Bio FT-diesel in the European maritime sector: a technical economic valuation of straw crops potential

Vinicius Andrade dos Santos*

MIT-Portugal – The Energy for Sustainability Initiative (EFS),
Sustainable Energy Systems,
Department of Mechanical Engineering,
University of Coimbra,
3030-194 Coimbra, Portugal
and
Chemical Process Engineering and Forest
Products Research Centre CIEPQPF),
Chemical Engineering Department,
University of Coimbra,
3030-790 Coimbra, Portugal
Email: viniciussantos.vs55@gmail.com
Email: vinicius@eq.uc.pt
*Corresponding author

Antonio A.T.G. Portugal

Deceased; formerly of: University of Coimbra,
Portugal

Patrícia Pereira da Silva

Centre for Business and Economic Research (CeBER),
Faculty of Economics of the University of Coimbra,
University of Coimbra,
Av Dias da Silva, 165 3004-512 Coimbra, Portugal
Email: patsilva@fe.uc.pt
and
INESC-Coimbra and Energy for Sustainability Initiative Pólo II,
3030-290 Coimbra, Portugal

Luis M.V. Serrano

School of Technology and Management,
Polytechnic of Leiria,
2411-901 Leiria, Portugal
and
Department of Mechanical Engineering,
Rua Luís Reis Santos, Pólo II,
3030-788 Coimbra, Portugal
Email: luis.serrano@ipleiria.pt

Abstract: The present study has as an objective on exploring the lignocellulosic residues from European agriculture as an energy source for the production of bio Fischer-Tropsch diesel (bio FT-diesel) as a low carbon alternative to be used in the European maritime sector, based on a techno-economic methodology of residue collection combined with the production yield of FT-Diesel available on literature. It permitted us to find a potential production of 8.5 million tons (Mton) of biofuel across 11 countries, and the reduction of 26 Mton of CO_2 annually. The study contributes to the understanding that the fuel could be only cost-competitive if the crude oil reaches values between 10.45–16.91 €/GJ. In addition, the low technology status of bio FT-diesel production and the lack of biofuel standards to the maritime sector are limitations that can only be addressed with effective regulations added to research and development from collection to production and consumption.

Keywords: maritime transportation; agriculture biomass; Fischer-Tropsch diesel; decarbonisation.

Reference to this paper should be made as follows: Andrade dos Santos, V., Portugal, A.A.T.G., Pereira da Silva, P. and Serrano, L.M.V. (2022) ‘Bio FT-diesel in the European maritime sector: a technical economic valuation of straw crops potential’, *Int. J. Environment and Sustainable Development*, Vol. 21, No. 4, pp.427–455.

Biographical notes: Vinicius Andrade dos Santos is a PhD student in Sustainable Energy Systems (SES) – MIT Portugal and Master’s in Energy for Sustainability and Energy Policies in the University of Coimbra, experience in bio ethanol and co-generation production in the industry. His research field has been focusing on biomass, consolidated and advanced biofuels production, maritime transport decarbonisation, and sustainable development

Antonio A.T.G. Portugal (in memoriam) was an Associate Professor of the Chemical Engineering Department of the University of Coimbra. He received his PhD and Master’s in University of Aston, Birmingham, UK. He had several contributions to the academy in the field of nanomaterials, energy, biofuels, and modelling and numerical methods in chemical and paper engineering. He was the Vice-director of the Faculty of Science and Technology of the UC in 2011 and Head of Department of Chemical Engineering twice, Director of CIEPQPF research centre, as well as responsible for the doctoral programs in chemical engineering and bio refineries.

Patrícia Pereira da Silva is an Associate Professor with Habilitation at the University of Coimbra (UC) and Researcher at CeBER and INESC-Coimbra. She is a board member of the energy for sustainability at UC. She is a faculty member at the Faculty of Economics of UC and at the Sustainable Energy

Systems PhD – MIT Portugal program. Her research interests are focused on energy markets, interactions between economy-business-energy-environmental aspects and sustainability.

Luis M.V. Serrano is an Assistant Professor of Mechanical Engineering Department of Polytechnic Institute of Leiria. He is a coordinator of Automotive Engineering and received his PhD in Mechanical Engineering at the University of Coimbra. He is a researcher in ADAI-IP Leiria that belongs to ADAI-LAETA and has developed several research works in the area of fuels and combustion in engines, namely biofuels (biodiesel, bioethanol, and biomethane), alternative fuels (LPG, natural gas), and additive fuels. His research area is in sustainable mobility and energy efficiency of transport.

1 Introduction

Since the discovery of trade routes in the 15th century, the naval sector has continually modernised and has been a major player in the trades that sustain the world economy (Bouman et al., 2017). Maritime transport is by far the most cost-effective and, consequently, pollutes the least. However, if the maritime sector were considered a country, it would be the 6th highest emitter of CO_2 in the world (Balcombe et al., 2019). Therefore, decarbonisation of this sector has been widely demanded, leading its players to research cleaner alternatives to the negative externalities of using fossil-fuel.

Biofuels emerge as an important alternative to reduce the carbon footprint of the maritime sector. First-generation biofuels such as biodiesel and ethanol are commercially available today, but their sustainability has been questioned due to their indirect impact on the environment (Balcombe et al., 2019).

Advanced biofuels produced via advanced routes [pyrolysis, hydrothermal liquefaction, and Fischer-Tropsch (FT)] and based on lignocelluloses resources have been widely discussed. This production is cleaner than the first generation of biofuels, emitting fewer greenhouse gases (GHG) (Florentinus et al., 2012; Balcombe et al., 2019).

The FT, in combination with the gasification process, emerges as an important route to convert biomass to hydrocarbons similar to diesel fuel – called biomass to liquid (BTL) fuels (Gousi et al., 2017; Douvartzides et al., 2019). The BTL is suitable for internal combustion engines (ICE) such as those used in maritime transport (Douvartzides et al., 2019). However, BTL and the other advanced transformation routes are still in an early stage of development.

The production of advanced biofuels from lignocellulosic resources, as in the case of BTL stresses the relevance of agricultural residues. This material has been widely discussed as a vast and important primary energy resource to be transformed into biofuel.

