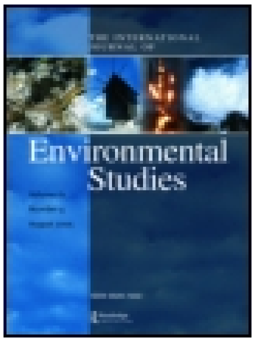

International Journal of Environmental Studies

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/genv20

An economic and CO_2 assessment of using Fischer-Tropsch diesel in the European maritime sector

Vinicius Andrade dos Santos, Patrícia Pereira da Silva & Luís Manuel Ventura Serrano

INTERNATIONAL JOURNAL OF ENVIRONMENTAL STUDIES
https://doi.org/10.1080/00207233.2022.2157633

Routledge
Taylor & Francis Group

ARTICLE

An economic and CO_2 assessment of using Fischer-Tropsch diesel in the European maritime sector

Vinicius Andrade dos Santos [a,b], Patrícia Pereira da Silva [a,c,d,e] and Luís Manuel Ventura Serrano [f,g]

[a]Sustainable Energy Systems, MIT-Portugal—The Energy for Sustainability, Initiative (EFS), Department of Mechanical Engineering, University of Coimbra, Coimbra, Portugal; [b]Chemical Process Engineering and Forest Products Research Centre (CIEPQPF)—Chemical Engineering Department, University of Coimbra, Coimbra, Portugal; [c]Centre for Business and Economic Research (CeBER), University of Coimbra, Coimbra, Portugal; [d]Faculty of Economics, University of Coimbra, Coimbra, Portugal; [e]Department of the Faculty of Sciences and Technology, INESC-Coimbra and Energy for Sustainability Initiative, University of Coimbra, Coimbra, Portugal; [f]School of Technology and Management, Polytechnic of Leiria, Leiria, Portugal; [g]ADAI—Department of Mechanical Engineering, University of Coimbra, Coimbra, Portugal

ABSTRACT
This study examines FischerTropsch Diesel as a source of decarbonisation by use of lignocellulosic residues (wheat, barley, and maize) contributing to the European maritime sector. A techno-economic methodology from the literature and well-to-tank analyses were used to calculate the production, cost, and carbon emissions of the fuel. By exploiting an area of 23.27 million hectares, nine countries could potentially produce 4.9 million tonnes of renewable diesel annually, to be distributed to their respective ports. That amount could eliminate 8.4% of the current CO_2 emissions of the sector in Europe, at a cost ranging from 51.20 to 68.69 €/GJ. The study includes a sensitivity analysis of biomass, electricity, interest rate, and sub-product cost variables, as well as blend variation (1–100%) with the current marine fossil fuel used, with a cost of CO_2 saved varying between 678.46–1,457.86 €/tCO_2.

KEYWORDS
Biomass; Fischer-Tropsch; maritime sector

Introduction

European maritime transport is responsible for the emissions of 138 million tonnes of carbon dioxide equivalent (MtCO_2eq), which corresponds to more than 40 million tonnes (Mt) of marine fuel consumed [1]. The negative impacts caused by fossil fuel consumption in the European Union (EU) have opened the door for the exploration of the advanced biofuels from lignocellulosic resources as a major contributor to the decarbonisation of maritime transport [2,3].

The Fischer-Tropsch (FT) process can convert biomass to hydrocarbons similar to diesel fuel called biomass to liquid (BTL) fuels [4,5] or bio-FT diesel, suitable for internal combustion engines (ICE) such as those used in maritime transport [5]. The process is still at an early stage of development.

CONTACT Vinicius Andrade dos Santos viniciussantos.vs55@gmail.com Sustainable Energy Systems, MIT-Portugal—The Energy for Sustainability, Initiative (EFS), Department of Mechanical Engineering, University of Coimbra, Coimbra 3030-194, Portugal

Published online 09 Jan 2023

The production of advanced biofuels from lignocellulosic resources, as in the case of bio-FT diesel, highlights the relevance of agricultural residues in Europe, which is one of the world's largest producers of wheat, barley, and maize. Therefore, it has the potential to offer a large quantity of straw to be transformed into bio-FT diesel for use in the maritime transport sector.

A combination of methodologies from agriculture residue recovery [6,7] and techno-economic analysis [8] allowed us to determine the potential biofuel output from each crop. Moreover, the well-to-tank assessment will be presented to show the carbon footprint of each region selected as a potential bio-FT diesel source for the European ports.

Finally, this research enabled us to determine how substituting fossil fuels with a biofuel can reduce greenhouse gas (GHG) emissions in the European maritime sector. Furthermore, it allowed us to foresee the number of plant units and the potential regions for exploiting the residual biomass from large harvests of crops in Europe to produce this alternative fuel.

Material and methods

Figure 1 shows the methodology procedure, as follows:

- Key crops (wheat, barley, and maize) biomass availability data survey in the EUROSTAT of the UE-27 plus UK.
- Technical simulation of biofuel production.
- Techno-economic and well-to-tank assessment.

Fischer-Tropsch biofuel production and economic assessment are based on Isabela et al. [8] who used residues from wood as feedstock.

Biomass availability

For the recovered agriculture residues, a bottom-up approach was used within a 30 km radius of a supposed factory [6,8–10]. Table 1 displays the residual biomass factors of the crops used in this work, followed by the determination of the energy potential using the following equation:

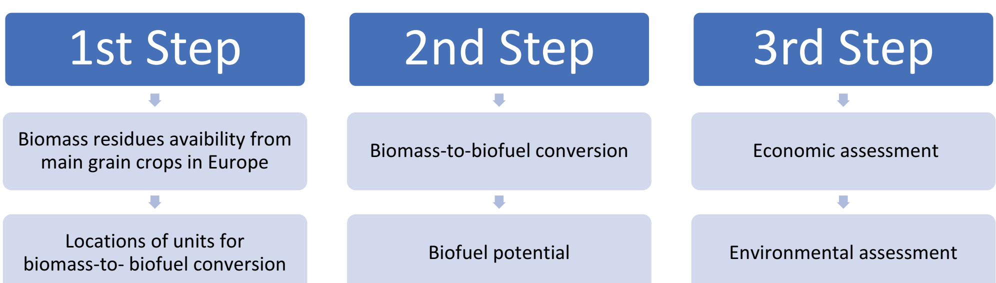

Figure 1. Methodology chart flow.

Table 1. Residue characterization [6,7].

Biomass Type	RPR	RAF	SRR	LHV (MJ/kg)
Maize Straw	1.53	100%	25%	18.67
Barley Straw	1.48	100%	50%	19.68
Wheat Straw	1.55	100%	15%	19.54

$$BPr = Yr * RPR.RAF.SRR \tag{1}$$

Where *BPr* is the biomass residue potential in tonnes per hectare (t/ha), Yr is the average commodity [11] productivity in tonnes per hectare (t/ha). RPR is the ratio of product residue (%), RAF is the residue availability factor (%), and SRR is the sustainable removal rate (%). Table 1 shows all the necessary data.

$$EPr = BPr * LHVr \tag{2}$$

Where *EPr* is the energy potential of the residue gigajoule per hectare (GJ/ha), *BPr* is biomass residue potential in tonnes per hectare (t/ha). *LHVr* (Table 1) is the low heat value of the residue (GJ/t).

$$THPr = EPr * n \tag{3}$$

Where *THPr* represents the theoretical potential residues based on the FT diesel of each commodity residue (GJ/ha), *EPr* is the energy potential of the residue (GJ/ha), and *n* is the conversion process efficiency in terms of biomass-based FT diesel production yields [8].

Equation 4 calculates the number of plants units that should be operating, per NUTS region.

$$Number\ of\ plants = harvested\ land/0,283 \tag{4}$$

Where harvested land is the area of each crop in million hectares (Mha) (Appendix A), and the factor 0.283 represents the conversion of 30-km radius in Mha.

Bio-FT diesel process

The FT process includes several steps, from the type of biomass chosen to the gasifier, and the target biofuel.

Gasification

The biomass gasification was calculated according to the straw compositions, and Equation 5 was assumed (wheat, barley, and maize straw compounds in Table 2). The

Table 2. Composition analysis of Barley, Wheat, and Maize straw.

Compounds	Barley straw [12]	Wheat straw [12]	Maize straw [13]
C	45.6	45.6	47.28
H	5.6	5.7	5.06
O	42.5	40	40.63
N	0.5	0.7	0.8
S	0.09	0.09	0.22
Ash	5.7	7.9	6
LHV	19.51	19.68	18.67

partial oxidation is made in 0.4 air/fuel ratio in the molar base (95% O_2 molar base) coming from an Air Separation Unit (ASU) with 4 megapascals (Mpa) of pressure and energy demand of 0.2 megawatt-hours per tonnes of oxygen (MWh/tO_2) [8].

$$CHONS + O_2 + N_2 + Ar = CO_{2a} + COb + H_2C + H_2Od + H_2Se + NH_3f + Arg \quad (5)$$

Gas cleaning

The water quench is capable to retain the total NH_3 and Slag [8,14,15].

Water-gas shift

The literature suggests that the ideal H_2:CO ratio to the FT diesel production must be 2:1. Thus the mass of water steam feeding the process is determined according to Equation 6 [13].

$$\dot{m}\ STM, addition = 3 * \dot{m}\ CO - \dot{m}\ H_2O \quad (6)$$

Where $\dot{m}STM$, addition is the inlet mass flow of steam in the water-gas shift (WGS) reactor in tonnes per hour (t/h), $\dot{m}CO$ is the CO content in the syngas in t/h and $\dot{m}H_2O$ is the water content in the syngas entering the WGS reactor. As suggested in the National Renewable Energy Laboratory (NREL) [13] a ratio of 3:1 H_2O to CO ensures enough water for the conversion.

Acid gas removal

The acid gases CO_2 and H_2S are considered 95% of removal and 100% respectively through the solvent selexol in a ratio of 54 tonnes of solvent per tonnes of CO_2 (tsolv/ $toCO_2$) coming from the syngas 2 stream. All sulphur content in the process was assumed to be sent to a CLAUS plant to transform all H_2S into elemental sulphur to be commercialised as a by-product.

Fischer-Tropsch

The Fischer-Tropsch step will receive the syngas 3 after the acid gas removal process, using as a model the fixed bed reactor and the cobalt catalyser with temperature and pressure established at 200ºC and 2500 Kilopascal (KPa) respectively [8,13,14,16].

Pressure swing adsorption

Pressure swing adsorption (PSA) is used to separate the surplus H_2 to be used in the hydrocracking process [8]. The high hydrogen purity (99.9% v/v) can be obtained in a cyclic process of solid adsorbent, which removes the impurities coming from the syngas [17].

Upgrading process

The range of hydrocarbons (C1-C4 and C20-C30) formed in the FT process must be separated [10,18]. The distillation and hydrocracking are done based on Schmidt [10], data with Microsoft Excel support. The first step assumed the total separation of the products formed (C1-C4, C20-C30) from the non-converted gases (CO_2, H_2O, CO, and AR), and the hydrocarbons formed (liquefied petroleum gas (LPG), naphtha, diesel and, gasoil) are sent to the upgrading stages.

Distillation

In this process, all the hydrocarbons are separated according to their composition on FT products formed (Equation 7).

$$Products\,(LPG, Naphtha, Diesel, Gasoil)(t/h) = FT\,products\,(t/h) * hydro.\,ratio\,yield \quad (7)$$

Hydrocracking

The hydrocracking is modelled, using as the base the mass flow of gasoil leaving the distillation process. The yield is based on data from the Schmidt studies [10,19], following the yield product formation in the table and Equation 8

$$Mass\,prod.\,flow = Yield\,ratio * Gasoil\,in\,(t/h) \quad (8)$$

Where the mass prod. flow is the product formed during the hydrocracking process in t/h, the yield ratio is in Table 3 and the gasoil is the gasoil that leaves the distillation process in t/h.

The H_2 demand in the hydrocracking process is established at 0.34 tH_2/toil based on the typical demand of 53 cubic metres per barrel (m^3/bbl) mentioned in the literature [10,19]. The LPG, naphtha, diesel, and gasoil are sent to their respective storage.

Power demand

For the power demand, several different works are considered to calculate the energy consumption to maintain the process (Equation 9).

$$Power\,demand\,(MW) = Reference\,demand\,(MW) * SS/SR \quad (9)$$

Where Power is calculated in megawatt (MW), the reference demand is the power demand taken from the literature, SS is the scale of simulation and SR is the scale of reference from literature (Table 4).

Table 3. Distillation yield [10].

Products	Yield ratio
GLP	0.02
Naphtha	0.20
Diesel	0.62
Gasoil	0.15

Table 4. Energy demand references.

Energy demand	Demand of reference	Scale of reference	Reference
Pre-treatment	3.5 MW	2220 t/d	[8,13]
ASU		0.20 MWh/tO2 (95%)	[15,20,21]
Gasifier	6.6 MW	4310.40 t/d	[10]
Sulphur removing	1.8 MW	1.44 t/d	[22]
FT	1.65 MW	427 t FT/d	[10,13]
HCC	2.24 MW	427 t FT/d	[10,13]

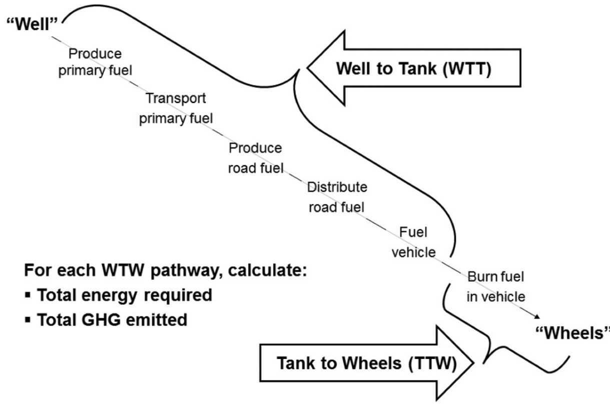

Figure 2. Well-to-wheels approach [23].

