by 56% – 83%), with results strongly affected by the electricity mix of the European country considered. This study demonstrates that the deployment of biomass-to-jet/marine fuel pathways could favor the industrial adoption of circular economy strategies for transport biofuels production.

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1. Introduction

The transportation sector constitutes the second highest proportion (about 25 %) of the overall Greenhouse Gas (GHG) emissions in Europe (EU), after the energy industry (Siddiqui and Dincer, 2021). This is mainly attributed to its large dependence on the combustion of conventional fossil fuels (carbon-based fuels). In 2021, the aviation and maritime sector accounted for about 29 % of the total transport emissions in Europe (EEA, 2023a). To tackle GHG emissions problems and improve the EU's security of energy supply, the recast European Renewable Energy Directive 2018/2001/EU (RED II) (EEA, 2018) drives the deployment of alternative fuels and related technologies towards decarbonizing transport in Europe. RED II gives particular focus on (liquid or gaseous) biofuels produced from agricultural, industrial and food waste, and sets a GHG emission savings requirement of 65 % and 75 % compared to fossil fuels, for biofuels and renewable fuels of non-biological origin, respectively.

Despite the environmental advantages of biofuels over conventional fossil fuels from the viewpoint of reducing the GHG emissions and optimizing waste management (Sandaka and Kumar, 2023), it is important to adopt a Life Cycle Assessment (LCA) approach to quantify their actual climate change mitigation potential and ascertain their viability. This happens, since a notable amount of energy is consumed resulting in significant amounts of GHG emissions in the production (including biomass pre-treatment) and the transportation phase of biofuels (Bengtsson et al., 2011; Siddiqui and Dincer, 2021).

Numerous comprehensive life cycle assessments associated with sustainable aviation and maritime biofuels have been carried out, as presented in (See Supplementary material). The majority of the LCA studies focus on evaluating the environmental performance, from the viewpoint of GHG emissions, of the aviation and maritime biofuels in comparison to conventional fossil fuels, from a "cradle to gate" perspective (i.e., from feedstock production to fuel combustion in aircraft / ship engine). As far as the production of aviation fuels is concerned, Oehmichen et al. (2022) compared the life cycle GHG emission figures of three different conversion technologies, i.e., alcohol-to-jet (ATJ) using sugars, hydro-processed esters and fatty acids (HEFA), and synthetic iso-paraffinic (SIP) using sugarcane or other sugars, and found that the ATJ process is environmental wise the least sustainable, with 35.8 gCO_{2eq}/MJ. The authors outlined that multi-blends could reduce the GHG emissions by 35 %, compared to conventional jet fuels. Similar arguments were raised by the studies of Pavlenko and Searle (2021) and Kolosz et al. (2020). Pavlenko and Searle (2021) showed that the gasification Fischer-Tropsch (FT) technology using waste and residues as feedstock has lower GHG emissions (3–12 g CO_{2eq}) than the HEFA (13–60 g CO_{2eq}/MJ) and the ATJ process (3.8–66 g CO_{2eq}/MJ). However, if non-biogenic content is included in the FT feedstock, the GHG emissions will increase significantly to 170 g CO_{2eq}/MJ. Kolosz et al. (2020), who carried out a critical review of 37 LCA studies of "drop-in" alternative aviation fuels, pointed out that the HEFA and the FT conversion technologies are very favorable for sustainable development. The researchers indicated that variations of GHG emissions from the different biomass-to-biojet fuel conversion technologies strongly depend on the type of biomass feedstock, as well as on the allocation method and the energy intensity of each one of the technologies employed.

Regarding the maritime transportation, LCA studies tend to focus on the environmental benefits of cleaner alternative marine fuels, by evaluating the GHG emissions reduction to be incurred by the replacement of conventional heavy fuel oil (HFO) (Al-Enazi et al., 2021; Ha et al., 2023). Al-Enazi et al. (2021) conducted a thorough review of life cycle GHG emissions analyses of using liquefied natural gas (LNG), hydrogen, ammonia and biofuels as bunker fuels. The authors concluded that the LNG has lower global warming effects than the HFO, as shown in (see Supplementary material). However, the hydrogen fuel can significantly reduce the GHG emissions generated upon utilization. Especially with regard to biofuels, Kesieme et al. (2019) estimated the range of GHG emissions at 0.9–5.0 $kgCO_{2eq}$/kg for straight vegetable oil (SVO) production, and 1.3–5.5 $kgCO_{2eq}$/kg for biodiesel production (see Supplementary material). These figures strongly depend on the location of feedstock production and the allocation method employed. Last, but not least, Tan et al. (2021) showed that an important GHG emissions reduction of 67–93 % can be achieved by using 100 % renewable feedstock, and 40–45 % with co-feeding as compared to the fossil HFO production.

The present work provides an integrated LCA of a novel thermochemical – biochemical Biomass-to-Liquid (BtL) pathway for aviation and maritime biofuel production. The main contribution of this work is the investigation of different types of biomass residues to be utilized as feedstock, as well as different biomass collection points and biorefinery locations. The proposed circular economy-driven approach quantifies both the GHG emissions and the fossil and nuclear energy use. These environmental metrics are compared and discussed in relation to those of future electricity mixes forecasted for 2030 and 2050, so as to quantify the environmental benefits of the intended increased penetration of renewables. It is envisaged that computational results and suggestions included in this paper could provide significant information for environmental and energy policies development, with the aim to adopt sustainable strategies for aviation and marine biofuels production at industrial scale.