Europe is one of the largest world 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 to be used in the maritime transport sector.

This study is based on a survey from the food and agriculture organisation of the United Nations (Food Agriculture Organisation – FAO) and data of the aforementioned crops in European countries. The research adopted agricultural residue recovery quantification methodologies used by Portugal-Pereira et al. (2015), Silva (2017), and

Tagomori et al. (2019), which allows determining the potential of biofuel production from each culture.

This study presents the efficiency calculation by Tagomori et al. (2019), who studied the bio FT-diesel production in Brazil using eucalyptus and pine residues. The research also explores methodologies to calculate the total investment and levelised cost (LCOE) of Bio-FT diesel production in Europe and tests the valuation sensitivity regarding the interest rate (IR) variation.

Finally, this research enables us to determine how substituting fossil fuel for biofuel can reduce GHG emissions in the maritime sector. Furthermore, it allows us to predict the number of plant units involved in exploring the residual biomass from large harvests of crops in Europe to produce this alternative fuel.

2 Literature review

2.1 *International maritime transport emissions*

Maritime freight contributes to 70% of the world's transportation of goods (UNCTDA, 2018). However, it represents a share of 2.5% of the world's GHG emissions, and this figure is projected to reach 17% of those shares in 2050 in a business-as-usual scenario (Bannon, 2015).

The third international maritime organisation green house gas study (IMO, GHG) (IMO, 2014) estimated growth in emissions of between 50% and 250% by 2050 compared to current levels. For this reason, the IMO remains committed to driving effective plans to reduce the impacts associated with the anthropogenic missions from this sector. Under the 72nd Marine Environment Protection Committee (MEPC) resolution, the IMO sector set an emissions target of 50% lower than in 2008 (IMO, 2018). This represents an ambitious goal that will only be met if the government commits to a significant number of actions and a considerable share of low and zero-carbon fuels (around 213 MT CO_{2eq} saved) (IEA, 2018).

2.2 *Emission reduction measures*

For the target to become a reality, effective regulations will be necessary to ensure new emission reduction measures in the maritime transport sector, and some rules are already in place. MARPOL Annex VI has imposed strict regulations regarding SOx (0.1%) and NOx (< 0.5 g/kWh) emissions that are in force in the Baltic Sea, North Sea, North American Coast, and Caribbean Sea (IMO, 2019). Since 2011, IMO has implemented an international regulatory measure of energy efficiency requirements for global ships. In this context, Energy Efficiency Design Index Standards (EEDI) and Ship Energy Efficiency Management Plan monitoring (SEEMP) were adopted to reduce the GHG from the shipping sector (IMO, 2011; Johnson et al., 2013; Acomi and Acomi, 2014; Ančić and Šestan, 2015).

2.3 *Biofuel as an option in the European maritime transport sector*

Carbon emission has been a source of concern in the European Union (EU) since their ports are responsible for 15% of the world's activity and almost 30% of the world's maritime fossil fuel consumption (UNCTDA, 2019). Thus, the investigation into alternative fuel sources has been one of the most recent discussions in the region.

Biofuels emerge as one of the alternatives for the shipping sector. However, concerns related to the lack of land in Europe, such as environmental impacts from the first generation of biofuel production, have opened up new opportunities for advanced routes of biofuels.

2.4 The FT route

Advanced renewable sources in the maritime sector still lack development, but some experts point out that biofuels can be a short and medium-term transitional alternative in the decarbonisation of this sector. The FT route emerges as an important technology to produce Bio-FT Diesel similar to fossil fuels obtained from lignocelluloses biomass residues (Geerlings et al., 1999).

FT biofuel is a promising alternative to be disseminated and explored in the maritime sector to replace fossil fuels. Some authors argue that the added value in its refining process makes it expensive. Therefore, its application in the aviation sector could be more competitive than in the maritime sector in terms of costs. The advantage of the FT process is that different hydrocarbons can be produced similarly to fossil fuels (Hsieh and Felby, 2017).

The FT products from natural gas (GTL) and coal (CTL) are at an advanced stage of development with several plants in operation around the world (Andrews and Logan, 2008; Johansson et al., 2014). Nevertheless, the conversion of BTL through the FT route is still in the early stages of development and commercialisation (Damartzis and Zabaniotou, 2011; Johansson et al., 2014). This diminishes the interest in private sector investments that require more in-depth research and development (R&D).

2.5 European agriculture residues as FT feedstock

Agriculture in Europe comprises 173 million hectares (Mha), which corresponds to approximately 40% of the continent. The presented high rate of the planted area ensures total independence and food security for the region. Countries such as France, Spain, the UK, Germany, Poland, Italy, and Romania represent two-thirds of the occupied agricultural area in the region. Appendix A contains data on the production, agricultural area, and productivity per hectare of the main cereals consumed (wheat, barley, corn, rice, and soybeans) in the European countries (Eurostat, 2018).

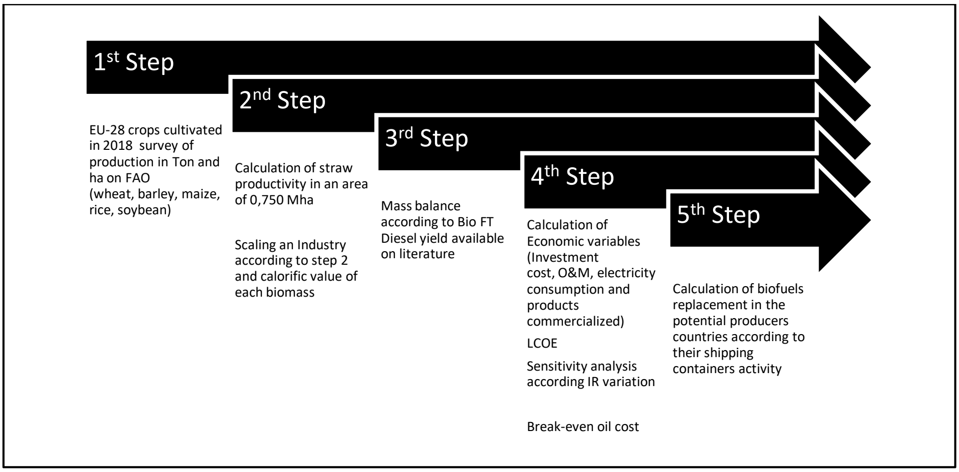
The production of these grains occupies approximately 28% (47Mha) of the European agricultural area. In this sense, a huge amount of energy resources are available for bioconversion proposed as bio FT-diesel production. Finally, it can be used in ICE without engine changes (Lapuerta et al., 2010; Tagomori et al., 2019) or compromising the competition for agricultural areas.