GHG assessment

A well-to-wheel (WTW) analysis (Figure 2) serves as an important tool for measuring the carbon emissions from all steps, from biomass harvesting to fuel burning in the ship engines [23]. The present study will be limited to a well-to-tank analysis (WTT). Figure 2 shows the steps of the methodology.

Fertiliser compensation

Table 5 shows the nitrogen (N), phosphorus (P), and Potassium (K) in each tonne of straw, which must be compensated with mineral fertiliser, based on the calculation of the carbon dioxide equivalent (CO_2eq) of this stage.

Equation 10 below calculates the number of nutrients necessary to make up their removal for the FT process.

$$Fertiliser\left({}^{t}\!/_{year}\right) = \frac{Straw\ removal\left({}^{t}\!/_{year}\right) * Mineral\ compounds\left({}^{kg}\!/_{t}\right)}{1000} \tag{10}$$

Where Fertiliser is the number of mineral nutrients in tonnes per year (t/year), straw removal is the biomass removed from the ground to be processed in the industry in t/year, and mineral compounds are the nutrients in kilograms per tonnes (kg/t) available in Table 5. It was assumed that all nutrients removed must return to the soil through mineral fertilisation.

Table 6 below shows the data needed to calculate the carbon emissions related to fertiliser production and the fertilisation data for carbon emissions.

Table 5. Nutrients per tonne of straw.

Compounds	N	P	K	Reference
Wheat (kg/straw)	7.35	1.09	9.35	[24]
Barley (kg/straw)	5.81	0.73	14.98	[24]
Maize (kg/straw)	7.72	1.82	15.44	[25]

Table 6. CO_2eq of fertiliser production.

Compounds	N	P	K	Reference
Fertizer emission (kgCO_2eq/kg)	14.09	2,36	0,6	[26]
Fertilising (kgCO_2eq/ha)	65.21			[27]

Using Equation 11 below plus the data available in Table 6, it is possible to calculate the carbon emissions from fertiliser production and their fertilisation on the respective lands.

$$Fertilizing\left({}^{tCO_2eq}/_{year}\right) = Harvested\ area * emissions \tag{11}$$

Where Fertilising is the CO_2 emissions in tonnes per year associated with the manuring process, Harvested is the collected biomass area (Area available in Appendix A) in hectares per year (ha/year), and emissions are the released greenhouse gases associated with mineral inputs accumulated over the lands annually in tonnes of CO_2eq per hectare (tCO_2eq/ha).

Harvesting, baling, and transportation of straw

Table 7 shows the data regarding the activity data from the process to harvest, baling, and transporting the biomass straw from the field to the projected plant within a 30 km radius.

Equation 12 calculates the CO_2 emissions from biomass collection.

$$Emissions = Fuel\ consumption * biomass\ collected * emission\ factor \tag{12}$$

Where Emissions are the CO_2eq in t/year, Fuel consumption is the diesel in the collection of the biomass in kg of diesel per tonnes of biomass, the biomass collected is in t/year, and the emission factor in kgCO_2/kgdiesel is given in Table 8.

Industry process

To calculate the power demand of the industry, we considered the CO_2eq emitted in each country, related to the different energy matrices for each European country.

Equation 13 is used to calculate the CO_2eq.

$$Industry\ emissions = Power\ demand * emission\ factor \tag{13}$$

Table 7. Emission factors of biomass collection activity.

Activity data	Maize straw	Wheat straw	Barley straw	Reference
Harvesting kgdiesel/tbiomass	0.36	1.20	1.20	[28]
Bales loading kgdiesel/tbiomass	0.31	0.58	0.58	
transportation kgdiesel/tbiomass.km	0.01	0.01	0.01	

Table 8. Emission factor of 1 kg of diesel [29].

Compounds	Kg	GWP
CO_2	3.164	1
CH_4	0.0003	28
N_2O	0.04199	265

Table 9. Truck emissions factor data [29].

Truck 33t capacity	Factor $kgCO_2$/t.km	Factor $kgCH_4$/t.km	Factor kgN_2O/t.km
	0.07111	0.00001	0.00101

Where Industry emissions are CO_2 per hour (CO_2eq/h), the power demand in MW, and the emission factor in kilograms of CO_2 $kgCO_2$eq/MWh.

Port distribution

The CO_2eq calculation for the Bio-FT-Diesel distribution to the countries' ports was performed following Equation 14, assuming a 33t loaded truck with 20t of fuel transportation per trip. Table 9 shows the factor emissions regarding transportation.

$$\mathit{Distribution\ Emissions} = (\text{Diesel production}/20)*33 * \text{Distance} * \text{Emission Factor} \tag{14}$$

The emissions are presented as tCO_2eq per year, the 20 represents the t of fuel transported per trip in t, 33 represents the total weight of the truck in t, and distance represents the km travelled per trip from the region of production to the port of distribution.

Total investment cost

The method selected for the cost curve (Equation 15) uses the exponential factor 0.7, and this factor is the average used for processes in chemical plants [30]. (See Table C1 in appendix C to Investment Cost Calculations)

$$C = Cbase\left(\frac{S}{Sbase}\right)^{f} \tag{15}$$

C = Investment Cost of Equipment (M€)
Cbase = Known Investment Cost Equipment (M€)
S = Equipment Capacity (MWth)
Sbase = Known Equipment Capacity (MWth)
f = Scale Factor

Equation 16 shows the Chemical Cost Index Correlation rate with the respective years of other work. The calculation of this factor is expressed in (16) by:

$$CB = CA * \frac{Index\ Value\ B}{Index\ Value\ A} \tag{16}$$

Where:
CB = Current Cost (M€)
CA = Older Cost (M€)
Index Value B = CEPCI (Chemical Engineering Plant Cost Index) updated (Dimensionless)
Index Value A = CEPCI Respective year (Dimensionless)

Table 10 describes the steps to quantify the total capital investment cost, adding the Total Installed Costs considered to be 1.50 of the total purchase equipment cost (C)

Table 10. Total capital investment cost.

Total Installed Cost (TIC)	TIC = 1.50*TPEC
Contingency Costs (CC)	CC = 0.20*TIC
Fixed Capital Costs (FCI)	FCI = TIC+CC
Working Capital (WC)	WC = 0.10*FCI
Total Capital Investment	TCI = FCI+WC

Table 11. Adjustment costs.

Parameters	Value	Reference
Current Interest Rate (IR) (%)	−0.509	[33]
Biomass Cost (€/tonnes)		
Wheat Straw	59.00	[34]
Barley Straw	65.00	[34]
Maize Straw	36.40	[35]
Electricity ((€/MWh)	118-222	[32]
Bio – LPG (€/tonnes)	1160.00	[32]
Bio – Naphtha (€/tonnes)	780.00	[36]
Bio – Gas oil (€/tonnes)	880.00	[37]
Bio-FT-Diesel (€/tonnes)	1040.00	[37]
Hydrogen (€/tonnes)	1500.00	[38]
Sulphur (€/tonnes)	36.40	[39]

[8,31], a contingency cost of 20%, and working capital of 10% [8]. The operation and maintenance (O&M) cost was established at 4% of the total TCI [8].

Table 11 shows the data used to quantify the respective biomass, electricity, the current interest rate, and the revenues that come from the bio-FT diesel and its by-products. The electricity cost will calculate differently according to the respective countries [32]

Levelized cost

The Levelized Cost of the bio-FT diesel will be determined according to Equation 17 and Equation 18.

$$CRF = r/(1-(1+r)^{-L} \tag{17}$$

Where CRF is the capital recovery factor based on the 0.14 IR, r is the interest rate, and L is the lifespan of the factory (20 years).

$$LCOE = (CRF * TCI) + (O\&M + Biomass + Electricity - subproduct)/(FTDiesel) \tag{18}$$

Where LCOE is the Levelized Cost of the bio-FT diesel €/GJ, CRF is the capital recovery factor %, TCI is the total capital investment in millions of euros (M€), O&M is the operation and maintenance M€, annual biomass cost in M€, the electricity in M€, the by-products in M€, and annual bio-FT diesel in Gigajoule per year (GJ/year), all those values based on 8000 hours of work per year and a life span of 20 years.

Table 12 displays the conversion rates considered in this work, and the rates were based on the rates of May 2021.

Table 12. Currency conversion rates.

Conversion		Reference
Pounds	Euro	[40]
1	1.00	
Dollar	Euro	
1	0.98	

Results

Limitation of explored areas

The applied limitation area of 30 km of radius (0.283 Mha) could provide a total primary of 1.251 petajoules (PJ) (Figure 3). The wheat straw represents 66.83% of the technical energy potential (TEP).

Wheat straw technical potential

The results from wheat straw are limited to the exploitation of the biomass resource (Figure 4) in 9 countries, and 28 sub-regions delimited by the Nomenclature of

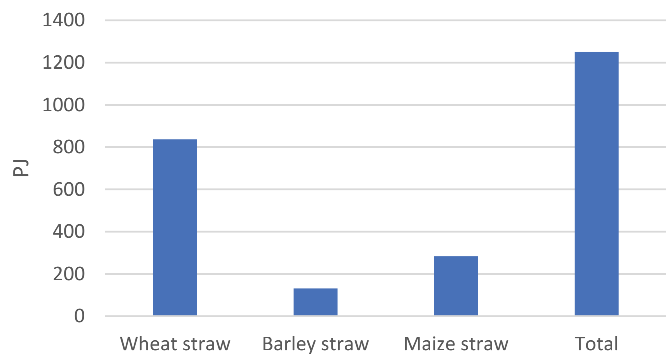

Figure 3. Technical energy potential.

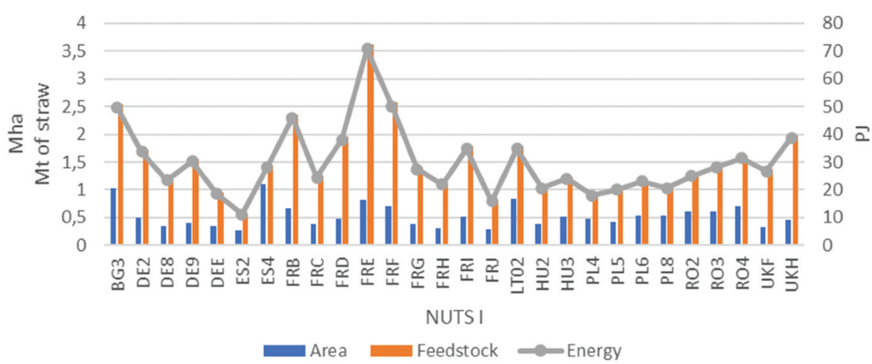

Figure 4. Wheat straw potential per NUTS I.

Territorial Units for Statistics (NUTS 1), with a total of 42.80 Mt of wheat straw available and 836.35 PJ. France alone represents 40% of the total.

Barley straw technical potential

The barley straw is limited to 4 countries and 6 sub-regions (NUTS 1) (Figure 5) to process a total of 6.68 Mt of straw and 131.47 PJ. Spain alone represents 40% of the total.

Maize straw technical potential

The maize straw is limited to 4 countries and 8 sub-regions (NUTS 1) to process a total of 15.19 Mt of straw annually (Figure 6). Romania alone accounts for 53% of the total (150 PJ).

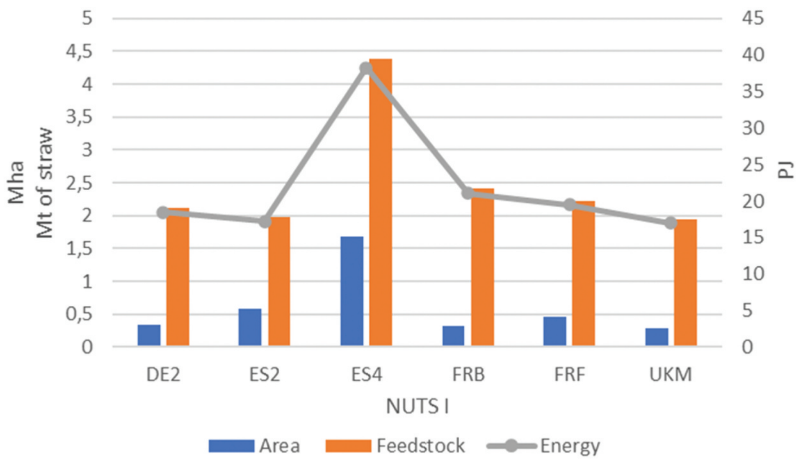

Figure 5. Barley straw potential per NUTS.

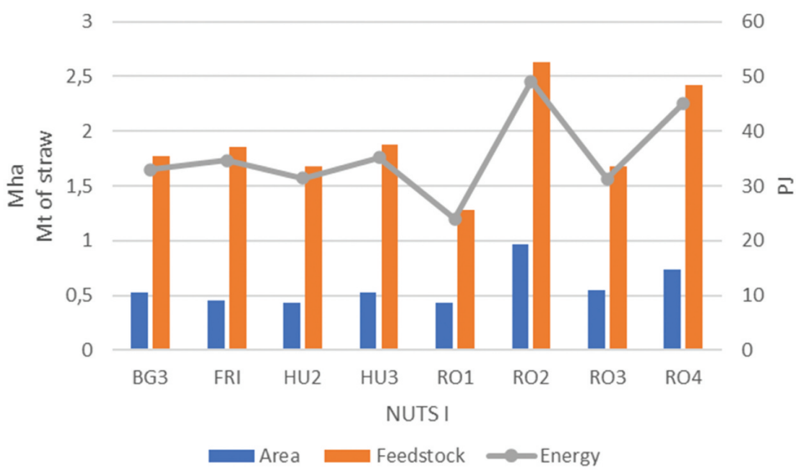

Figure 6. Maize straw potential per NUTS I.