2. Materials and methods

2.1. Concept description

The present work aims to identify the most sustainable integrated thermochemical-biochemical pathway for aviation and maritime biofuel production. The methodology proposed in this work is applied to a 200 MW_{th} plant, with different residual biomass categories as feedstock. The operation time of the plant, which reflects the total annual full load operation of the plant, is estimated to be 6000 h/year, while the annual biomass residues demand amounts to around 250 kt/year (H2020 Project BioSFerA, 2021a; H2020 Project BioSFerA, 2021b; 2020). This study is based on the BioSFerA project (Biofuels production from - Syngas FERmentation for Aviation and maritime use) ("BioSFerA Project," 2023), funded by European Union's Horizon 2020 research program. The objective of the project is to develop innovative and high performing biofuels to tackle the issue of constantly increasing GHG emissions and negative impacts on air quality of conventional aviation and marine fuels. The scenarios investigated have been retrieved from the research work of Detsios et al. (2023), which focuses on the scale up activities of BioSFerA project. In their study, heat and mass balances were assessed for all scenarios investigated through full-scale process simulations in the commercial tool Aspen Plus^{TM}.

2.1.1. Alternative Biomass-to-Liquid route for biofuels production

The main technologies considered in this work for the production of drop-in aviation and maritime biofuels, include: (i) the conversion of each biomass feedstock into syngas through the Dual Fluidized Bed Gasification (DFBG) technology (also referred to as "thermochemical part"), (ii) a compression stage followed by a double-stage fermentation process for the conversion of syngas to triglycerides (TAGs) (also referred to as "biological part"), (iii) the purification of TAGs through advanced steam explosion-based technologies, and (iv) the conversion of TAGs into liquid fuels via a hydrotreatment process (also referred to as "thermocatalytic part").

As indicated in Detsios et al. (2023), the conversion of the biomass feedstock into syngas is carried out with the DFBG technology. The DFBG system consists of two interconnected Circulating Fluidized Bed (CFB) reactors, i.e., a gasifier where gasification takes place, and an oxidizer, where partial combustion takes place in order to secure the heat requirements of the gasifier. The syngas, in turn, is cleaned in a catalytic reformer so as to achieve the desirable requirements. The reformer is heated by partial combustion with oxygen or air, whilst the reforming reactions consume steam and/or carbon dioxide (CO_2). Depending on the desired purity level, scrubbers and adsorbents can be implemented, so as to remove other contaminants. Due to the fact that the used gasifier type can handle a wide range of raw feedstock, a pre-treatment process (i.e., a drying stage) is not included when the moisture content is up to 20 % w/w. Concerning the two-stage process for the biological conversion of syngas, in the first stage, the produced syngas is converted into acetate under anaerobic conditions; produced off-gas can be recirculated back to the fermenter or hydrogen can be extracted via pressure swing adsorption (PSA) in order to be utilized in the hydrotreatment process. In the second stage, the conversion of the dilute acetate effluent stream into TAGs through an aerobic fermentation process takes place. The final stages of the value chain include the purification of TAGs and the catalytic hydrotreatment process for the production of aviation and marine biofuels. The catalytic hydrotreatment process is divided into three main steps: hydrogenation, subsequent hydrodeoxygenation and decarboxylation. The organic product is a mixture of straight and branched C_vH_{2v+2} that can be used as drop-in liquid fuel. It is noted that a Heat Recovery Steam Generator (HRSG) section system is also utilized for efficient heat recovery and steam generation (Detsios et al., 2023; H2020 Project BioSFerA, 2021b). A simplified flowchart of the relevant processes involved in the thermochemical-biochemical biomass-to-liquid route for maritime and aviation biofuel production is illustrated in Fig. 1.

2.1.2. Feedstock selection – Investigated case studies

The present work concerns different promising types of feedstock to be utilized for the production of maritime and aviation fuels. From an environmental perspective, the selection of feedstock strongly depended on avoiding both land use restrictions and conflict with food production, as well as compiling with the EU's biofuels policy related to the promotion of biogenic residues-based biofuels, which is demonstrated in the RED II Directive. From the technical point of view, the feedstock selection was based on the desirable quality characteristics of biogenic residues in order to optimize the thermochemical-biochemical process performance. These quality characteristics include: (i) high heating value, (ii) particle size distribution, (iii) low ash and moisture content, and (iv) low sulfur, chlorine, and nitrogen content. Last, but not least, the market competitiveness from the viewpoint of feedstock cost-effectiveness (storage and pre-treatment requirements costs) and the available capacity for large-scale applications, were also considered (H2020 Project BioSFerA, 2020). In this context, the selected residues for environmental performance assessment are agricultural residues (olive and vineyard pruning and cereal straw), forestry residues (logging and wood residues), and biogenic wastes from airports and ports.

Considering the type of biomass feedstock, the associated suppliers and the potential biorefinery location, five scenarios are defined, as shown in Table 1. It should be noted that Greece, Spain and Italy (Mediterranean countries) were chosen as pruning and straw suppliers, because of the high percentage of their total area used for agricultural activities. On the other hand, Finland (Nordic country) is chosen as logging residues supplier, since it is abundant in forest wood resources (H2020 Project BioSFerA, 2020; IRENA, 2018; Sagani et al., 2019). All five scenarios presented in Table 1 are thoroughly investigated from an environmental life cycle perspective in order to establish the most sustainable thermochemical-biochemical biomass-to-liquid pathway as an alternative to fossil-based aviation and maritime fuels production (H2020 Project BioSFerA, 2021a, 2020).