The following section describes the material and method used in this study.

3 Material and method

The FAO survey was conducted to quantify the most consumed commodities in EU-27 plus the UK in 2018. Wheat, barley, maize, rice, and soybeans accounted for 47 Mha of the European agricultural area. Due to the annual cycles, these crops provide the regions with a high annual biomass availability to map the potential FT-Diesel producer countries to be used in the maritime sector as a low-carbon fuel alternative. All procedure steps are displayed in Figure 1.

Figure 1 Overview of methodology steps



3.1 Feedstock potential

The biomass availability from agriculture residues must be recovered in equilibrium between environmental and techno-economic factors. The biomass left on the ground creates a layer that provides barriers against soil erosion from wind and rain (Pimentel and Kounang, 1998; Portugal-Pereira et al., 2015). Furthermore, the organic material contributes to the plant unit's productivity due to its high nutrient content (Altieri, 1999; Wight et al., 2012; Portugal-Pereira et al., 2015) and, for this reason; part of the residues should be left on the ground for soil conservation.

The techno-economic factor points out the percentage that can be environmentally recovered without constraining the competition of the residues with other non-energy uses.

For the recovered agriculture residues, a bottom-up approach was used, limiting it to a scenario of a 50 km radius from a supposed factory. Some authors believe this to be the maximum feasible length (Machado, 2014; Schmidt, 2017; Tagomori et al., 2019). In Table 1, the factors of residual biomass of the cultures crafted in this work are presented, followed by the determination of the energy potential equation as follows:

$$B\,\mathrm{Pr} = Yr * RPR.\, RAF\ SRR \tag{1}$$

where BPr is the biomass residue potential in tons per hectares (ton/ha), Yr is the average commodity productivity (tons/ha). RPR (Table 1) is the rate product-residue (%), RAF (Table 1) is the residue availability factor (%), and SRR (Table 3) is the sustainable removal rate (%).

$$E\,\mathrm{Pr} = B\,\mathrm{Pr} * LHVr \tag{2}$$

where *EPr* is the energy potential of the residue (GJ/ha), *BPr* is biomass residue potential (ton/ha). *LHVr* (Table 1) is the low heat value of the residue (GJ/ton).

$$TH\,\text{Pr} = E\,\text{Pr} * n \tag{3}$$

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 (Tagomori et al., 2019).

Table 1 Residue characterisation

Grain	*RPR*	*RAF*	*SRR*	*LHV (MJ/kg)*
Soybean straw	2.01	100%	30%	20.09
Maize straw	1.53	100%	25%	18.67
Barley straw	1.48	100%	50%	19.68
Wheat straw	1.55	100%	15%	19.54
Rice straw	1.54	100%	50%	17.22

Source: Portugal-Pereira et al. (2015) and Silva (2017)

The plant units' design will be determined according to the energy each residue can provide in the agricultural area explored, following equation (4) in an 8,000-hour annual operation.

$$Biomass\ in = \frac{TH\,\text{Pr} * n * 3.61 \cdot 10^6}{8{,}000} \qquad (4)^1$$

where *biomass in* represents the biomass entering the system in MW, *n* is the FT diesel efficiency (%). Finally, *THPr*: is the theoretical energy potential of the residue (GJ).

Equation (5) calculates the number of plant units that should be operating, per country.

$$Number\ of\ \ plants = harvested\ lands / 0.785 \tag{5}$$

where harvested land is the area of each crop in Mha (Appendix A), and 0.785 factor represents the conversion of 50 km radius in Mha.[2]

Table 2 FT efficiency

Products	*Yield (n)*	*HHV (MJ/kg)(Tagomori et al., 2019)*
LPG	0.07	49.35
Naphtha	0.09	47.54
Diesel	0.22	45.15
Gasoil	0.02	45.36

Source: Tagomori et al. (2019)

The FT-Diesel was based on research by Tagomori et al. (2019). Their study adopted EF Shell Gasifier oxygen-blow, and operating pressure and syngas temperature of 1,427ºC. In this research, the FT Diesel process, with three sub-products (naphtha, LPG, and gasoil), uses the efficient conversion observed in Tagomori et al. (2019) as a parameter to determine the plants' dimension necessary to explore the respective capacities, calculate the tons of biomass to be processed, products produced and energy consumption.

Table 2 shows how products and efficiency were calculated, following Tagomori et al. (2019). As their study was based on eucalyptus, it was adapted to use the overall energy potential for FT-Diesel from other biomass sources.

3.2 Power demand

The overall power demand estimation data of 51 MW was collected from the study by Tagomori et al. (2019) and uses the following equation.

$$Power\ Demand\ (MW) = Reference\ Demand\ (MW) * \frac{Project\ Scale}{Reference\ Demand} \tag{6}$$

3.3 Economic impacts

The investment costs may appear in different models and variations. The valuation can be problematic when comparing thermo chemical routes based on different sources and years. The method selected for the cost curve uses the exponential factor of 0.7, and this factor is the average used for processes in chemical plants (Wetterlund, 2012). Given the variability of published equipment cost estimates in the literature, this research used equation (7) (Holmgren, 2015).

$$C = Cbase\left(\frac{S}{Sbase}\right)^{f} \tag{7}$$

where C is the investment cost of equipment in millions of Euros (*M€*), *Cbase* is the known investment equipment cost in *M€*, S is the equipment capacity in MWth, *Sbase* is the known equipment capacity in MWth, and f is the dimensionless scale factor. Table 3 shows the values adopted and the respective references.