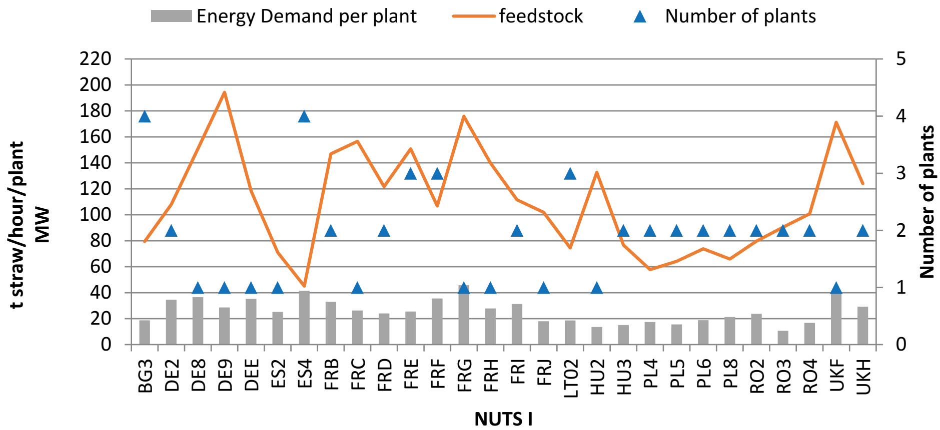

Figure 7. Barley straw potential per NUTS.

Industry processing

The following sections display the results regarding the number of plants and hourly capacity in the respective NUTS I regions.

Wheat straw bio-based industry

According to the calculations (Figure 7), 53 bio-based potential industries can be built in those regions, with a total biomass process capacity of 42.80 Mt/year and diesel and gasoil production of 3.72 Mt/year (Figure 8) with an average energy demand per industry of 26.04 MW.

Barley straw biobased industry

Thirteen barley straw bio-based industries can be built in four countries (Figure 9) with a biomass processing of 6.68 Mt/year and producing 0.5 Mt of bio-FT diesel annually (Figure 10) with an average power demand of 19.85 MW.

Maize straw

A total of 18 bio-based industries could process 15.20 Mt/year of biomass (Figure 11) and annually deliver 1.3 Mt of bio-FT diesel (Figure 12) with an average energy demand of 29.45 MW.

Biofuel transportation

Within the potential regions of the study, the biofuel could be delivered inside the respective ports (12 potential ports). Figures 13–15 regarding the wheat, barley, and maize straw respectively show the regions and the distance from the points of production to the ports of their potential use by ships.

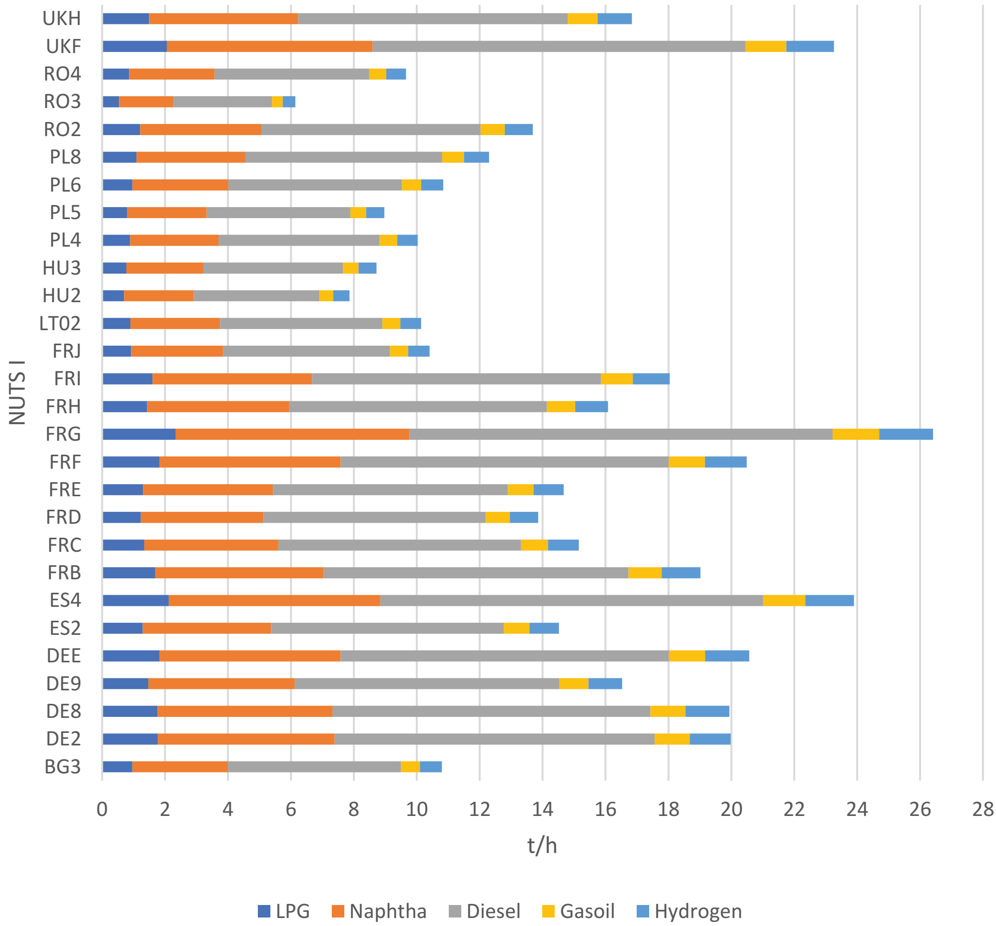

Figure 8. Bio-based wheat industry, output.

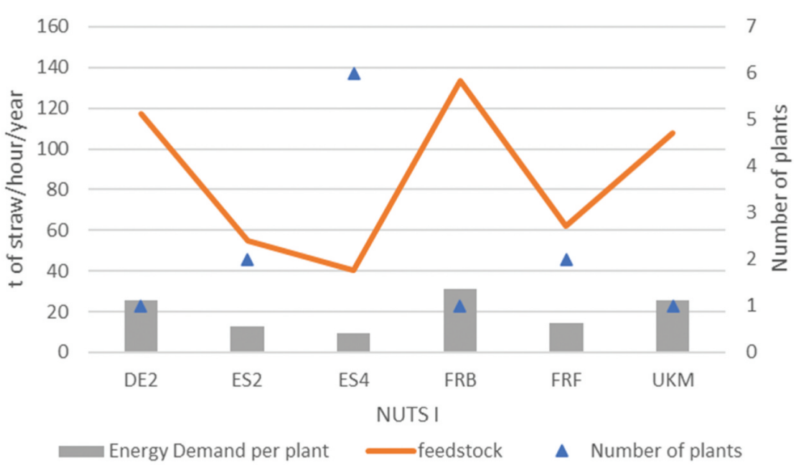

Figure 9. Bio-based barley industry, output.

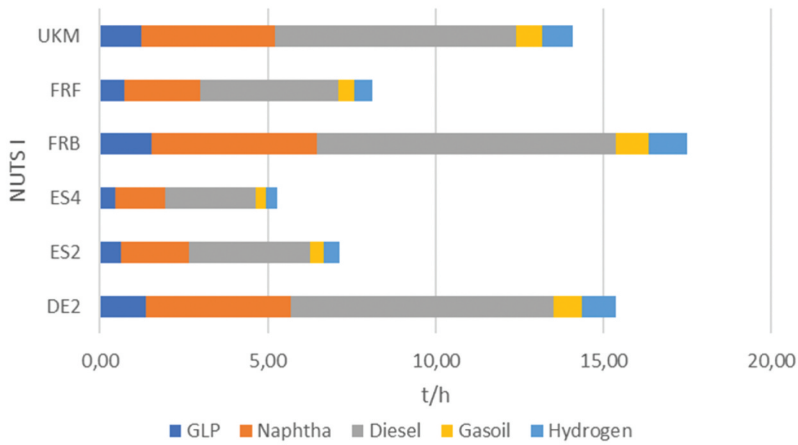

Figure 10. Bio-based barley industry output.

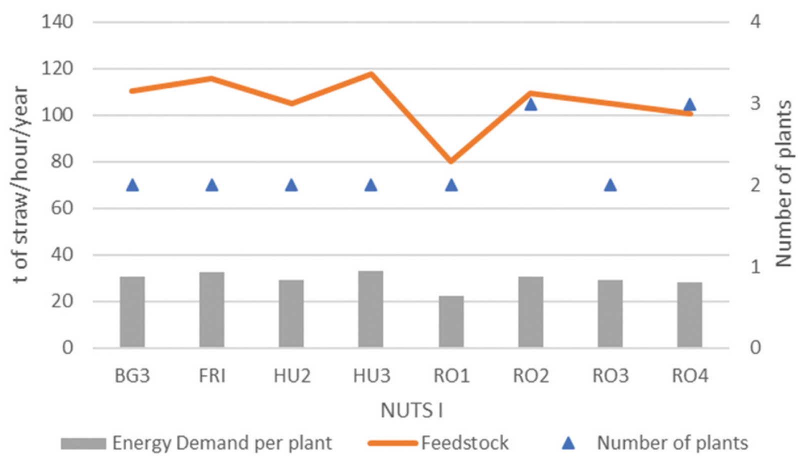

Figure 11. Bio-based maize industry, output.

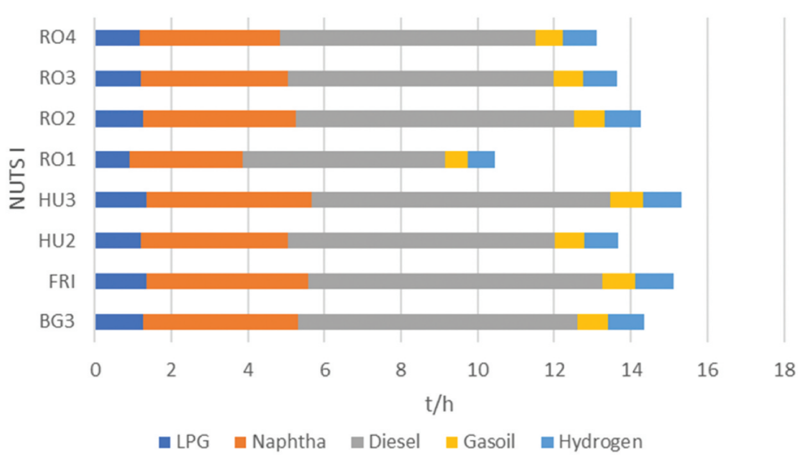

Figure 12. Biobased maize industry output.

Final location	Port of Varna	Port of Hamburg				Port of Barcelona	Port of Valencia	Port of Rijeka		Port of Klaipėda
km	307	786	121	147	238	321	562	412	584	326
City	Pleven	Munique	Schwerin	Hanover	Magdeburgo	Saragoça	Valladolid	Pécs	Szeged	Vilnius
NUTS I	BG3	DE2	DE8	DE9	DEE	ES2	ES4	HU2	HU3	LT02
Country	Bulgaria	Germany				Spain		Hungary		Lithuania
Final location	Port of Dunkirk					Port of Le Havre		Port of Marseilhe		
km	425	534	231	143	324	378	295	409	661	
City	Orleães	Dijon	Ruão	Amiens	Châlons en Champagne	Nantes	Rennes	Bordeux	Tolouse	
NUTS I	FRB	FRC	FRD	FRE	FRF	FRG	FRH	FRI	FRJ	
Country	France									
Final location	Port of Gdańsk				Port of Constanta			Port of Immingham		
km	292	444	182	524	217	275	511	145	210	
City	Poznan	Breslávia	Bydgoszcz	Lublin	Galati	Ploiesti	Craiova	Leicester	Norwich	
NUTS I	PL4	PL5	PL6	PL8	RO2	RO3	RO4	UKF	UKH	
Country	Poland				Romania			United Kingdom		

Figure 13. Distribution of Wheat straw bio-FT diesel from NUTS I to the ports.

Final location	Port of Hamburg	Port of Barcelona	Port of valencia	Port of Dunkirk		Port of Immingham
km	786	321	562	425	459	418
City	Munique	Saragoça	Valladolid	Orleães	Grand Est	Edinburgh
NUTS I	DE2	ES2	ES4	FRB	FRF	UKM
Country	Germany	Spain		France		UK

Figure 14. Distribution of Barley straw bio-FT diesel from NUTS I to the ports.

Final location	Port of Varna	Port of Le Havre	Port of Rijeka		Port of Constanta			
km	307	661	412	767	656	209	275	511
City	Pleven	Bordéus	Pécs	Debrecen	Cluj-Napoca	Galati	Ploiesti	Craiova
NUTS I	BG3	FRI	HU2	HU3	RO1	RO2	RO3	RO4
Country	Bulgaria	France	Hungary		Romania			

Figure 15. Distribution of Maize straw bio-FT diesel from NUTS I to the ports.

Activity data and emissions factors

The indirect fertiliser use represented the most carbon-intensive sector, followed by the industry, harvest/bale/transportation, and distribution to the respective ports defined in the previous section.

There is high carbon emission in ES4 (Spain) and BG3 (Bulgaria) regions with 51.73 and 46.50 gCO_2eq/MJ of marine diesel produced (Figure 16) respectively, because of the higher areas of land which impact the fertiliser compensation (65 kgCO_2eq/ha) (Appendix A) and the lowest value was found in the FRH (France) region with 12.85 gCO_2eq/MJ. In terms of industry, the highest carbon emitter is Poland, because of its use of its coal for energy, which corresponds to 73% of the electricity production. The lowest emissions were in France, because of the high share of nuclear energy.