2.2. Life Cycle Assessment under European Renewable Energy Directive II methodology

An integrated Life Cycle Assessment (LCA) was carried out in order to evaluate the environmental impact of the different scenarios considered for the production of sustainable aviation and maritime biofuels, using the SimaPro PhD 9.3 Software. LCA is a holistic methodology for evaluating the environmental impacts associated with a product, a process, or a system throughout its entire life cycle (Bessou et al., 2011). In the current research work, the relevant guidelines and modelling framework for conducting the LCA are in accordance with the European Renewable

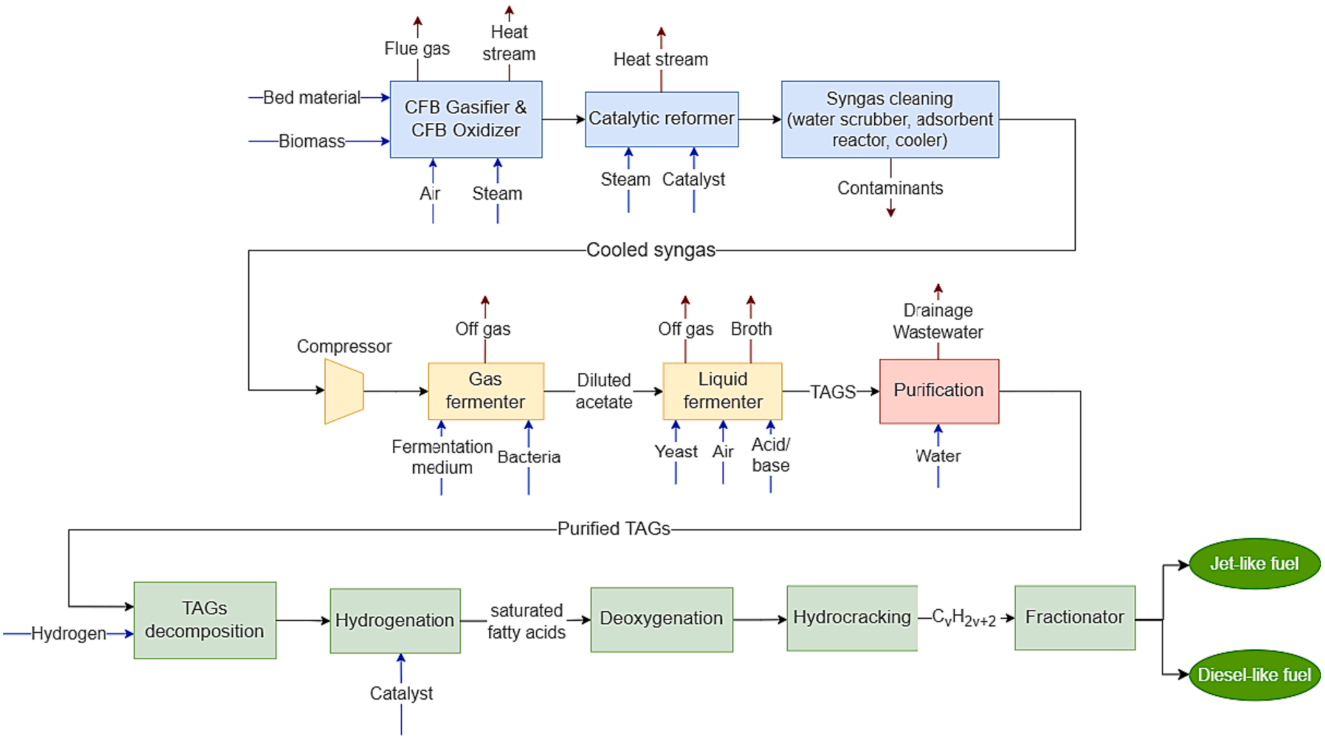

Fig. 1. Simplified flowchart of biomass-to-liquid pathway for biofuel production.

Table 1
Investigated scenarios of biomass-to-liquid pathway.

Scenario	Country	Sub-regions		Feedstock
		Biomass feedstock location	Biorefinery location	
1	Greece – Case 1	Argolida – Arcadia (sub-region i); Corinthian (sub-region ii); Laconia –Messenia (sub-region iii)	Argolida – Arcadia	20/80 % w/w dry matter basis organic waste/olive tree pruning
2	Greece – Case 2	Argolida – Arcadia (sub-region i); Corinthian (sub-region ii); Laconia –Messenia (sub-region iii)	Argolida – Arcadia	Olive tree pruning
3	Finland	Varsinais – Suomi (sub-region i); Satakunta (sub-region ii); Helsinki (sub-region iii)	Varsinais – Suomi	Logging and wood residues
4	Italy	Udine (sub-region i); Venezia (sub-region ii); Pordenone (sub-region iii)	Udine	Straw-derived residues
5	Spain	Granada (sub-region i); Almería (sub-region ii); Murcia (sub-region iii)	Granada	Vineyard pruning

Energy Directive 2018/2001/EU (RED II) (EEA, 2018). RED II includes three main steps: (a) the evaluation of GHG emissions related to biofuels and bioliquids, (b) the normalization of the partial results to a functional unit, and (c) the estimation of the GHG emission savings (Lee and Atsushi, 2004).

According to the RED II Directive, the system boundaries for the production and use of biofuels (or bioliquids) include: (i) crop cultivation, (ii) extraction of raw materials, (iii) transportation, (iv) processing, (v) final distribution, and (vi) fuel use/combustion. As indicated in the Directive, the manufacturing stage of machinery/equipment is excluded from the system boundaries. The corresponding equation for the calculation of the GHG emissions of biofuels (bioliquids), considering all the aforementioned phases of the production and use of biofuels (bioliquids), reads (Part C, Annex V of RED II) (EEA, 2018):

$$E = e_{ec} + e_l + e_p + e_{td} + e_u - e_{sca} - e_{ccs} - e_{ccr}\ [gCO_{2eq}/\mathrm{MJ}_{\mathrm{biofuel}}] \tag{1}$$

Where:

E = total emissions from the use of biofuel;

e_{ec} = emissions from the extraction or cultivation of raw materials;

e_l = annualized emissions from carbon stock changes caused by land-use change;

e_p = emissions from processing;

e_{td} = emissions from transport and distribution;

e_u = emissions from the liquid in use;

e_{sca} = emission savings from soil carbon accumulation via improved agriculture management;

e_{ccs} = emission savings from carbon capture and geological storage;

e_{ccr} = emission savings from carbon capture and replacement.