Table 3 Investment cost adjustment

Parameters	*Value*	*References*
Cbase – known investment cost (M€)	498	Swanson et al. (2010)
S – equipment capacity wheat/barley/maize straw (MWth)*	–	–
Sbase – known equipment capacity (MWth)	389	Swanson et al. (2010)
f – Scale factor	0.7	Holmgren et al. (2015)

Note: Depends on the straw productivity of each country and the calorific value (Appendix B).

Since the associated cost references may refer to different dates, we applied the factor based on the updated Chemical Engineering Plant Cost Index (CEPCI) correlation rate according to the year of the reference, i.e., Swanson et al. (2010). The calculation of this factor is expressed in (8) by:

$$CB = CA * \frac{ValorIndiceB}{ValorIndiceB} \tag{8}$$

where *CB* was the current cost in *M*€, *CA* is the older cost in *M*€, value index *B* is the updated CEPCI (dimensionless), and value index *A* is the CEPCI considering the year of the reference (i.e., 2010) (dimensionless) (Table 4).

Table 4 Inflation adjustment

Parameter	*Value*	*References*
CB*	–	–
CA	498	Swanson et al. (2010)
Value B (CEPCI, 2018)	603.1	CEPCI (2019)
Value A (CEPCI, 2007)	525.4	CEPCI (2019)

Note: Depends on the straw productivity of each country and the calorific value (Appendix B).

Table 5 describes the steps to quantify the total capital investment cost, adding the total installed costs, being 1,.0 of the total capital investment cost (TCI) (NETL, 2010;Tagomori et al., 2019). A contingency cost of 20% and a working capital of 10% (Tagomori et al., 2019) were applied. The operation and maintenance (O&M) costs were established at 4% of the TCI (Tagomori et al., 2019).

Table 5 Total capital investment cost (TCI)

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 6 Adjustment costs

Parameters	*Value*	*References*
10 years average interest rate (IR) (%)	0.14	CEIC (2020)
Biomass cost (€/ton)		
Wheat straw	59.00	PigWorld (2020)
Barley straw	65.00	PigWorld (2020)
Maize straw	36.40	NDA (2020)
Electricity ((€/MWh)	76.00–269.00	GlobaPetrolPrices.com (2020)
Bio – LPG (€/ton)	770.00	GlobaPetrolPrices.com (2020)
Bio – naphtha (€/ton)	600.00	Trading Economics (2020)
Bio – gas oil (€/ton)	750.00	Ship and Bunker (2020a)
Bio FT-diesel (€/ton)	750.00	Ship and Bunker (2020a)

Table 6 demonstrates the data to quantify the respective cost of biomass, electricity, average EU 10-year IR, revenues obtained from bio FT-diesel, and its by-products. It is worth emphasising that the electricity cost will be calculated differently according to the respective countries' prices (GlobaPetrolPrices.com, 2020).

The LCOE of the bio FT-diesel will be determined according to equations 9 and 10 (Tagomori et al., 2019).

$$CRF = r / \left(1 - (1 + r)\right)^{-L} \tag{9}$$

where CRF is the capital recovery factor based on the 0.14 IR (CEIC, 2020), r is the IR, and *L* is the lifespan of the plant unit (20 years).

$$LCOE = (CRF * TCI) + (O \& M + Biomass + Electricity - by - prduct) / (FT\ Diesel) \tag{10}$$

where LCOE of the bio FT-diesel €/*GJ*, *CRF* is the capital recovery factor (%). TCI is the total capital investment in M€, O&M is the operation and maintenance in M€, annual biomass cost in M€, the electricity in M€, the by-products in M€, and annual Bio FT-diesel in GJ/year. All these values are based on 8000 hours of work per year.

Table 7 Currency rates conversion

Conversion		*Reference*
Pounds	Euro	Exchange Rates (2020)
1	1.16	
Dollar	Euro	
1	0.91	

Table 7 displays the conversion rates used in this study and were based on the rates from May 3rd, 2020.

Table 8 MGO and Barrel of oil cost over the years

Year	*EU Brent Spot Price €/GJ (EIA, 2020)*	*MGO €/GJ (Ship and Bunker, 2020a)*
2000	4.26	10.87
2001	3.64	10.11
2002	3.72	9.86
2003	4.29	10.11
2004	5.69	12.64
2005	8.11	20.22
2006	9.69	27.81
2007	10.77	28.31
2008	14.42	30.33
2009	9.18	25.28
2010	11.84	30.33
2011	16.54	40.44
2012	16.60	45.50
2013	16.14	37.92
2014	14.72	40.44
2015	7.78	25.28
2016	6.49	20.22
2017	8.05	22.75
2018	10.61	14.41

To determine the break-even oil price, the historic price of the Europe Brent Spot (EIA, 2020) and the MGO (Ship and Bunker, 2020b) were used and split into two periods (average cost of crude oil between 2000–2018 and maximum value of crude oil already registered in 2012). Table 8 presents these prices, followed by equations (11) and (12) (Tagomori et al., 2019).

$$Ratio\ Oil\_MGO = {Oil\ \ price\ (€ / GJ)} \Big/ {MGO\ \ price\ (€ / GJ)} \tag{11}$$

where *Ratio Oil_MGO* represents the correlation of the *Oil price* (€/*GJ*), and *MGO* price (€/*GJ*).

$$Break\ even\ oil\ \ price = bio\ FT\text{-}diesel\ cost * Ratio\ MGO \tag{12}$$