Regarding the results of the barley straw bio-FT diesel, Figure 17 displays the results found in 4 countries and 6 NUTS I regions. The ES4 (Spain) region has the highest emissions with 73.59 grammes of CO_2eq per megajoule (gCO_2eq/MJ) of bio-FT diesel

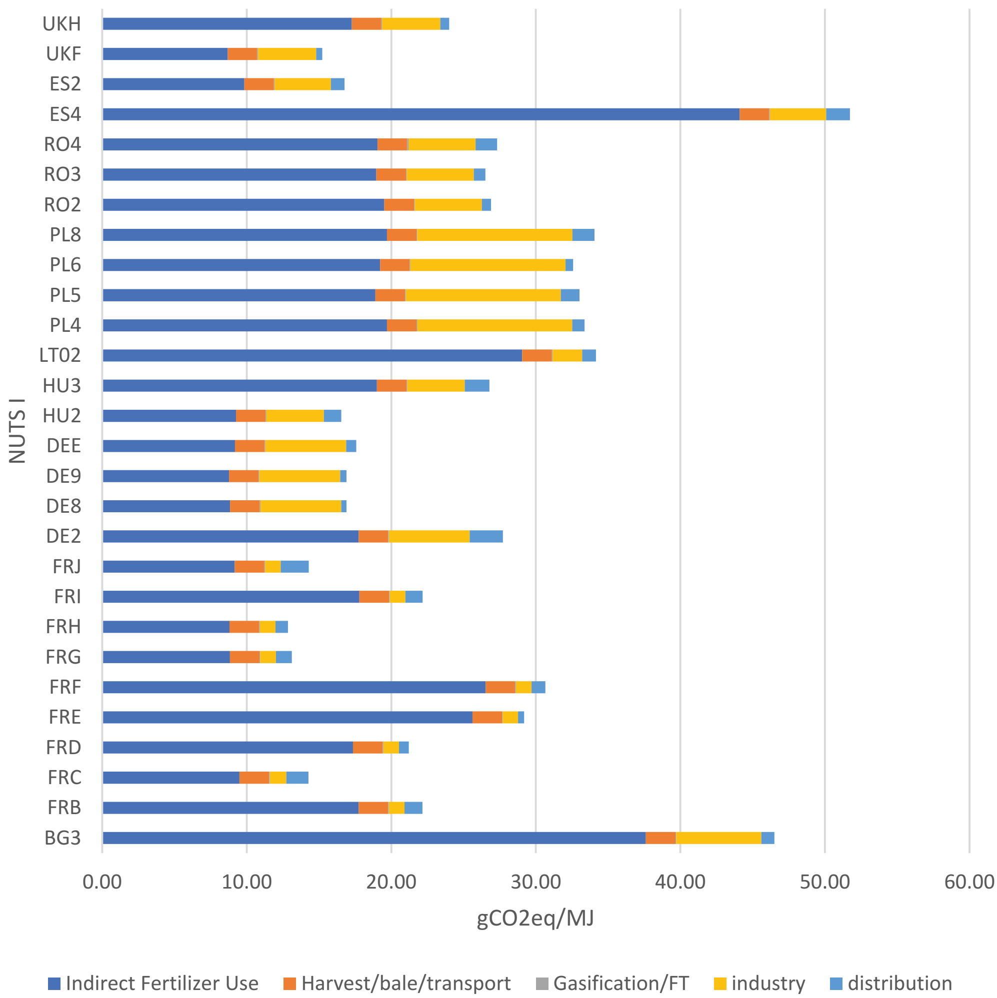

Figure 16. Carbon emissions composition of Wheat Straw bio-FT diesel.

production because of the low productivity of straw, where the high value of land exploited contributes to high emissions from the fertiliser compensation. The FRB (France) region, represents the lowest contribution with 15.29 gCO_2eq/MJ of diesel produced, influenced by the high productivity of its crops.

In the bio-FT diesel from maize straw (Figure 18), the results were similar in almost all NUTS I regions, with the RO2 and RO4 regions in Romania, representing the highest factors of 38.37 and 38.36 gCO_2eq/MJ of diesel produced, respectively. The FRI region in France had the lowest with 23.80 gCO_2eq/MJ.

The highest value found in RO4 and RO2 is because of the high area of land to compensate for the fertiliser use and the high carbon emissions in Romania's power production [41,42].

The carbon emissions showed different numbers in all scenarios, resulting from the high influence of the area of land explored, which affected the installed capacity and the fertiliser used to compensate for the organic material lost through the harvest process.

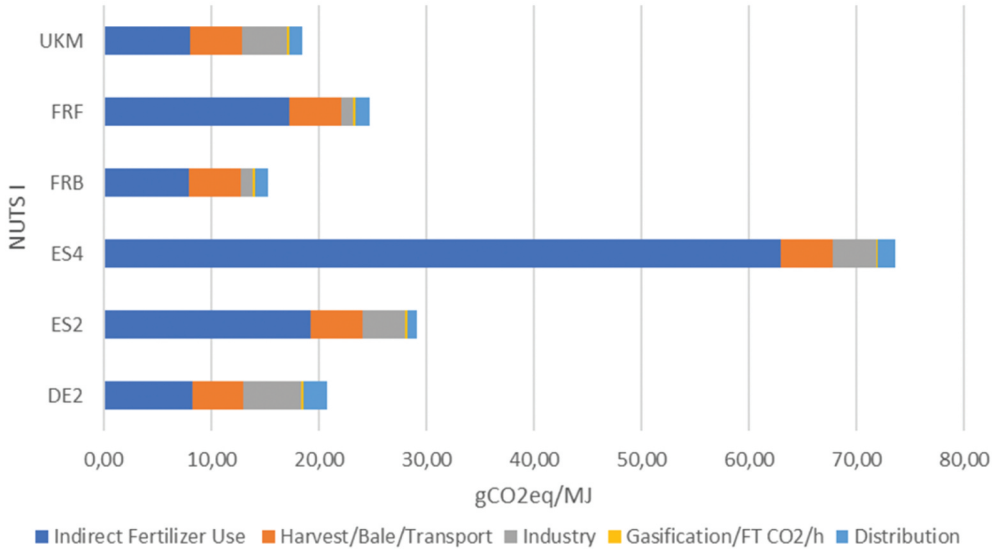

Figure 17. Carbon emissions composition of Barley Straw bio-FT diesel.

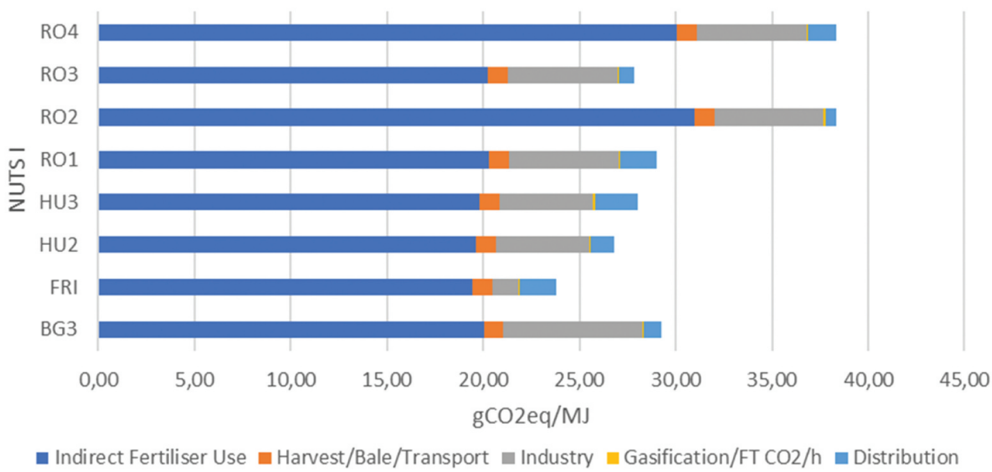

Figure 18. Carbon emissions composition of Maize Straw bio-FT diesel.

Spain and Bulgaria showed up as the two highest polluters and France and Germany with the lowest values (Figure 19).

Economic results

The LCOE presented high costs in all scenarios of straw exploration (wheat, barley, and maize) with a current IR of –0.509%. Figure 20 below displays the average percentage of each component that comprises the total LCOE in each bio-FT diesel production.

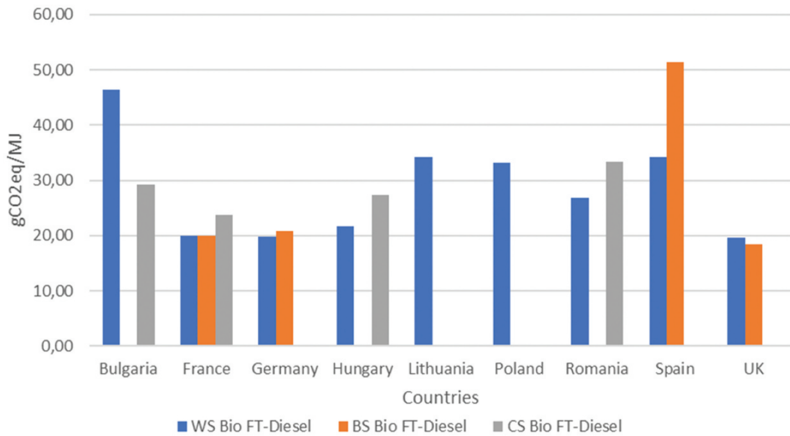

Figure 19. Total absolute carbon emissions per country.

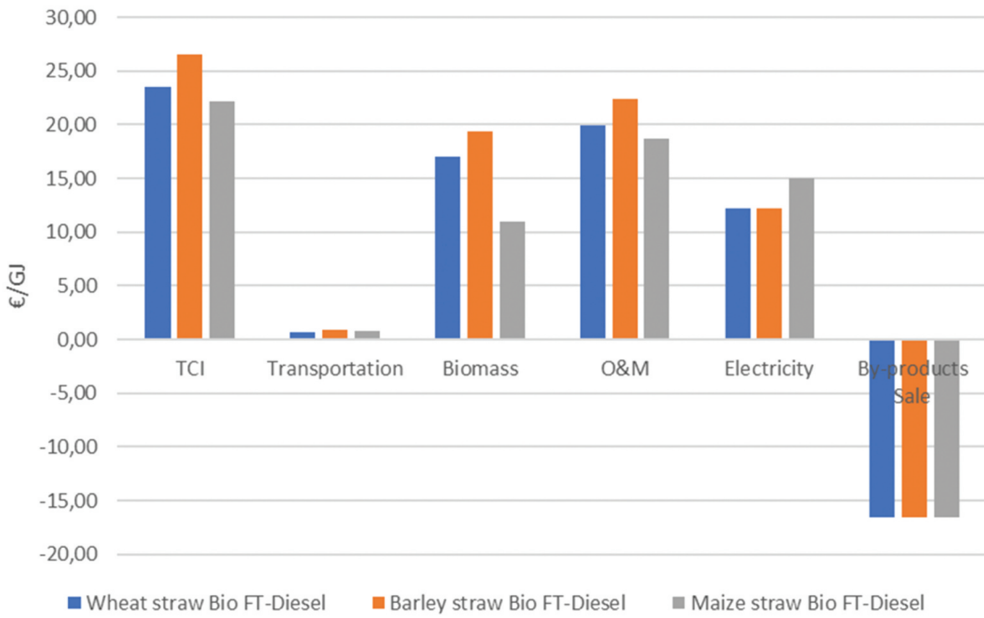

Figure 20. Average percentage of composition cost.

The highest average LCOE was in barley straw, followed by wheat straw and maize. This difference results from the efficiency of bio-FT diesel production of each feedstock (17.77% for wheat, 16.95% for barley, and 17.78% for maize).

Considering all the NUTs I region for wheat straw bio-FT diesel, Figure 21 shows the results. The average LCOE was 56.70 euros per gigajoule (€/GJ) produced with the highest cost (67.22 €/GJ) in the ES4 region and the lowest (45.80 €/GJ) in the UKF region. The TCI influenced the high or low costs of both regions.

The difference between the wheat straw bio-FT diesel and the current fossil fuel options (Figure 22) is 42.82 €/GJ compared with the cheapest fossil fuel (IFO 380).

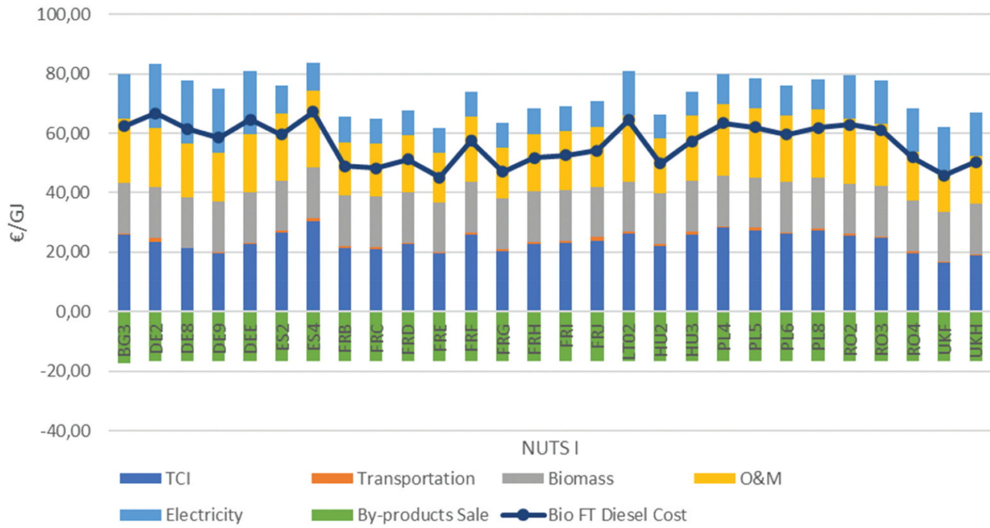

Figure 21. LCOE composition costs wheat straw bio-FT diesel.