Since the RED II Directive exclusively focuses on the GHG emissions evaluation, the unit of the analysis (functional unit) is defined and quantified as follows: *"Greenhouse gas emissions from biofuels, E, expressed in terms of grams of CO_2-equivalent per MJ of fuel, $gCO_{2eq.}/MJ$"*. It should be noted that the CO_2 equivalent accounts for emissions of CO_2, CH_4, and N_2O. The relative GHG emissions reduction (savings) to be incurred by replacing the fossil fuel comparator with biofuels (or bioliquids) is evaluated as follows (Annex V, Part C in paragraph 3) (EEA, 2018):

$$Emission\ Savings = \frac{E_{F(t)} - E_{B(t)}}{E_{F(t)}} \tag{2}$$

Where, E_B denotes the total emissions from the biofuel in [g CO_{2eq}/MJ] and E_F refers to the total emissions from the fossil fuel comparator for transport in [g CO_{2eq}/MJ]. For the purposes of the calculation of equation (2), RED II defines the fossil fuel comparator at 94 gCO_{2eq}/MJ for the biofuels case (Annex V, part C in paragraph 19). It is worth mentioning that the calculation method of the fossil fuel comparator is based on the average energy consumption from fossil fuels, petrol, diesel, gasoil, liquefied petroleum gas (LPG) and compressed natural gas (CNG), in particular (European Commission, 2015).

At this point, it should be noted that, in the current study, the emissions related to the cultivation, processing and transport and distribution of biofuels (see equation (1)), have not been calculated using the corresponding disaggregated default values reported in RED II Directive (Article 31, Annexes V and VI). For the relevant emissions calculations, the ISO 14040–14044 Standards were applied (Finkbeiner et al., 2006). Based on these Standards, the LCA study includes four interrelated phases: (i) system boundaries identification, (ii) inventory analysis, i.e., quantification of the inputs and outputs considering the specific system boundaries, (iii) impact assessment, i.e., quantification of environmental impacts based on a specific methodology, and (iv) interpretation of results, i.e., utilization of calculated results to make inferences and provide recommendations (Siddiqui and Dincer, 2021). These phases are addressed in the following sections.

2.2.1. System boundaries

The system boundaries of this work include (See Supplementary material): (1) the biomass feedstock pre-treatment (2) the transportation of biomass feedstock from the collection points (see Table 1) to the biorefinery plant, (3) the thermochemical conversion of biomass feedstock to syngas using catalyst ("thermochemical part"), (4) the compression of the produced syngas, (5) the production of acetate and its conversion into TAGs ("biological part"), (6) the purification of TAGs, and (7) the catalytic hydrotreatment process for the production of aviation and marine biofuels ("thermocatalytic part").

Especially with regard to the pre-treatment stage, biomass drying and size reduction (including chopping and grinding processes) may be considered, depending on the type of feedstock. More specifically, drying is adopted for organic waste, due to its high moisture content (60 % w/w) (See Supplementary material), chopping is adopted for all types of feedstock under analysis, while grinding is applied to all feedstocks but for the organic waste. It should be noted that the effect of biomass cultivation was excluded from this LCA study.

2.2.2. Data sources and Life Cycle Inventory

The Life Cycle Inventory (LCI) analysis phase of LCA includes data compilation for materials, energy flows and environmental emissions involved in the entire life cycle of aviation and maritime biofuel production. Primary (foreground) data associated with mass and energy balances for all unit processes included in the system boundaries, are those reported in the work of Detsios et al. (2023), and are summarized in Table 2. The data referring to the main specifications (chemical and physical characteristics) of each type of biomass feedstock, which are required for setting up the mass and energy balances in process modelling, are also taken from the works of Detsios et al. (2023) and H2020 Project BioSFerA (2020), and are included in (See Supplementary material). Finally, data required for compiling background LCI of catalysts used in both the "thermochemical" and the "thermocatalytic part", were obtained from the Ecoinvent 3.9 database. Ecoinvent is the

Table 2
Life Cycle Inventory data related to investigated scenarios (Batidzirai et al., 2016; Fan et al., 2011; Handler et al., 2016; Sikarwar et al., 2016).

	Value					Unit[a]
Process	**Greece Case 1**	**Greece Case 2**	**Finland**	**Italy**	**Spain**	
Input						
Feedstock Mass	370	270	250	295	270	kt/y
Transportation distance[b]						
Sub-region (i)	30	30	30	30	30	km
Sub-region (ii)	80	80	175	130	160	km
Sub-region (iii)	100	100	170	85	280	km
Mass Allocation						
Sub-region (i)	60	60	60	60	60	%
Sub-region (ii)	15	15	25	25	25	%
Sub-region (iii)	25	25	15	15	15	%
Harvesting						
Diesel consumption	–	905	838	903	905	tn/y
Size reduction						
Electricity consumption	7,291[c]	10,044	9,300	9,882	10,044	MWh/y
Drying						
Heat consumption[d]	255,377	–	–	–	–	GJ/y
Thermochemical Part						
Water for steam production and catalytic reformer	156	166	149	177	166	kt/y
Catalyst to reformer Ni/Al_2O_3 (10 % Ni)	8	8	8	8	8	tn/y
Biotechnological Part						
Electricity consumption in compressor	45,600	46,740	45,420	47,640	46,740	MWh/y
Thermochemical Part						
Catalyst (NiMo/Al_2O_3)	9	9	9	9	9	tn/y
Output						
Produced acetate	166	165	1691	165	165	kt/y
Produced fuel	32.00	31.84	32.59	31.96	31.84	kt/y

[a] Where kt; kilotonnes, km; kilometers, tn; tonnes, y; year, MWh; Megawatt-hours, GJ; Gigajoule.
[b] The distances have been calculated using a distance calculator ("Distance calculator," n.d.).
[c] Includes only the size reduction of olive tree pruning.
[d] A conventional drying method is considered (natural gas as energy source), in order to account for the worst-case scenario in environmental terms.

most widely accepted LCA database and has been established by employing European industrial data (Frischknecht et al., 2005). It is worth noting that for all the examined scenarios the produced drop-in aviation and marine biofuels were considered to have the same heating value (42 MJ/kg).