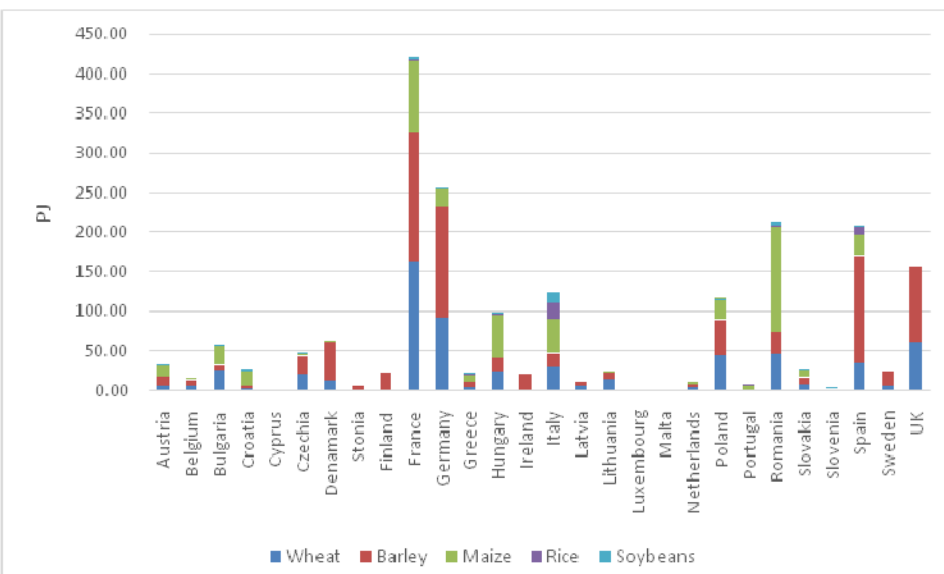
where the break-even oil price should be the crude oil cost (€/*GJ*) to make bio FT-diesel LCOE (€/*GJ*) competitive compared with the *MGO*.

4 Results and discussion

4.1 Preliminary results of the European crops energy potential

The FAO (2019) research on the main cereal crops produced in Europe demonstrated that the continent has a total primary energy potential of 2,000 PJ (Figure 2), which corroborates the IRENA (2016) results.

Figure 2 TPES from agriculture residues in Europe (see online version for colours)



France, Germany, Hungary, Poland, Romania, Spain, and the UK, represented more than 70% of the total primary energy supply (TPES). However, the assumptions were valid for agricultural areas of 0.750 Mha (50 km radius) from the collection centre, obtaining high concentration of biomass for bio-based transformation plants.

4.2 Limitation of explored areas

The applied limitation area (0.750 Mha) reduced the TPES significantly to the commodities of wheat, barley, and maize to a technical potential of 1,450 PJ (Figure 3). The technical potential energy is important to find the total potential number of plants[3] per country.

Figure 3 Total and technical potential of TPES in EU-28 (see online version for colours)

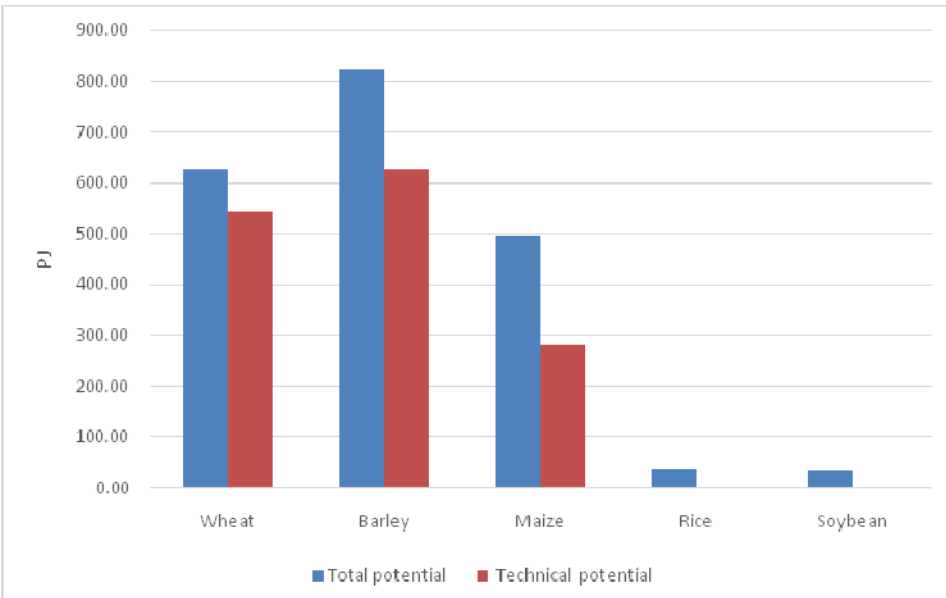


Table 9 Mass balance from wheat straw bio FT-diesel

Countries	*Biomass input (ton/h)*	*Bio LPG (ton/h)*	*Bio Naphtha (ton/h)*	*Bio FT-diesel (ton/h)*	*Bio-gasoil*	*Number of plant units*
Bulgaria	84.71	2.35	3.13	8.07	0.73	2
Czechia	128.40	3.56	4.75	12.23	1.11	1
France	148.57	4.12	5.50	14.15	1.28	7
Germany	147.14	4.08	5.44	14.01	1.27	4
Hungary	152.59	4.23	5.64	14.53	1.31	1
Italy	100.86	2.80	3.73	9.60	0.87	2
Poland	95.07	2.64	3.52	9.05	0.82	3
Romania	98.22	2.72	3.63	9.35	0.85	3
Spain	77.37	2.14	2.86	7.37	0.67	3
UK	176.81	4.90	6.54	16.83	1.52	2
Total	1,209.75	33.53	44.75	115.18	10.42	28

The results from wheat straw (Table 9) limited the exploration of the biomass resource in ten countries only, with the input biomass ranging between 77.37–176.81 ton/h and bio FT-diesel production of 7.37–16.83 ton/h. The total potential number of plants reached 28. France and Germany have the highest potential number as they are the largest wheat producers in Europe.