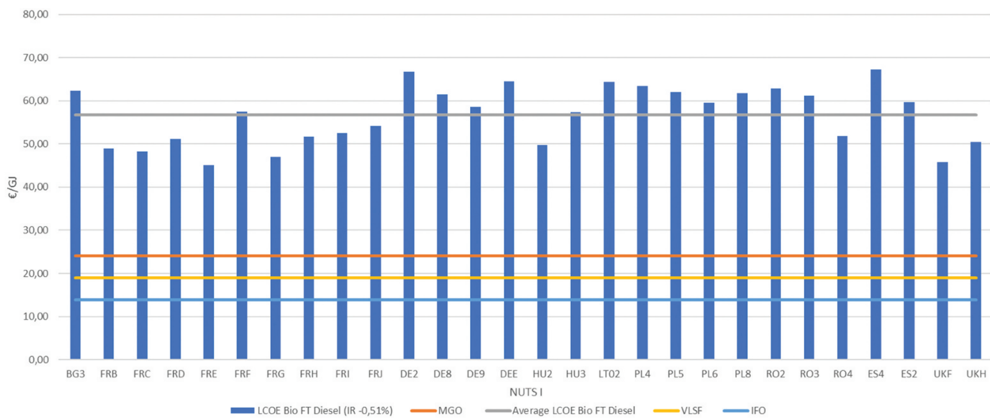

Figure 22. LCOE of Wheat straw Bio-FT-diesel.

Figure 23 illustrates the composition cost results of the barley straw bio-FT diesel production. The ES4 region presents the most expensive LCOE (74.15 €/GJ) influenced by the TCI. The FRB region accounted for the lowest LCOE (54.64 €/GJ). The average cost found was 64.75 €/GJ (Figure 24), being 50.87 €/GJ more expensive than the IFO 380.

Figure 25 shows the results regarding the LCOE from maize straw bio-FT diesel. The highest cost was found in the RO1 region (57.89 €/GJ) and the lowest in the HU3 region (44.93 €/GJ). Comparing the average (51.16 €/GJ) LCOE (Figure 26) there was also a huge difference between the current fossil sources and the renewable fuel projected in this work.

All scenarios using the respective feedstocks showed an unfeasibility of the bio-FT diesel use compared either to the conventional fossil fuel sources or the lowcarbon

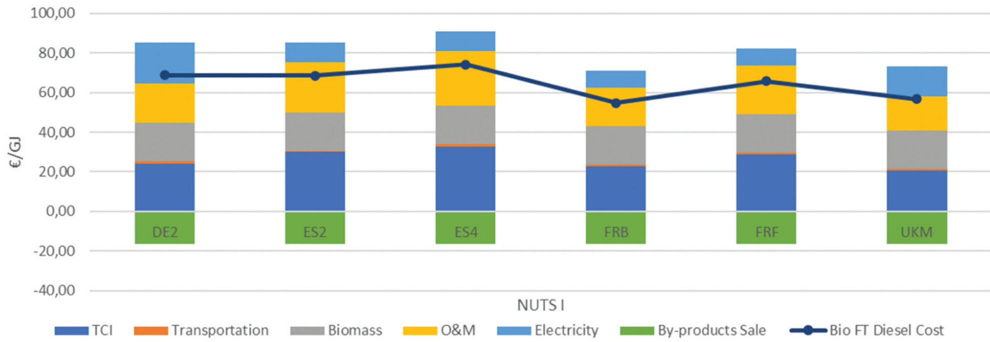

Figure 23. LCOE composition costs barley straw bio-FT diesel.

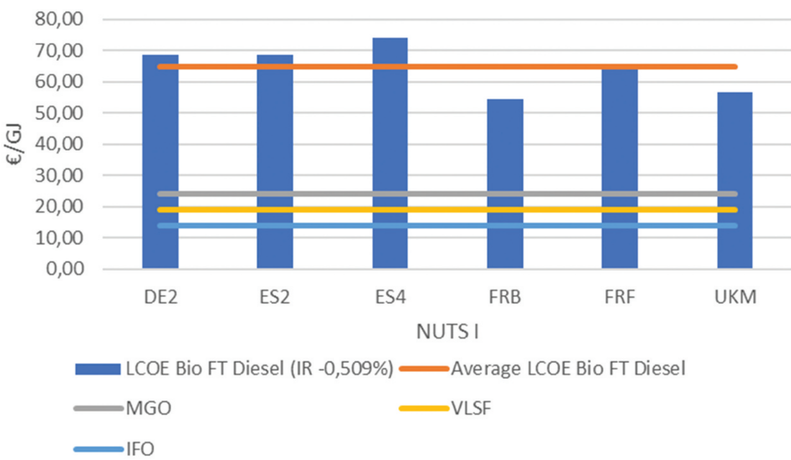

Figure 24. LCOE of barley straw Bio-FT-diesel.

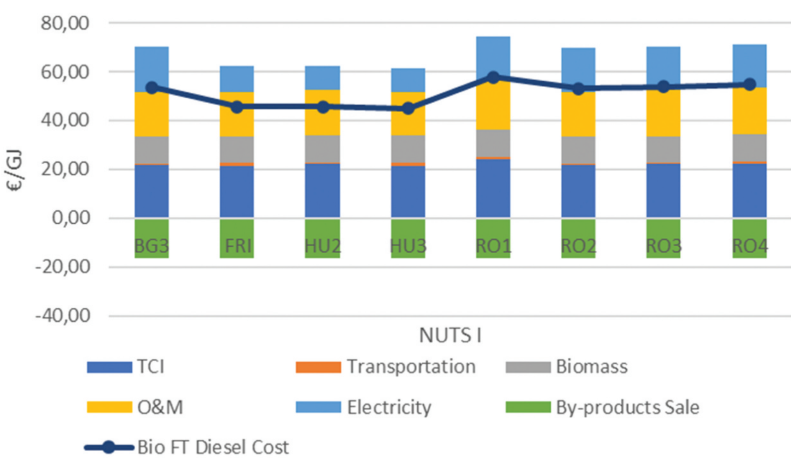

Figure 25. LCOE composition cost of maize straw bio-FT diesel.

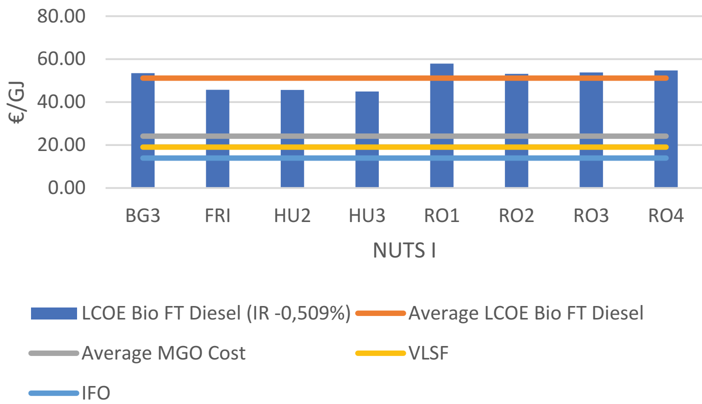

Figure 26. LCOE of maize straw bio-FT diesel.

alternatives. The advantage of the bio-FT diesel is its similarity to the current fuel used, which requires no need to modify engines and allows the same infrastructure of distribution at the ports.

Sensitivity analysis

To understand the variation of the bio-FT diesel costs in different scenarios, a sensitivity analysis was conducted with the variables: 1) Interest Rate; 2) Biomass Cost; 3) By-product costs; 4) Electricity cost; 5) Carbon credits. All the calculations were done supported by Microsoft Excel.

IR variation. The LCOE in the 3 crops processed (Figure 27) presented a variation between 53.20 and 90.57 €/GJ. In all scenarios, the cost increased significantly as the IR rises where the rates were established between −2% and 8%. The interest rate was established at an average cost of all regions concerning their feedstock processed.

Biomass cost variation. Figure 28 shows the LCOE for the 3 crops with a variation in the biomass cost, setting the IR at 0.509% p.a.

By-product cost variation. The by-product prices (LPG, naphtha, hydrogen, and sulphur) were varied in a range between −25% and 100% to determine the LCOE oscillation. Figure 29 shows all data. For all regions established I.R. was set at −0.509% per year.

Electricity cost variation. Figure 30 shows the LCOE for the bio-FTdiesel in all crops, with variations in the electricity altered in a range of −25% to 100% of the current cost and the I.R. −0.509%.

Avoided carbon emissions

The results for all feedstocks used (wheat, barley, and maize straw) have shown up positive for their hypothetical exploitation in terms of tCO_2eq saved. Assuming the quantity of fossil diesel used is the same as the projected advanced bio-FT diesel, the

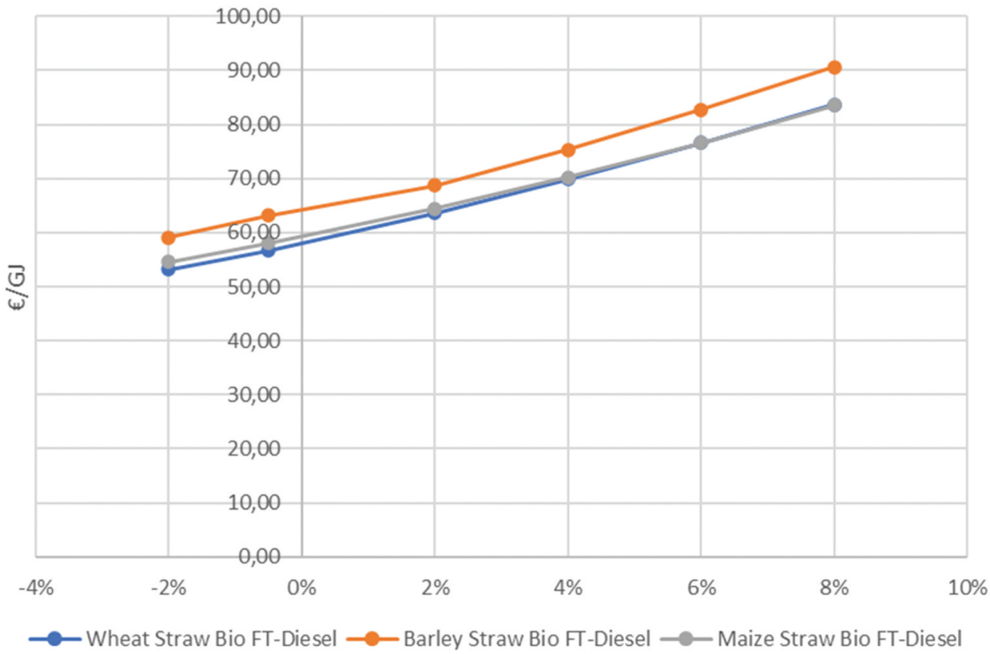

Figure 27. LCOE with I.R. variation.

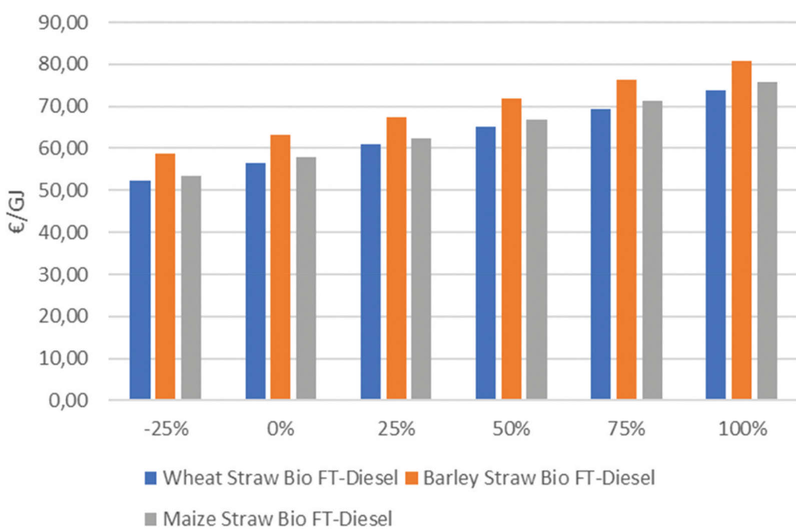

Figure 28. Biomass cost variation.

avoided carbon for the wheat, barley, and maize straw Bio-FT-Diesel would be 9.36, 1.18, and 1.16 $MtCO_2eq$/year, respectively, with a total of 11.59 $MtCO_2eq$/year.

Figures 31–33 display the results of CO_2eq saved by region for all bio-FT diesel.

Figure 34 highlights the cost of the CO_2eq saved using wheat straw bio-FT diesel with an average cost of 529,91 euros per tonnes of CO_2eq (€/tCO_2eq) saved. The ES4 region

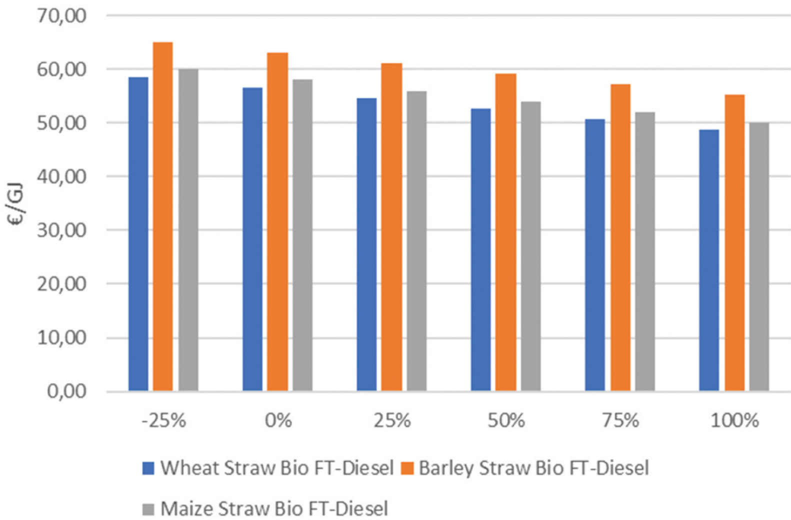

Figure 29. By-products cost variation.