2.2.3. Life Cycle impact assessment methodology

Following the work of Rejane Rigon et al. (2019), which carries out a thorough literature review on the existing Standardized Life Cycle Impact Assessment (LCIA) Methodologies, it was decided to apply the IMPACT World + Midpoint methodology, one of the most popular LCIA methods, in order to assess the potential environmental impacts of the different scenarios considered for the aviation and maritime biofuel production. IMPACT World + Midpoint was selected mainly because of its ability to address the two particular environmental impact categories, namely the climate change (expressed in kg of CO_{2eq}) and the non-renewable (fossil and nuclear) energy use (expressed in MJ). It is worth noting that the climate change impact is evaluated following both the Impact World + methodology combined with RED II Directives. In accordance with other LCIA methods, Impact World + evaluates only GHG emissions from fossil fuels, i.e., biogenic emissions are considered neutral (Bulle et al., 2019). Apart from the GHG emissions indicator, the nuclear and fossil consumption-related indicator is also of interest of this study. This is mainly due to the fact that most of the processes included in the thermochemical-biochemical biomass-to-liquid pathway are energy intensive, with the required process electricity being generated from conventional thermal power systems. Therefore, the contribution of the existing electricity mix in the overall non-renewable energy consumption associated with the production and utilization of biofuels was investigated, as well as the potential environmental benefits to be incurred by increasing the penetration of renewables in future electricity mixes.

3. Results and discussion

3.1. Life Cycle Analysis results

3.1.1. Climate change impact category

Estimated climate change emissions of the five scenarios considered in this work are presented in Table 3. The corresponding percentage share of the relevant processes of the thermochemical-biochemical biomass-to-liquid pathway in the overall climate change impact is presented in Fig. 2.

The highest GHG emissions are associated with Scenario 1 (Case 1, Greece), estimated at 38.0 gCO_{2eq} /$MJ_{biofuel}$ (see Table 3). The most significant contributor to climate change impact category (~42 %) is the compression stage (see Fig. 2). The compression stage is energy intensive with the required energy being generated mostly via conventional fossil fuels (lignite and natural gas in case of Greece in 2021, see Supplementary material) (EEA, 2023b). The pre-treatment process of organic waste is another important contributor to the global warming potential. Among the different pre-treatment stages, i.e., harvesting, size reduction and drying, the latter exhibits the most adverse GHG impact (~84 %, refer to Fig. 3). This is due to the fact that the drying process is energy intensive, with the required energy being generated via natural gas. It is interesting to note that if the dryer is powered by grid electricity (Tun and Juchelková, 2019), instead of using natural gas, the total GHG emissions of Scenario 1 will increase significantly by 25 % (i.e., from 38.0 to 47.4 $gCO_{2eq}/MJ_{biofuel}$). This is attributed to the electricity mix of Greece, which is dominated by both lignite and natural gas.

Scenario 2 (Case 2, Greece) and Scenario 4 (Italy) are also important contributors to climate change emissions, with 25.6 $gCO_{2eq}/MJ_{biofuel}$ and 24.8 $gCO_{2eq}/MJ_{biofuel}$, respectively. The poor performance of these scenarios could be attributed to the compression stage (~59 %) and the biological part (~24 %). Similar to Greece, the electricity mix of Italy,

Table 3
Life Cycle GHG[e] emissions associated with the scenarios investigated.

Processes	Emissions ($kgCO_{2eq}/y$)				
	Greece Case 1	**Greece Case 2**	**Finland**	**Italy**	**Spain**
Feedstock Pre-treatment	21,750,151	4,813,970	2,284,043	4,489,507	2,574,158
Harvesting	375,726	444,830	441,879	443,945	444,830
Size reduction process	3,171,672	4,369,140	1,872,163	4,045,562	2,129,328
Drying	18,202,753	–	–	–	–
Transport of Feedstock	1,376,957	1,005,524	1,470,859	1,265,447	1,828,222
Transport of feedstock from sub-region (i) to biorefinery	450,639	329,081	305,193	360,127	329,081
Transport of feedstock from sub-region (ii) to biorefinery	300,429	219,386	445,073	650,230	731,290
Transport of feedstock from sub-region (iii) to biorefinery	625,889	457,057	720,594	255,090	767,851
Thermochemical part	31,717	31,731	31,717	31,738	31,731
Water consumption	133	148	133	157	148
Catalyst consumption	31,584	31,584	31,584	31,584	31,584
Biotechnological part					
Fermentation medium	8,041,162	7,999,171	8,194,259	8,041,162	7,999,171
Compressor unit					
Operation of compressor unit	19,836,000	20,331,900	9,143,404	19,484,760	9,908,880
Thermocatalytic part					
Catalyst consumption	43,349	43,349	43,349	43,349	43,349
Total GHG emissions	51,079,337 or 38.0 g CO_{2eq}/MJ	34,225,631 or or 25.6 g CO_{2eq}/MJ	21,167,631 or or 15.5 g CO_{2eq}/MJ	33,355,943 or or 24.8 g CO_{2eq}/MJ	22,385,498 or 16.7 g CO_{2eq}/MJ
GHG emission savings	60 %	73 %	86 %	74 %	82 %

[e] Where GHG; Greenhouse Gas.