Table 10 Overall energy balance from wheat straw

Countries	*Biomass input (GJ/year)*	*Bio LPG output (GJ/year)*	*Bio naphtha (GJ/year)*	*Bio FT diesel (GJ/year)*	*Bio gasoil (GJ/year)*	*Electricity consumption MWh/year*	*Number of plant units*
Bulgaria	13.240.000	926.974	1.191.824	2.913.347	264.850	221.883	2
Czechia	20.070.000	1.405.025	1.806.460	4.415.792	401.436	336.310	1
France	23.224.286	1.625.696	2.090.181	5.109.331	464.485	389.131	7
Germany	23.002.500	1.610.112	2.070.144	5.060.352	460.032	385.400	4
Hungary	23.850.000	1.669.751	2.146.823	5.247.790	477.072	399.676	1
Italy	15.765.000	1.103.630	1.418.952	3.468.550	315.323	264.167	2
Poland	14.863.333	1.040.322	1.337.557	3.269.583	297.235	249.014	3
Romania	15.353.333	1.074.787	1.381.870	3.377.903	307.082	257.264	3
Spain	12.093.333	846.600	1.088.486	2.660.743	241.886	202.644	3
UK	30.770.000	1.934.715	2.487.490	1.689.037	552.776	463.098	2

The overall energy balance from wheat straw from the 28 plant units (Table 10) gives a TPES of 544.10^6 GJ, capable of delivering more than the equivalent of 19 million barrels of oil per year (MBOE)[4] in bio FT-diesel. France and Germany represented almost 50% of the capacity. In total, energy consumption would be 3.168.587 MWh/year.

The energy consumption and product output were proportional to the input of biomass in each plant unit.

The results for barley straw show that the comparison of the European TPES was limited to Denmark, France, Germany, Poland, Spain, and the UK only, who were capable of processing a range of biomass between 94.40–602.12 ton/h (11 plant units in total). Table 11 illustrates the mass balance from barley straw bio FT-diesel.

Table 11 Mass balance from barley straw bio FT-diesel

Countries	*Biomass input (ton/h)*	*Bio LPG (ton/h)*	*Bio naphtha (ton/h)*	*Bio FT-diesel (ton/h)*		*Number of plant units*
Denmark	322.22	8.99	12.00	30.90	2.80	1
France	517.46	14.44	19.28	49.62	4.49	2
Germany	443.35	12.38	16.52	42.51	3.85	2
Poland	94.40	2.64	3.52	9.05	0.82	1
Spain	281.25	7.85	10.48	26.97	2.44	3
UK	602.12	16.81	22.43	57.74	5.22	1
Total	2,260.80	63.11	84.23	216.80	19.62	11

The six countries would be capable of processing around 356.106 GJ of TPES and delivering around 13 MBOE of bio FT-diesel (Table 12). The main producers would be France, Germany, and Spain with 70% off all products.

Table 12 Energy balance from barley straw bio FT-diesel

Countries	*Biomass input*	*(GJ/year)*	*Bio LPG output (GJ/year)*	*Bio naphtha (GJ/year)*	*Bio FT diesel GJ/year*	*Bio gasoil GJ/year*	*Electricity consumption MWh/year*
Denmark	50.730.101	3.551.107	4.565.709	11.160.622	1.014.602	850.002	1
France	81.469.373	5.702.856	7.332.244	17.923.262	1.629.387	1.365.050	2
Germany	69.801.563	4.886.109	6.282.141	15.356.344	1.396.031	1.169.551	2
Poland	14.861.742	1.040.322	1.337.557	3.269.583	297.235	249.014	1
Spain	44.279.847	3.099.589	3.985.186	9.741.566	885.597	741.925	3
UK	94.797.112	6.635.798	8.531.740	20.855.365	1.895.942	1.588.361	1

The maize straw scenario had the fewest limitations as Europe is not the most representative producer (11.2% of the world's production) (FAO, 2019). However, France, Hungary, and Romania presented harvesting areas capable of being explored for bio FT-diesel production. Six plants could explore a total of $146.5.10^6$ GJ per year and produce 5.3 MBOE of bio FT-diesel (Table 14) a process between 297.41–302.89 ton/h of biomass, and produce between 27.06–34.65 ton/h of bio FT-diesel (Table 13).

Table 13 Mass balance from maize straw bio FT-diesel

Countries	*Biomass input (ton/h)*	*Bio LPG (ton/h)*	*Bio naphtha (ton/h)*	*Bio FT-diesel (ton/h)*	*Bio gasoil (ton/h)*	*Number of plant units*
France	302.89	8.02	10.71	27.55	2.49	2
Hungary	380.93	10.09	13.46	34.65	3.14	1
Romania	297.41	7.88	10.51	27.06	2.45	3
Total	981.23	25.99	34.68	89.26	8.08	6

Table 14 Energy balance from maize straw bio FT-diesel

Countries	*Biomass input (GJ/year)*	*Bio LPG output (GJ/year)*	*Bio naphtha (GJ/year)*	*Bio FT diesel (GJ/year)*	*Bio Gasoil (GJ/year)*	*Electricity consumption (MWh/year)*
France	45.238.935	3.166.725	4.071.504	9.952.566	904.779	757.995
Hungary	56.896.024	3.982.722	5.120.642	12.517.125	1.137.920	953.314
Romania	44.421.543	3.109.508	3.997.939	9.772.739	888.431	744.299
Total*	146.556.501	10.258.955	13.190.085	32.242.430	2.931.130	2.455.609

Note: Regarding six plant units.

The results for rice and soybean straw did not present effective numbers of areas to explore bio FT-diesel production as the continent is not a strong producer of those commodities.

France presented the best results as a potential bio FT-diesel producer among all others due to its large agricultural area. France alone would have the potential to produce more than 10 MBOE of Bio-FT Diesel (1/3 of the total potential producers).

4.3 Economic results

The LCOE presented high costs in all scenarios of straw exploration (wheat, barley, and maize). Figure 4 displays the average percentage of each component that composes the total LCOE in each bio FT-diesel production. A high influence of TCI on the wheat and maize straw LCOE can be seen, whereas the biomass had the greatest influence on barley.