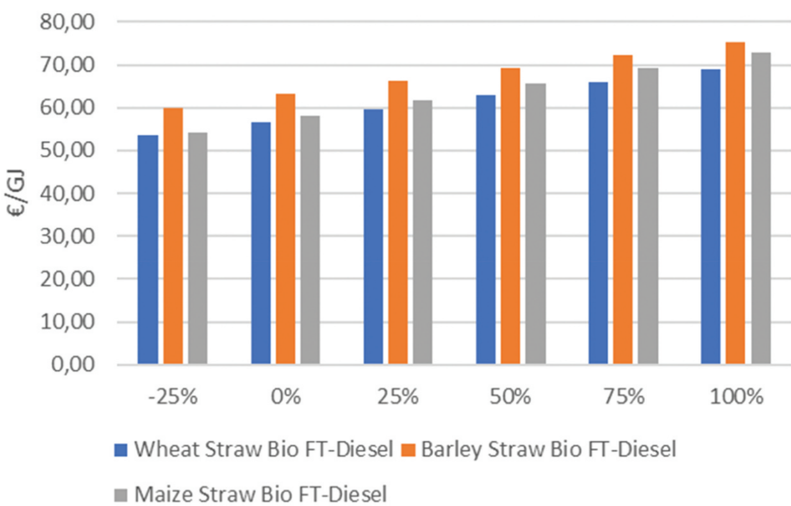

Figure 30. Electricity cost variation.

would account for the most expensive CO_2eq saved. Since the region had the highest carbon footprint (51.73 gCO_2eq/MJ) and the highest LCOE (67.23 €/GJ).

Figure 35 shows the results regarding the barley straw bio-FT diesel CO_2eq cost. The average cost of the carbon saved was 968.13 €/tCO_2eq. Again, the ES4 region presents the most expensive results (3034.19 €/tCO_2eq) influenced by the high LCOE (72.49 €/GJ) and the region's high carbon footprint (73.59 gCO_2eq/MJ).

The results from the maize straw bio-FT diesel (Figure 36) had an average cost of 591.97 €/tCO_2eq saved. The results have shown lesser variation than the other sources because of LCOE and carbon footprint. The RO4 region had the highest cost (731.66

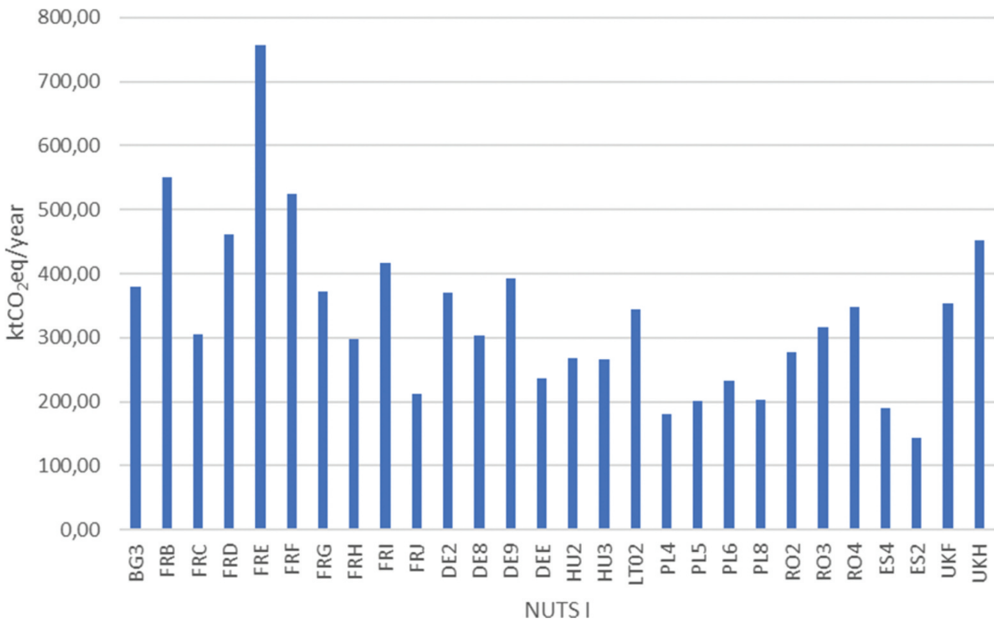

Figure 31. Wheat straw bio-FT diesel avoided CO_2eq.

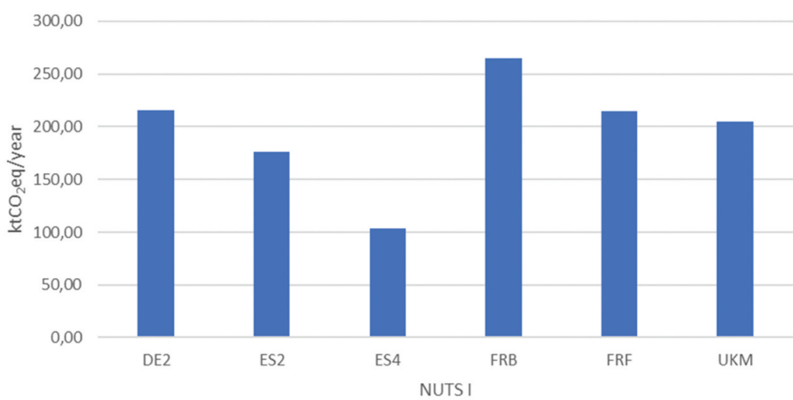

Figure 32. Barley straw bio-FT diesel avoided CO_2eq.

€/tCO_2eq). Those results are influenced by the highest carbon footprint (38.37 gCO_2eq/MJ).

The maritime sector is a long way from its ambitious goal of fifty per cent reduction compared to 2008 levels, but biofuels will play an important part in decarbonisation. Figure 37 shows that the use of bio-FT diesel in the shipping sector in Europe would reduce the CO_2eq emissions by 8.40%, by replacing about 40Mt of fossil fuel currently being used, accounting for 138 MtCO_2eq.

The company MSC cruises have presented an interesting action plan which will have zero negative impacts on its operation. Several measures are already in place in its fleet, such as energy efficiency through the ships' design, filters to avoid SOx and NOx

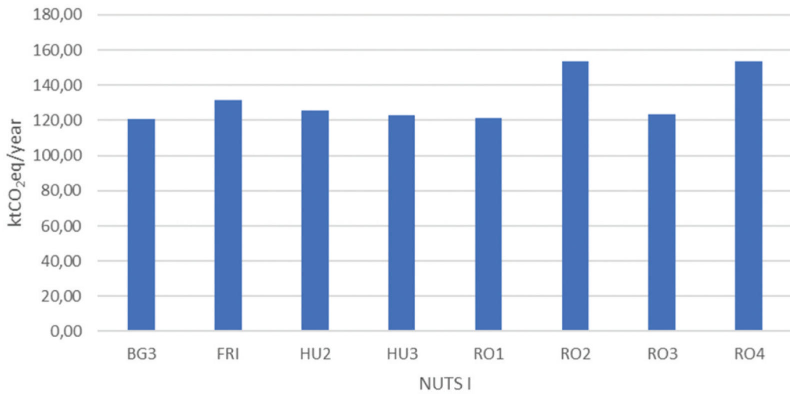

Figure 33. Maize straw bio-FT diesel CO_2eq avoided emissions.

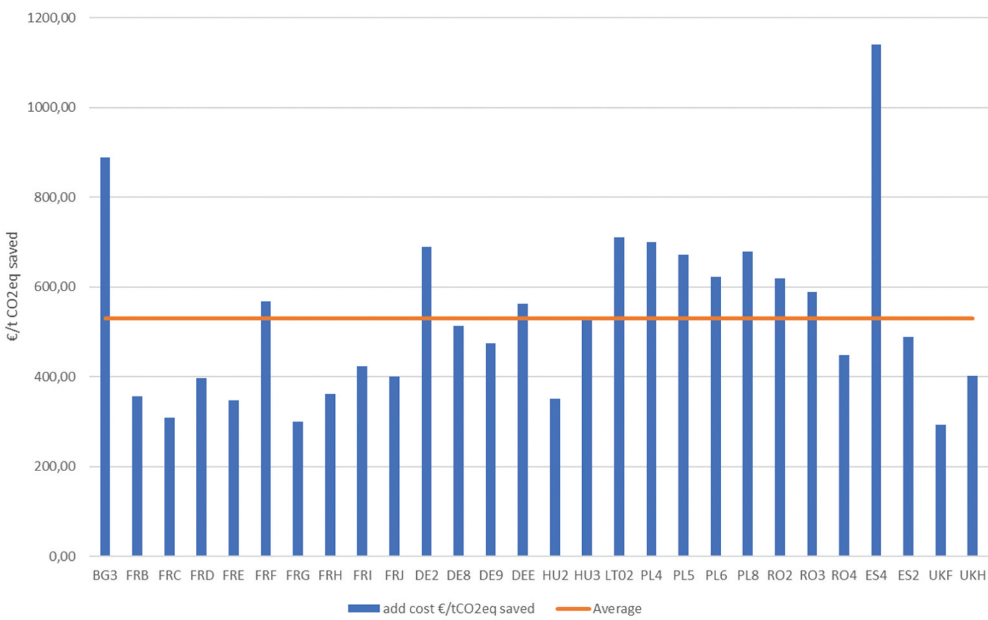

Figure 34. Cost of the CO_2eq using Wheat Straw bio-FT diesel.

emissions, offshore power supply, and velocity reduction during the voyage by 2 knots [43].

Blend versus cost and proportional CO_2 emissions

The application of the present biofuel has proved to be unfeasible to cover the high demand, and the problems caused to the equipment in the long term by using this new source are unknown. A blend variation was assumed as an alternative to inserting the bio-FT diesel in the maritime sector (89.55 kgCO_2/GJ and 24.09 €/GJ).

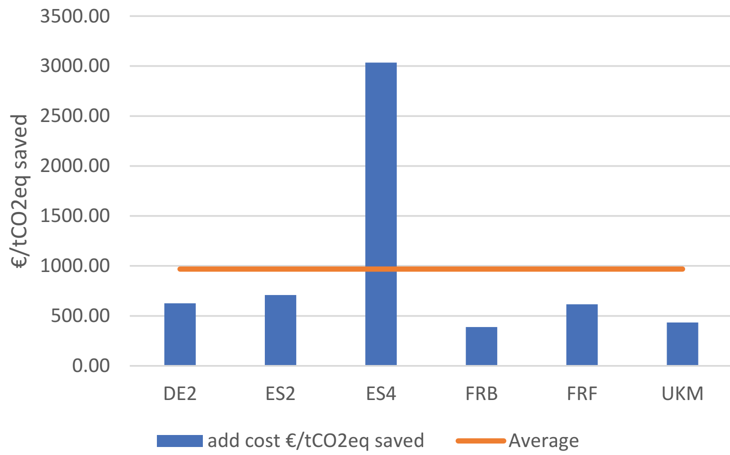

Figure 35. Cost of CO_2eq using Barley Straw bio-FT diesel.

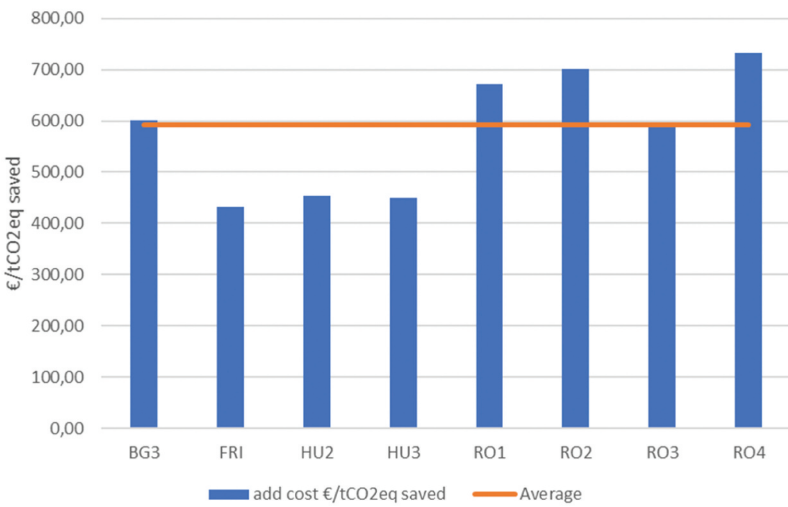

Figure 36. Cost of CO_2eq using Maize Straw bio-FT diesel.

Figure 38 was produced for a blend percentage variation of the bio-FT diesel from wheat straw and its costs and CO_2eq saved. The cost would vary between 24.41 and 56.70 €/GJ and the carbon saved between 0.64 and 64.38 kgCO_2eq/GJ of biofuel.

The variation of the blend percentage (Figure 39) with bio-FT diesel from barley straw from 1%-100% had a cost variation of 24.49–64.75 €/GJ and 0.59–59.21 kgCO_2eq saved/GJ of bio-FT diesel used.

Figure 40 shows the variation of the percentage blended (1–100%) using bio-FT diesel from maize straw. The results pointed to an oscillation of 24.36–51.16 €/GJ and 0.59–59.37 kgCO_2eq saved/GJ of bio-FT diesel used.

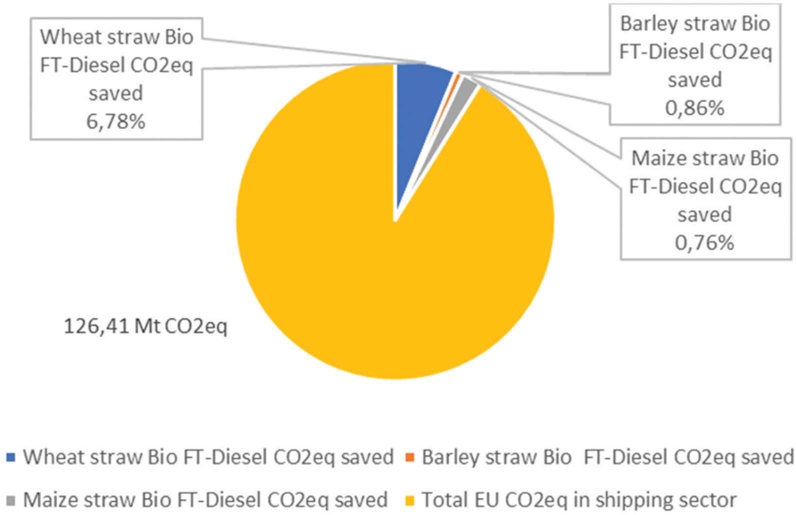

Figure 37. Co2eq saved in the EU shipping sector.