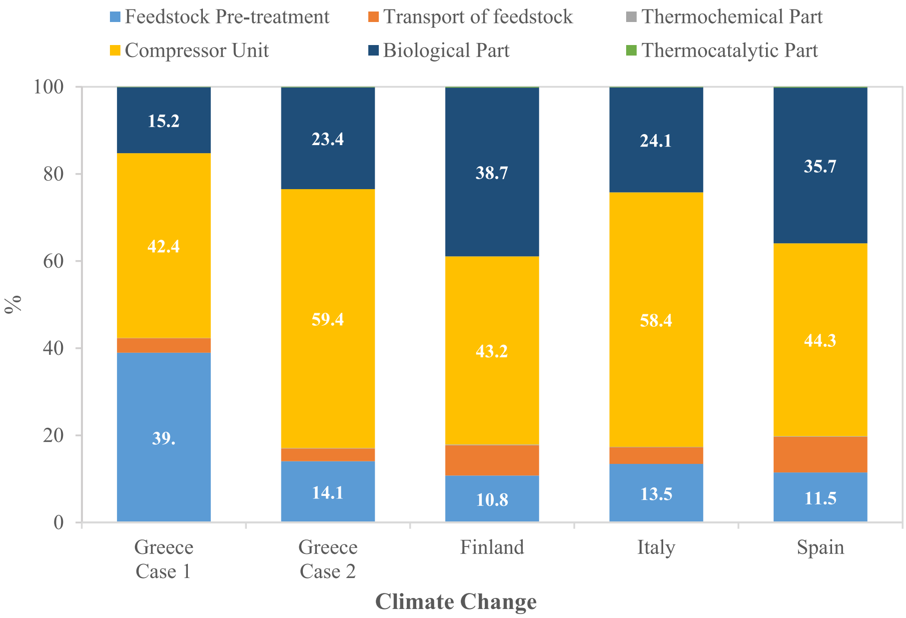

Fig. 2. Percentage share of the different processes in overall climate change missions associated with the investigated scenarios (IMPACT World + Midpoint Methodology - all impact scores are displayed on a 100 % scale).

used to power the compressor, is dominated by fossil oil and natural gas (in 2021) (see Supplementary material) (EEA, 2023b). The adverse impact of the biological part is associated with the consumption of significant amounts of nitrogen and phosphorus nutrients in the fermentation medium. As indicated in the research work of Handler et al. (2016), the GHG emission factor associated with the fermentation medium equals to 1.8 g $CO_{2eq}/MJ_{biofuel}$.

On the other hand, Scenario 3 (Finland) and Scenario 5 (Spain) have the lowest adverse impact on the environment, with estimated GHG emissions figures of 15.5 $gCO_{2eq}/MJ_{biofuel}$ and 16.7 $gCO_{2eq}/MJ_{biofuel}$, respectively. This is attributed to some extent to the presence of nuclear energy in the electricity mix of both Finland and Spain (in 2021), which is favorable as far as the GHG emissions are concerned (See Supplementary material) (EEA, 2023b).

It is highlighted that for the scenarios under analysis, the transportation of biomass feedstock from the collection points to the biorefinery plant clearly performs best, as compared to biomass pretreatment and the compression and biological stages. The GHG emissions from the transportation stage are exclusively because diesel-powered trucks are considered. Last, but not least, in all scenarios, the global warming potential of the thermochemical and the thermocatalytic stages is almost negligible (<3%).

Comparison results between all scenarios investigated and the fossil fuel comparator, as determined by the European Commission in RED II Directive for the transport sector, are illustrated in (see Supplementary material), where it is observed that the biofuels production in all scenarios lies well below the fossil fuel comparator of 94 $gCO_{2eq}/MJ_{biofuel}$. The relevant net annual GHG emission reduction, which is calculated using Equation (2), is quite high, ranging from 60 % (Greece, Case 1) to 86 % (Spain), as shown in Table 3.

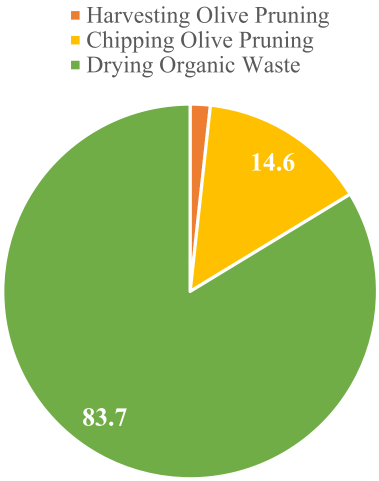

Fig. 3. Percentage share of the different processes involved in biomass pre-treatment in climate change emissions (Case 1, Greece) (IMPACT World + Midpoint Methodology - All impact scores are displayed on a 100 % scale).

3.1.2. Fossil and nuclear energy use

Calculated fossil and nuclear energy use-related indicator for the five scenarios investigated is presented in Table 4. The relevant percentage contribution of the relevant processes of the thermochemical-biochemical biomass-to-liquid pathway to the non-renewable energy use is shown in Fig. 4.

Scenario 1 (Case 1, Greece), which is associated with the utilization of both olive tree pruning and organic waste for biofuel production, exhibits the highest non-renewable (fossil and nuclear) energy consumption figure, estimated at 558 $kJ/MJ_{biofuel}$ (see Table 4). The poor performance of this scenario is mainly due the energy requirements associated with both the pre-treatment (harvesting, size reduction and drying) stage of feedstock and the compression stage. Energy required for the drying process is supplied by natural gas, energy required for the size reduction and compression stages is generated by conventional thermal plants (solid fossil fuels and natural gas, in particular) (see Supplementary material), while diesel-powered farming machineries are used for the harvesting process.

Scenario 2 (Case 2, Greece), Scenario 3 (Finland) and Scenario 5 (Spain) are also important contributors to fossil and nuclear energy consumption, with 364 $kJ/MJ_{biofuel}$, 371 $kJ/MJ_{biofuel}$ and 338 $kJ/MJ_{biofuel}$, respectively. These figures are directly related to the energy required for the compression stage, with this energy being generated mostly by conventional fossil fuels (i.e., solid fossil fuels and natural gas in case of Greece, nuclear power and natural gas in case of Finland and Spain, see Supplementary material).

Scenario 4 (Italy) associated with using straw-derived residues for biofuel production, presents the best option, with an estimated fossil and nuclear energy use-related indicator of 289 $kJ/MJ_{biofuel}$.