Figure 4 Average percentage of composition cost (see online version for colours)

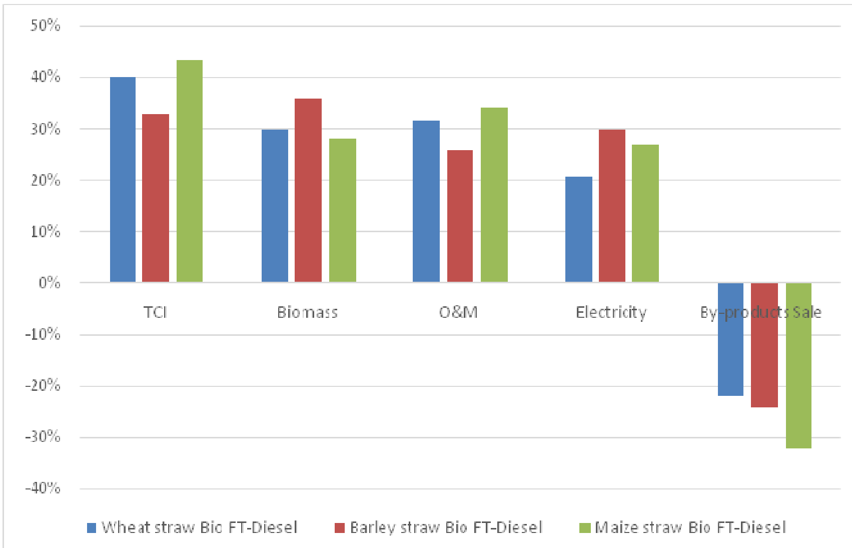
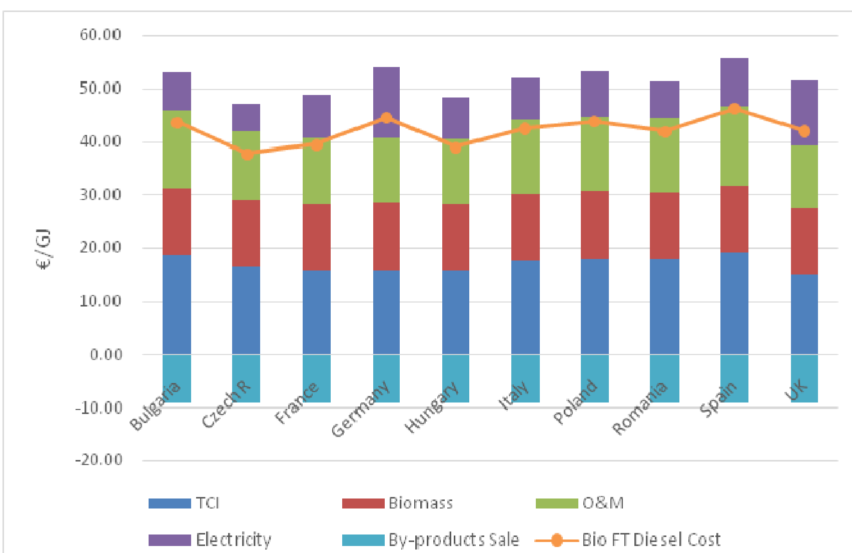


Figure 5 LCOE composition costs wheat straw bio FT-diesel (see online version for colours)

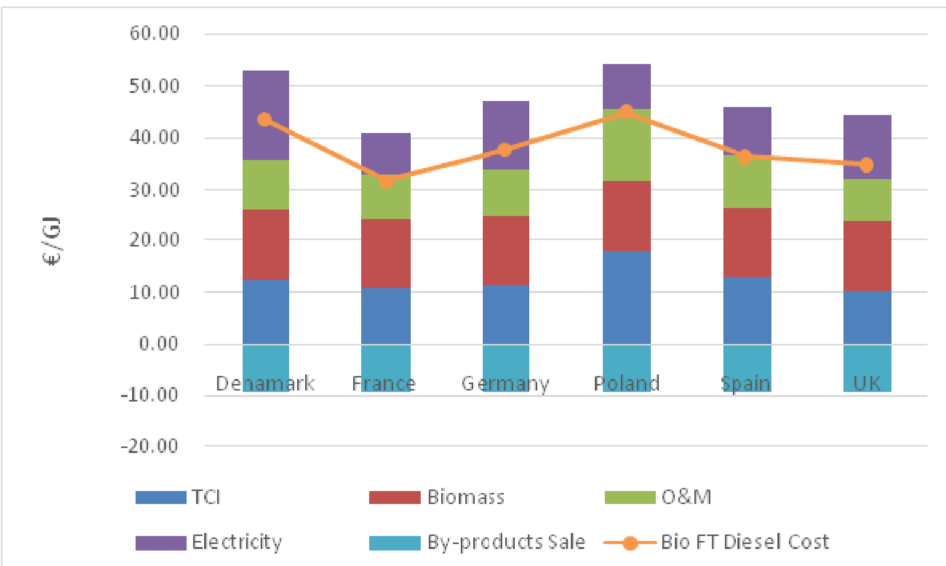


The maize straw bio FT-diesel had the lowest cost (24.25%, 31.23% less than barley straw bio FT-diesel and wheat straw bio FT-diesel respectively), due to the LCOE of the biomass. The maize straw cost used in €/ton is 38.98% and 44% cheaper than wheat and barley straw respectively and influenced by the low cost of electricity commercialised in France (117 €/MWh), Hungary (113 €/MWh), and Poland (101 €/MWh).

Wheat straw bio FT-diesel had the highest cost in comparison to the other biofuels (Figure 5). In total, the ten countries had an average LCOE production of 42.11 €/GJ, in a range of 38.89–46.30€/GJ. The lowest cost was the Czech Republic, influenced by the low cost of electricity (76 €/MWh) (GlobaPetrolPrices.com, 2020), and the highest was Spain with 46.30 €/GJ, influenced by the high TCI.