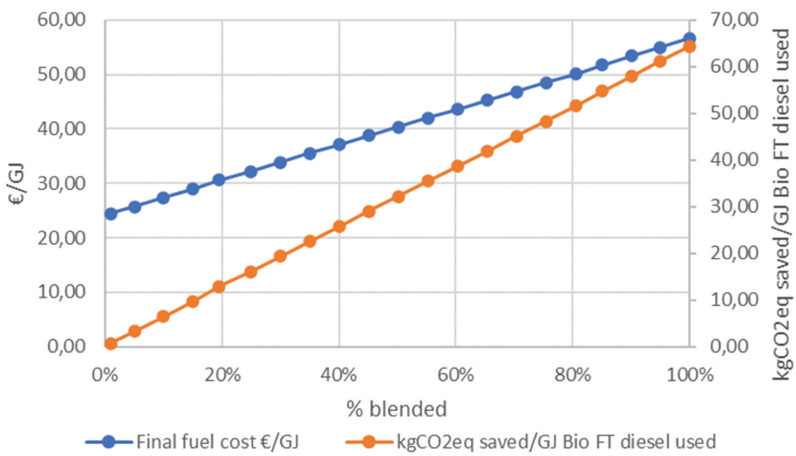

Figure 38. Cost variation vs percentage blended wheat straw bio-FT diesel.

Discussion

Bio-FT diesel production as an alternative source has been shown to be viable in terms of GHG emissions (25.16–30.18 gCO_2eq/MJ). The French territory would represent 31.22% of the total installed power in the continent, because of its large crop areas.

Another advantage for the French territory is the low carbon emissions of the well-to-tank process because of France's reliance on nuclear energy. Overall, the high emissions of the entire process come from the fertiliser compensation, corresponding to 70% of the emissions. Comparing similar studies in the literature (Figure 41) the present research has presented higher costs, which could be balanced if the product is used in lower proportions as blended alternatives.

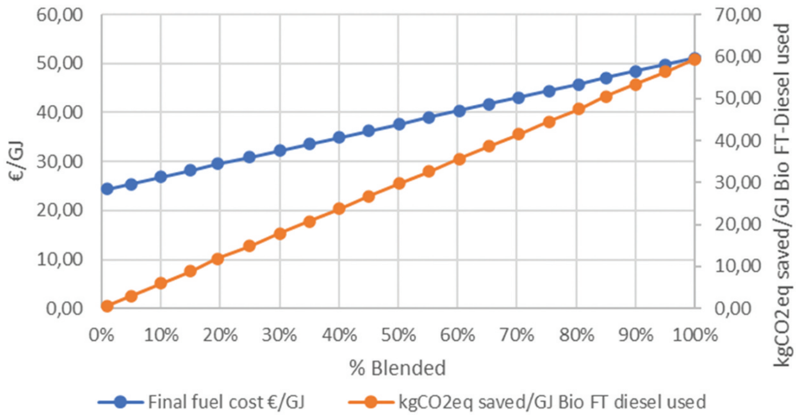

Figure 39. Cost variation vs percentage blended Barley straw bio-FT diesel.

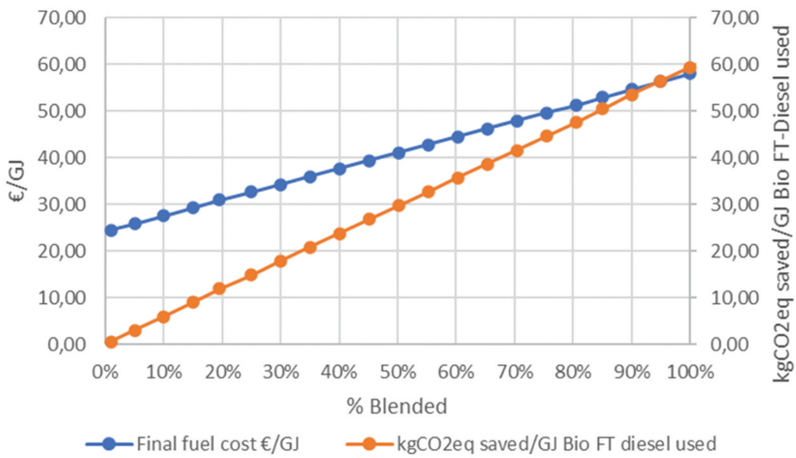

Figure 40. Cost variation vs percentage blended Maize straw bio-FT diesel.

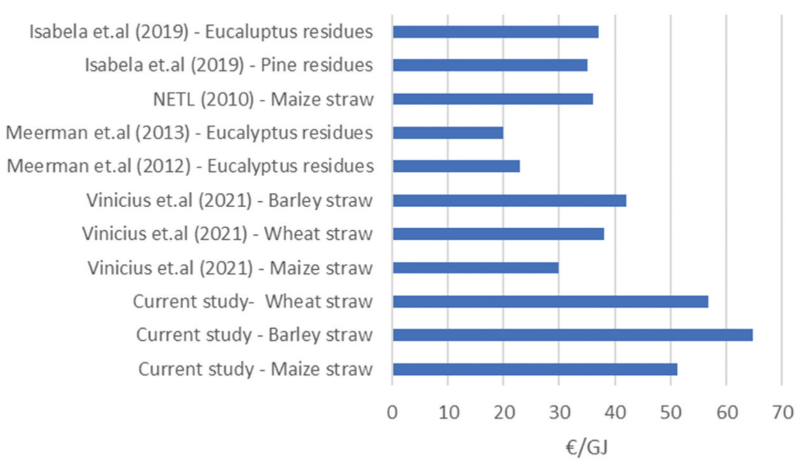

Figure 41. Bio-FT-diesel cost of several studies FT [8,20,31,44,45].

The drawback of the process is the competition between bio-FT diesel and electricity from biomass. A study from 2005 found a potential primary energy availability from barley and wheat straw of 230 PJ with a total capacity of 2.5 GW of installed power in 27 member states of the European Union [46].

Biomass and bioenergy represent 10% of the current total final energy consumption, and 60% of all renewable sources, with 13.4% (649 PJ) used for electricity and 74.6% (3,613 PJ) for heat and cooling production respectively [47].

From all biomass sources (forest, crops, agricultural residues, waste) the agricultural residues correspond to 27% of the total (1500 PJ) [47]. The literature lacks accurate information on how much wheat, barley, and maize straw are used for the bioenergy proposed in Europe. Nevertheless, it is known that those sources will make important contributions to increasing the renewable energy power capacity and contribute to the net-zero emissions projections by 2050.

The bio-FT diesel production from straw residues from agriculture will certainly play an important role in biofuel production but may constrain the electricity generation that already uses those sources as feedstock. Thus, further studies should be done to identify and reduce the risks caused by hypothetical resource competition.

Conclusion

The maritime sector faces difficulty in implementing cleaner fuel options for several reasons, such as the lower cost of marine fossil fuels compared to renewable options, the lack of standards for alternative possibilities, ships from different flag nations, and few public incentives to promote the decarbonisation of the sector.

The European continent has made advances. The recent monitoring report on CO_2 emissions maps the main problems in order to reach practical solutions.

This study has demonstrated its pertinence by:

- mapping the potential regions with high agricultural land and biomass availability;
- showing that bio-FT diesel is one more alternative in favour of the renewable option in the shipping sector;
- assessing the economic point of view to be addressed with more research and development and incentives from the public sector;
- showing the carbon footprint from each region to point regions where this option could contribute to reduced emissions;
- explaining that, although blend options as the alternative fuel cannot replace all the fossil fuels currently used, starting with lower quotas could cover more regions in the European space;
- the creation and commercialisation of by-products to be commercialised and to reduce risks in the project;
- suggesting that further studies should be done to identify possible constraints caused by the competition of straw used for electricity versus bio-FT diesel production.

The low stage of development of the FT route using biomass and the high LCOE are the most important disadvantages of the present study. Nevertheless, it seeks to highlight the contribution of this source to the decarbonisation of the current vessels. There is a need for experimental work on these fuels in marine engines. It is now time for the shipping industry to consider advanced biofuel as part of the energy transition.

Acknowledgments

The author would like to acknowledge the financial support received from the Science and Technology Foundation (FCT), Ministry of Science and Higher Education (MCTES), European Social Fund (FSE), and European Union (EU), under the grant number PD/BD/142848/2018.

Disclosure statement

No potential conflict of interest was reported by the authors.

ORCID

Vinicius Andrade dos Santos http://orcid.org/0000-0002-9540-9292
Patrícia Pereira da Silva http://orcid.org/0000-0002-5862-1278
Luís Manuel Ventura Serrano http://orcid.org/0000-0003-2864-7597

References

[1] European Commission, 2020, 2019 Annual report on CO_2 emissions from maritime transport: Report from the European comission. Available online at: https://ec.europa.eu/clima/system/files/2020-05/swd_2020_82_en.pdf (accessed 20 July 2020).
[2] Florentinus, A., Hamelinck, C., van den Bos, A., Winkel, R. and Maarten, R., 2012, Potential of biofuels for shipping: Final report potential of biofuels for shipping. Available online at: http://webcache.googleusercontent.com/search?q=cache:41uL68qimRMJ:www.emsa.europa.eu/fc-default-view/download/1626/1376/23.html&cd=2&hl=pt-BR&ct=clnk&gl=br (accessed 22 July 2020).
[3] Balcombe, P., Lewis, C. and Speirs, J., *et al.*, 2019, How to decarbonise international shipping: Options for fuels, technologies and policies. *Energy Conversion and Management* 4, 72–88. doi:10.1016/j.enconman.2018.12.080.
[4] Gousi, M., Kordouli, E. and Bourikas, K., *et al.*, 2017, Green diesel production over nickel-alumina co-precipitated catalysts. *Applied Catalysis A: General* 536(8), 45–56. doi: 10.1016/j.apcata.2017.02.010.
[5] Douvartzides, S.L., Charisiou, N.D., Papageridis, K.N. and Goula, M.A., 2019, Green diesel: Biomass feedstocks, production technologies, catalytic research, fuel properties and performance in compression-ignition internal combustion engines. *Energies* 12, 5. doi:10.3390/en12050809.
[6] Portugal-Pereira, J., Soria, R., Rathmann, R., Schaeffer, R. and Szklo, A., 2015, Agricultural and agro-industrial residues-to-energy: Techno-economic and environmental assessment in Brazil. *Biomass & bioenergy* 81(10), 521–533. doi: 10.1016/j.biombioe.2015.08.010.
[7] Silva, F.F.D.S., 2017, *Avaliação da torrefação e densificação de resíduos agrícolas no Brasil*, Master thesis(Brasil: Universidade Federal do Rio de Janeiro.
[8] Tagomori, I.S., Rochedo, P.R.R. and Szklo, A., 2019, Techno-economic and georeferenced analysis of forestry residues-based Fischer-Tropsch diesel with carbon capture in Brazil. *Biomass & bioenergy* 123(4), 134–148. doi:10.1016/j.biombioe.2019.02.018.
[9] Machado, L.R., 2014, Dimensionamento de sistema de corte, carregamento e transporte de eucalipto, Escola de Economia de São Paulo da Fundação Getúlio Vargas - FGV-EESP.