In all scenarios, the transport stage performs better in environmental terms (up to 6.5 %) than the pre-treatment and the compression stages, mainly due to the small transportation distances from the feedstock collection points to the biorefinery plant (in a radius of 30–280 km). Last, but not least, the impact of the thermocatalytic and the thermochemical stages in the non-renewable energy category was found to be negligible (<1%).

3.2. Dynamic effect of future electricity mixes (2030 and 2050)

Having obtained the environmental results, a sensitivity analysis was carried out in order to investigate the environmental benefits from the penetration of Renewable Energy Sources (RES) in the electricity mix of the different countries considered in the present work. To this purpose, two different scenarios, i.e., “Scenario 2030” and “Scenario 2050”, were configured, considering the European and National targets for RES penetration in the corresponding milestone years, namely 2030 and 2050. It should be mentioned that a rather extended period was specified, mainly because the reaction time to energy policy changes is relatively long.

Towards a climate neutral economy in Europe by 2050, Greece is expected to have 73 % and 100 % RES penetration (mainly wind and solar) by 2030 and 2050, respectively (Anagnostopoulos and Papantonis, 2013). By the end of 2030, renewables in Finland (mainly hydro power and bioenergy) are anticipated to represent a share of 74 % of the total electricity produced, while biomass, wind, solar and hydro energy are expected to dominate (100 %) the energy production by the end of 2050 (Balogun and Bhattarai, 2016; Ministry of Economic Affairs and Employment of Finland, 2019). In case of Italy, forecasts anticipate that RES (mainly hydro, wind and solar) will reach 55 % of the total energy produced by 2030, and 93 % (solar, wind, biomass, and hydro) by the end of 2050 (Calise et al., 2017; Ministry et al., 2019). Finally, the renewables share in the electricity mix of Spain (mainly wind and solar) is expected to reach 74 % in 2030 and further increase to 100 % in the long term (by the end of 2050) (BloombergNEF, 2019; MITERD (The Ministry for the Ecological Transition and the Demographic Challenge, 2020)).

Considering the electricity mixes for the years 2022, 2030 and 2050, the estimated climate change and non-renewable (fossil and nuclear) energy consumption figures for the five scenarios investigated, are illustrated in Fig. 5a and Fig. 5b, respectively. For all the countries under analysis, the highest GHG emissions are exhibited in 2022, mainly due to the high contribution (>40 %) of thermal power plants to the electricity mix (see Supplementary material). As expected, future electricity mixes with increased penetration of renewables could certainly lead to a further decrease in GHG emissions. For instance, in case of Greece (Case 2), in 2030, the total global warming potential for biofuel production from olive tree pruning is estimated to be 17.9 $gCO_{2eq}/MJ_{biofuel}$, which is significantly lower, by almost 30 %, than the corresponding figure of 2022. In 2050, the global warming potential is expected to decrease further, reaching about 9 $gCO_{2eq}/MJ_{biofuel}$. It is worth noting that, among all countries and related scenarios investigated, the highest GHG emissions reduction is anticipated in case of Greece, due to some extent to the decommissioning of the majority of lignite power plants. Especially with regard to Spain and Finland, the lower GHG emissions reduction, as compared to Greece, is attributed to the presence of nuclear energy in their current electricity mixes, which is favorable as far as the GHG emissions are concerned. Results for non-renewable (fossil

Table 4
Fossil and nuclear energy use associated with the scenarios investigated.

Processes	Fossil and nuclear energy use (MJ/y)				
	Greece Case 1	**Greece Case 2**	**Finland**	**Italy**	**Spain**
Feedstock Pre-treatment	369,884,080	124,865,974	121,049,434	104,865,143	116,358,569
Transport of feedstock	30,835,027	15,774,935	23,075,246	19,852,692	28,681,667
Compressor unit	349,620,169	347,055,677	363,787,411	263,348,918	307,466,260
Total	750,354,219 or 558 $kJ/MJ_{biofuel}$	487,697,934 or 364 $kJ/MJ_{biofuel}$	507,913,439 or 371 $kJ/MJ_{biofuel}$	388,068,101 338 $kJ/MJ_{biofuel}$	452,507,844 289 $kJ/MJ_{biofuel}$

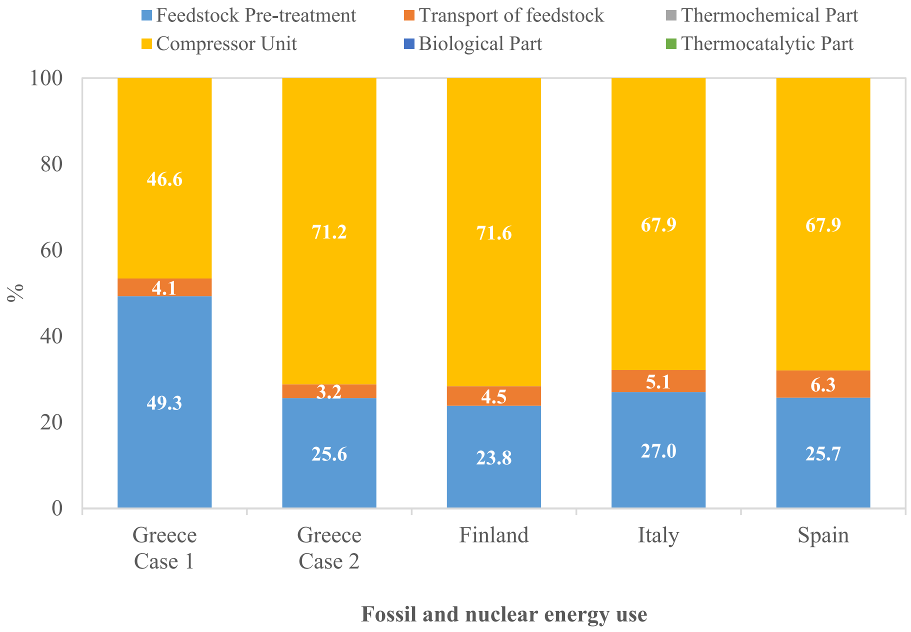

Fig. 4. Percentage share of the different processes in fossil and nuclear energy use associated with the investigated scenarios (IMPACT World + Midpoint Methodology - All impact scores are displayed on a 100 % scale).