[10] Schmidt, T.I., 2017, *Potencial técnico e econômico para a produção de Fischer-tropsch diesel a partir de biomass (FT-BTL) associada à captura de carbono no Brasil*. Tese PhD(Rio de Janeiro, Brazil: Federal University of Rio de Janeiro).
[11] EUROSTAT, 2021, Crop production in national humidity by NUTS 2 regions. Available online at: https://ec.europa.eu/eurostat/databrowser/view/APRO_CPNHR__custom_510268/default/table?lang=en (accessed 8 May 2021).
[12] Valero, A. and Usón, S., 2006, Oxy-co-gasification of coal and biomass in an integrated gasification combined cycle (IGCC) power plant. *Energy* 31(10–11), 1643–1655. doi: 10.1016/j.energy.2006.01.005.
[13] Swanson, R.M., Platon, A., Satrio, J.A. and Brown, R.C., 2010, Techno-economic analysis of biomass-to-liquids production based on gasification scenarios. Available online at: https://www.nrel.gov/docs/fy11osti/46587.pdf (accessed 14 August 2020).
[14] Swanson, R.M., Platon, A., Satrio, J.A. and Brown, R.C., 2010, Techno-economic analysis of biomass-to-liquids production based on gasification. *Fuel* 89(12), S11–19. doi: 10.1016/j.fuel.2010.07.027.
[15] Meerman, J.C., Ramírez, A., Turkenburg, W.C. and Faaij, A.P.C., 2011, Performance of simulated flexible integrated gasification polygeneration facilities. Part A: A technical-energetic assessment. *Renewable and Sustainable Energy Reviews* 15(6), 2563–2587. doi: 10.1016/j.rser.2011.03.018.
[16] Moen, K., 2014, Modelling and optimization of a GTL plant, *Trondheim*. Available online at: https://ntnuopen.ntnu.no/ntnu-xmlui/bitstream/handle/11250/2351764/11378_FULLTEXT.pdf?sequence=1 (accessed 12 October 2020).
[17] Hadden, R., 2020, Hydrogen production. *Synthesis Gas* 8(1), 377–397. doi:10.1002/9781119707875.ch12.
[18] van Vliet, O.P.R., Faaij, A.P.C. and Turkenburg, W.C., 2009, Fischer-Tropsch diesel production in a well-to-wheel perspective: A carbon, energy flow and cost analysis. *Energy Conversion and Management* 50(4), 855–876. doi:10.1016/j.enconman.2009.01.008.
[19] Guedes, F.P.D.C., 2015, *Avaliação de alternativas para redução do uso final de energia no setor de refino de petróleo brasileiro e estimativa de custos de abatimento de emissões de gases de efeito estufa* (Rio de Janeiro: Federal University of Rio de Janeiro).
[20] Meerman, J.C., Knoope, M., Ramírez, A., Turkenburg, W.C. and Faaij, A.P.C., 2013, The techno-economic potential of integrated gasification co-generation facilities with CCS going from coal to biomass. *Energy Procedia* 37(6), 6053–6061. doi: 10.1016/j.egypro.2013.06.534.
[21] Tranier, J.-P., Dubettier, R., Perrin, N. and Liquide, A., 2009, Air separation unit for oxy-coal combustion systems. Available online at: https://ieaghg.org/docs/oxyfuel/OCC1/Session%204_B/1st%20IEA%20GHG%20oxyfuel%20conf%20ASU%20090909_final.pdf (accessed 24 October 2020).
[22] de Álamo, G., Sandquist, J., Vreugdenhill, B.J., Almansa, G.A. and Carbo, M., 2018, Implementation of bio-CCS in biofuels production, *Bioenergy Task 33 special report* (Lulea: IEA). Available online at: https://www.ieabioenergy.com/wp-content/uploads/2018/08/Implementation-of-bio-CCS-in-biofuels-production_final.pdf (accessed 1 November 2020).
[23] European Commission, 2016, Well-to-wheels analyses. Available online at: https://ec.europa.eu/jrc/en/jec/activities/wtw (accessed 26 May 2021).
[24] Tarkalson, B.D.D., Brown, B., Kok, H. and Bjorneberg, D.L., 2009, Impact of removing straw from wheat and barley fields: A literature review. *Better Crops* 93(3), 17–19.
[25] Rees, J., Schmer, M. and Wortman, C., 2017. Corn stover removal: Nutrient value of stover and impacts on soil properties. Available online at: https://cropwatch.unl.edu/2017/corn-stover-removal-nutrient-value-stover-and-impacts-soil-properties (accessed 1 December 2020).
[26] Skowrońska, M. and Filipek, T., 2014, Life cycle assessment of fertilizers: A review. *International Agrophysics* 28(1), 101–110. doi: 10.2478/intag-2013-0032.
[27] Ecoinvent Centre, 2007, Life cycle inventories of bioenergy, *Uster: Ecoinvent Report*. Available online at: https://www.researchgate.net/profile/Niels-Jungbluth/publication/

230725648_Life_Cycle_Inventories_of_Bioenergy_ecoinvent_report_No_17/links/0c96051b76e2fb8dce000000/Life-Cycle-Inventories-of-Bioenergy-ecoinvent-report-No-17.pdf (accessed 22 January 2021).
[28] Suardi, A., Bergonzoli, S., Alfano, V., Scarfone, A. and Pari, L., 2019, Economic distance to gather agricultural residues from the field to the integrated biomass logistic centre: A Spanish case study. *Energies* 12(16), 3086. doi: 10.3390/en12163086.
[29] GOV.UK, 2021, Government conversion factors for company reporting of greenhouse gas emissions. Available online at: https://www.gov.uk/government/collections/government-conversion-factors-for-company-reporting (accessed 3 February 2021).
[30] Wetterlund, E., 2012, *System studies of forest-based biomass gasification*, PhD Thesis (Sweden: University of Linkoping).
[31] NETL, 2010, Cost and performance baseline for fossil energy plants, 1: Bituminous coal and natural gas to electricity. Available online at: https://www.netl.doe.gov/projects/files/CostAndPerformanceBaselineForFossilEnergyPlantsVol1BitumCoalAndNGtoElectBBRRev4-1_092419.pdf (accessed 15 May 2021).
[32] GlobaPetrolPrices.com, 2020, Retail energy price data. Available online at: https://www.globalpetrolprices.com/countries/(accessed 5 July 2020).
[33] Idealista/news, 2021, Euribor histórico anual. Available online at: https://www.idealista.pt/news/euribor/anual/historico/(accessed 5 May 2021).
[34] PigWorld, 2020, Straw prices for the week ending May 31, 2020. Available online at: http://www.pig-world.co.uk/news/weekly_bhsma_straw-prices.html (accessed 5 February 2020).
[35] NDA, 2020, Maize Stalk bale price - Nebraska department of agriculture. Available online at: https://nda.nebraska.gov/promotion/hay/sellers.pdf (accessed 5 February 2020).
[36] TradingEconomic, 2022, Naphta. Available online at: https://tradingeconomics.com/commodity/naphtha (accessed 11 August 2022).
[37] Ship&Bunker, 2022, Global 20 ports average. Available online at: https://shipandbunker.com/prices/av/global/av-g20-global-20-ports-average#IFO380 (accessed 8 August 2022).
[38] European Commission, 2020, A hydrogen strategy for a climate-neutral Europe, Brussels. Available online at: https://ec.europa.eu/energy/sites/ener/files/hydrogen_strategy.pdf (accessed 2 August 2021).
[39] Statista, 2021, Price of sulfur in the United States from 2014 to 2020. Available online at: https://www.statista.com/statistics/1031180/us-sulfur-price/(accessed 3 April 2021).
[40] Exchange Rates, 2022, Currency rates. Available online at:https://www.exchangerates.org.uk/GBP-EUR-exchange-rate-history.html (accessed 10 August 2022).
[41] IEA, 2021, Data and statistics, *International Energy Agency*. Available online at: https://www.iea.org/data-and-statistics/data-tables?country=UK&energy=Electricity&year=2019 (accessed 4 April 2021).
[42] Bruckner, T., Fulton, L. and Hertwich, E., *et al.*, 2014, Technology-specific cost and performance parameters - Annexe III
[43] MSC, 2022, Steering the course: Sustainability report 2021, *Annual Report 2021* (Geneva: MSC Cruises). Available online at: https://www.msccruises.com/en-gl/About-MSC/News/MSC-Sustainability-Report-2021.aspx (accessed 20 June 2022).
[44] dos Santos, V.A., Portugal, A.A.T.G., Da Silva, P.P. and Serrano, L.M., 2022, Bio-FT-diesel in the European maritime sector: A technical-economic valuation of straw crops potential. *International Journal of Environment and Sustainable Development* 21, 427. doi: 10.1504/IJESD.2021.10038672.
[45] Meerman, J.C., Ramírez, A., Turkenburg, W.C. and Faaij, A.P.C., 2012, Performance of simulated flexible integrated gasification polygeneration facilities, Part B: Economic evaluation. *Renewable and Sustainable Energy Review* 6(8), 6083–6102. doi:10.1016/j.rser.2012.06.030.
[46] Dallemand, J., Hamelinck, C., Ragwit, M., St, D. and Haddaway, N.R., 2005, GIS-based assessment of cereal straw energy resource in the European Union. In: *Proceedings of the 14th European Biomass Conference and Exhibition. Biomass for Energy, Industry and Climate Protection*, Paris, France, 1–4.

[47] Nicolae, S., Jean-Francois, D., Nigel, T., Manjola, B., Javier, S.L. and Marios, A., 2019, Brief on biomass for energy in the European Union. Available online at: https://ec.europa.eu/knowledge4policy/bioeconomy%0AContact:%0Ahttps://ec.europa.eu/jrc/en/publication/brochures-leaflets/brief-biomass-energy-european-union%0Ahttps://op.europa.eu/en/publication-detail/-/publication/7931acc2-1ec5-11e9-8d04-.
[48] Fout, T., Zoelle, A. and Keairns, D., *et al.*, 2015, Cost and performance baseline for fossil energy plants 1a: Bituminous coal (PC) and natural gas to electricity revision 3. Available online at: http://www.netl.doe.gov/FileLibrary/Research/EnergyAnalysis/Publications/Rev3Vol1aPC_NGCC_final.pdf (accessed 15 July 2021).
[49] De Barros, M.M., 2014, *Análise da flexibilidade do refino de petróleo para lidar com choques de demanda de gasolina no Brasil*, PhD Thesis(COPPE, Federal University of Rio de Janeiro (UFRJ)).
[50] CEPCI, 2021, Chemical engineering plant cost index. Available online at: https://www.chemengonline.com/site/plant-cost-index/(accessed 20 May 2021).

Appendices

Appendix A

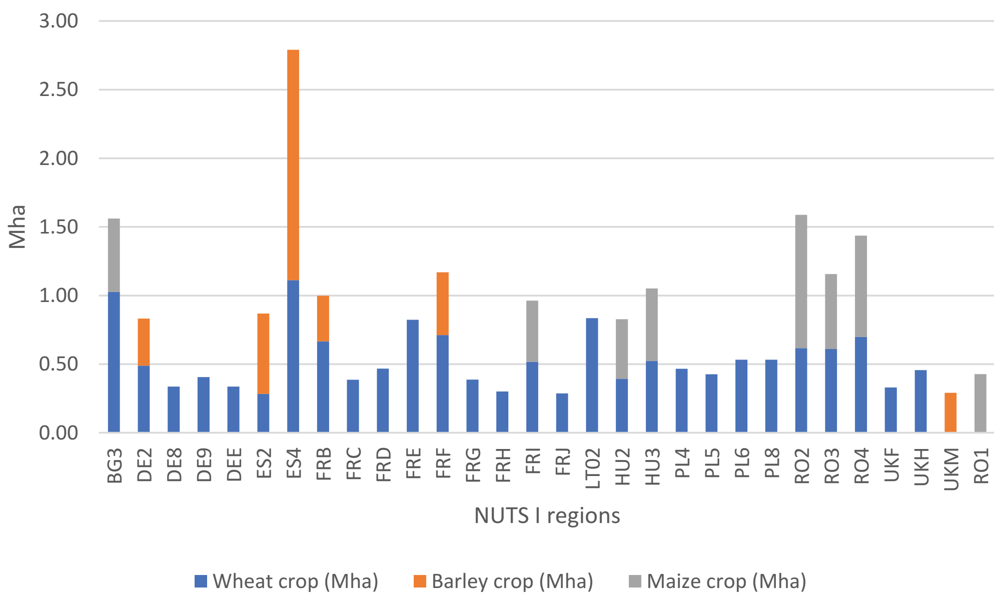

Figure A1. Wheat, Barley and Maize crops cultivation in EU NUTS I region [11].

Appendix B

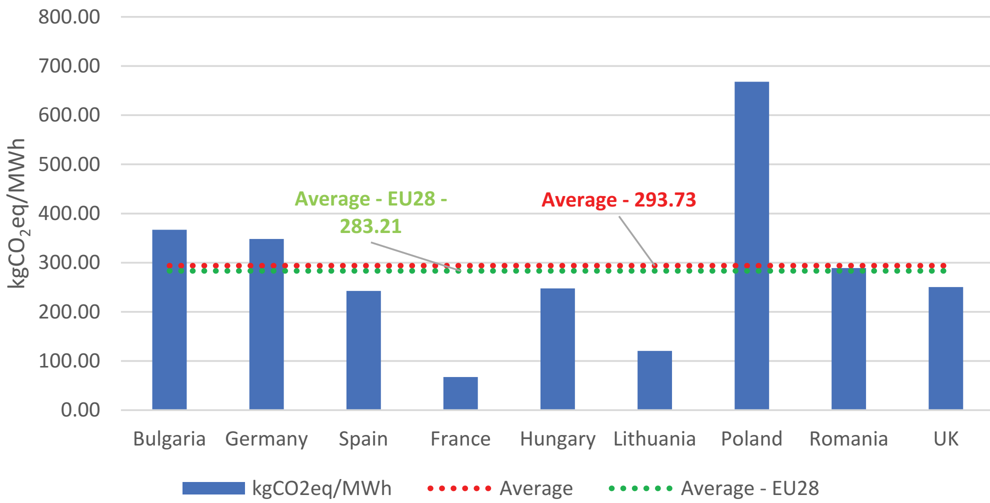

Figure B1. Carbon emissions from the electricity sector [41,42].

Appendix C

Table C1. Equipment cost references.

Equipment (process unit)	MUS$ 2015	Scale (Sbase)	unit	Factor Scale	C	CB	CA	Index Value B	Index Value A	Reference
Pre-treatment	10.00	2200.00	t/d	0.70	14.17	15.35	14.17	603.10	556.80	[8,13]
Biomass feeding	0.80	2200.00	t/d	0.70	1.13	1.23	1.13	603.10	556.80	[8,14]
ASU	157.20	2200.00	tO2/d	0.70	140.25	151.91	140.25	603.10	556.80	[8,48]
Shell EFG	183.30	2900.00	t/d	0.70	285.52	309.27	285.52	603.10	556.80	[8,48]
Syngas Cleaning	96.50	14400.00	t/d	0.70	48.96	53.03	48.96	603.10	556.80	[8,48]
AGR	74.50	554.00	tCO2/d	0.70	214.43	232.27	214.43	603.10	556.80	[20]
Claus/SCOT	30.80	56.00	tS/d	0.70	3.42	3.71	3.42	603.10	556.80	[20]
FTS	22.40	310.00	MWth FT	0.70	31.19	33.78	31.19	603.10	556.80	[20]
Upgrading	72.00	19080.00	m3/d	0.70	6.51	7.05	6.51	603.10	556.80	[8,49]
Hydrocracking	250.00	4770.00	m3/d	0.70	59.67	64.63	59.67	603.10	556.80	[8,49]
PSA	12.80	797.57	tH2/d	0.70	1.55	1.68	1.55	603.10	556.80	[20]
Power Generation	38.70	50.00	Mwe	0.70	0.00	0.00	0.00	603.10	556.80	[8,13,50]