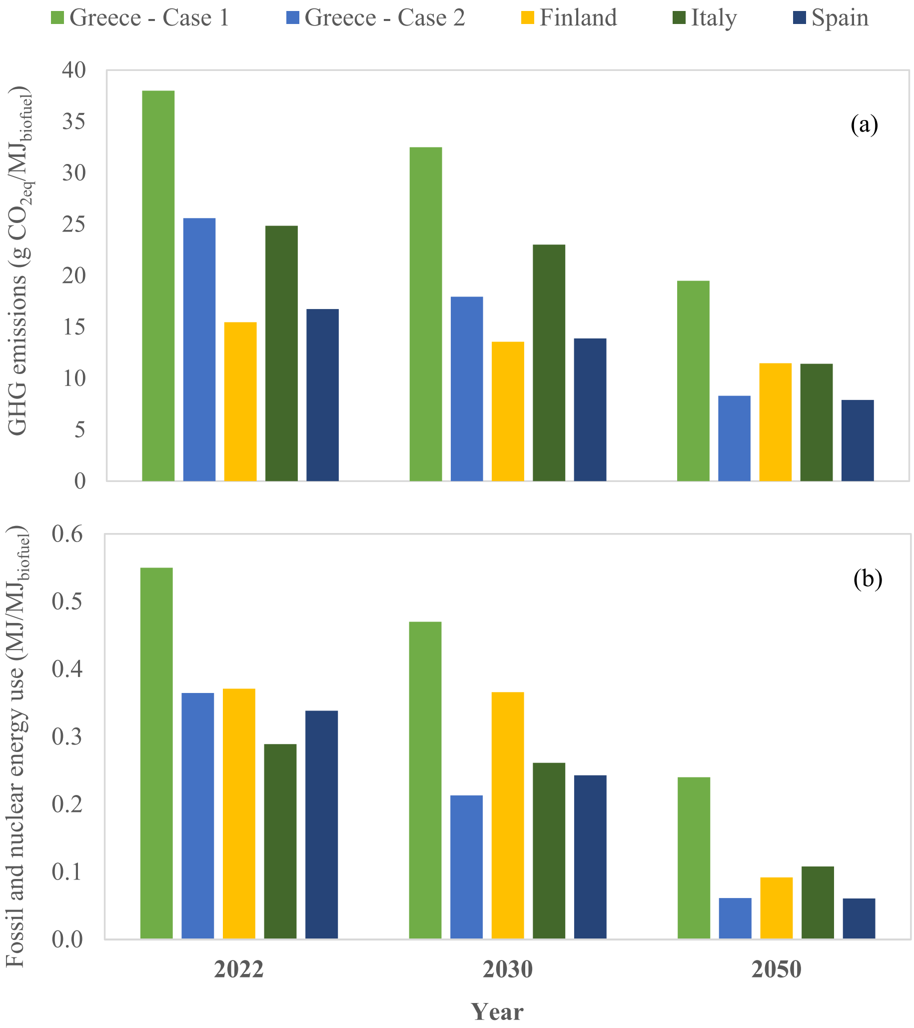

Fig. 5. (a) Overall GHG emissions related to the investigated scenarios within the timespan 2022–2050, (b) Estimated fossil and nuclear energy use related to investigated scenarios within the timespan 2022–2050.

and nuclear) energy consumption exhibit similar behavior; in all countries, electricity mixes with 100 % share of renewables have the lowest non-renewable energy consumption values.

3.3. Discussion on economic assessment of biomass-to-jet or -maritime fuel pathways

Calculated LCA results showed that the production of aviation and maritime biofuels from agricultural and forestry residues are a promising alternative solution to reduce the environmental adverse impact, from the viewpoint of GHG emissions and non-renewable energy consumption, as well as to support energy supply and food safety. Although the economic assessment of the examined technology is beyond the scope of the present work, a brief literature review was conducted in order to examine the potential of the cost effectiveness of biomass-to-jet or -marine fuel pathway. Based on the relevant literature, in order to evaluate the total cost of a particular biofuel, one has to have solid estimates of all costs involved in the entire production chain, i.e., from feedstock production to biofuel production and distribution at the fueling station (Sanz et al., 2014). However, especially with regard to aviation biofuels, Diederichs et al. (2016) pointed out that the hybrid (gasification and biochemical upgrading) processes for bio-jet fuel production have significantly higher minimum jet selling price than the fossil-derived jet fuel, estimated at $2.50/kg jet fuel. This is attributed to both the high biomass feedstock price and the high investment cost. Since alternative biomass-to-jet fuel potential pathways are still far from global commercialization and market predominance over conventional fossil jet fuels, national governments should find means of offsetting the price handicap of biomass feedstock and capital costs through investment incentives.

4. Conclusions

This study provides insight regarding the environmental performance of aviation and maritime biofuels, through the analysis of various biomass feedstock and biorefinery locations. LCA results show that replacing conventional fuels with the biofuels produced could reduce GHG emissions by 60–86 %. Future energy policies, with increased RES penetration, could further decrease emissions by up to 68 % compared to 2022 levels. The findings of this study are expected to inform policymakers and industries, contribute to international sustainability priorities, encourage the adoption of the proposed BtL pathway and encourage further research to minimize the significant contributors to emissions.

CRediT authorship contribution statement

Dimitrios-Sotirios Kourkoumpas: Writing – original draft, Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization. **Adamantia Bon:** Writing – original draft, Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization. **Angeliki Sagani:** Writing – original draft, Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization. **Konstantinos Atsonios:** Data curation, Writing – review & editing. **Panagiotis Grammelis:** Supervision, Writing – review & editing. **Sotirios Karellas:** Writing – review & editing. **Emmanouel Kakaras:** Writing – review & editing.

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.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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