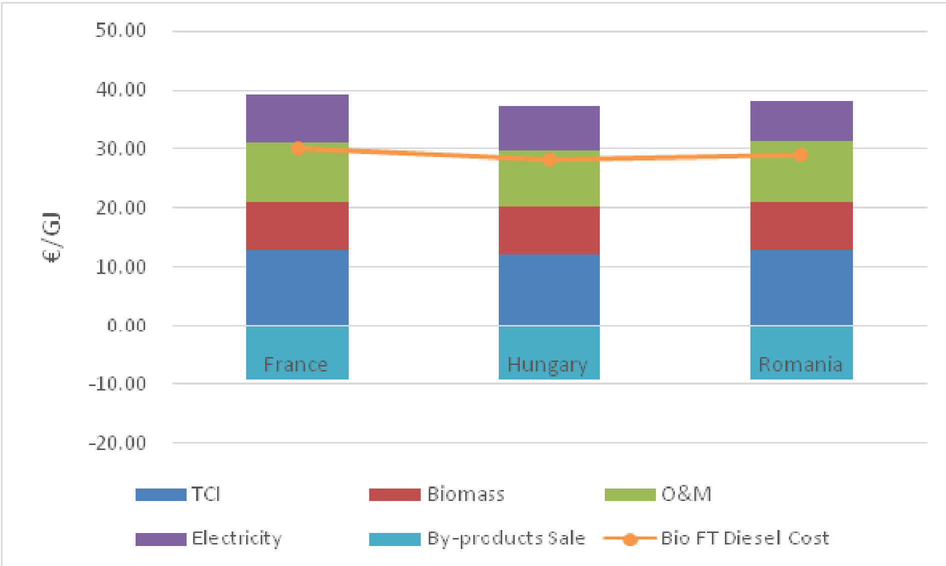
The high TCI of the LCOE in the wheat straw bio FT-diesel in Spain is due to the lowest biomass processing capacity (420 MWth of wheat straw processed) in comparison with the other countries. This impacts the final products in energy availability per year.

Figure 6 LCOE composition costs barley straw bio FT-diesel (see online version for colours)



The barley straw bio FT-diesel presented a slightly lower average LCOE than the wheat straw of 38.23 €/GJ, with values between 31.76–43.58 (Figure 6). France once again represented the lowest, influenced by the low cost of energy in comparison to the other countries. Poland showed the highest average LCOE due to its high TCI as a result of having the lowest factory capacity (516 MWth) (Appendix B), which impacts the final production and energy availability per year.

Figure 7 LCOE compositions costs maize straw bio FT-diesel (see online version for colours)



The LCOE of bio FT-diesel from maize straw, as mentioned before, presented the lowest value in comparison with the other crops. The results reached a range of 28.07–29.91 and an average of 28.96 €/GJ (Figure 7). All three countries (France, Hungary, and Romania) presented approximately similar values for all composition costs.

All the results were 1.45–2 times more expensive than the marine gasoil currently utilised in the maritime sector. It shows that the renewable option is not economically competitive.

The LCOE of different residues approached in this work were calculated for each country to present the share of costs. The capital cost corresponded to around one-third of the total LCOE of all crops used in this bio FT-diesel simulation.

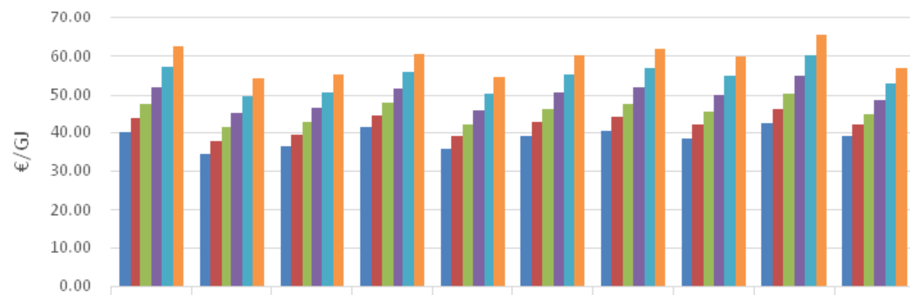
The results showed some LCOE similarities with Tagomori et al. (2019) whose results reached 36.33 €/GJ for eucalyptus-based diesel while for Pinus-based diesel 34.89 €/GJ. In the NETL (2010) study that explored corn stover, the results were 36.40 €/GJ. For Meerman et al. (2013, 2012) the results were 20 €/GJ and 22.75 €/GJ, respectively. It is important to mention that all the results presented in this paragraph were simulated in a cross flow gasifier operating between 1,300ºC–1,500ºC.

4.4 Valuation sensitivity regarding the IR variation

One of the main factors that influence the LCOE is the IR. In Europe, the rate has worked at a low value as part of the economic policies (0.14% ten-year average) (CEIC, 2020).

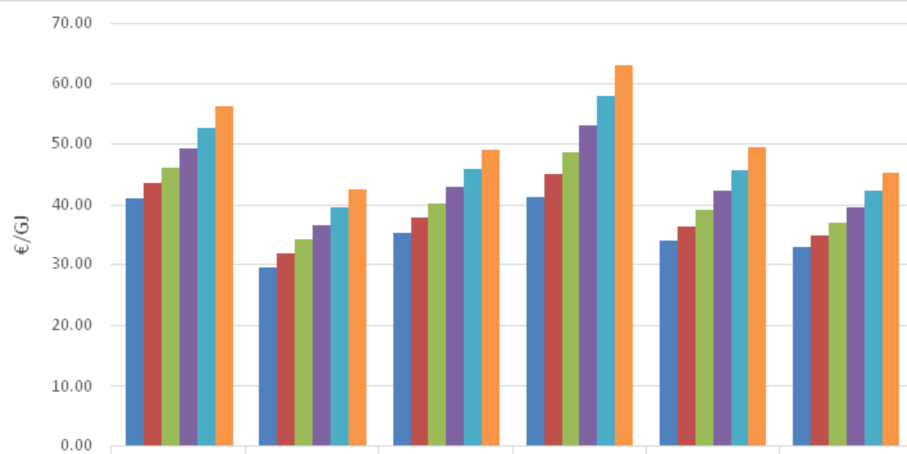
This section presented data on how the average LCOE would behave with the IR variation between –2% and 8%. Figure 8 displays the sensitive analysis regarding Bio FT-Diesel wheat straw, while Figures 9 and 10 show the same assessment for barley and maize straw bio FT-diesel, respectively.

Figure 8 Sensitivity analyses bio FT-diesel from wheat straw (see online version for colours)



	Bulgaria	Czech R	France	Germany	Hungary	Italy	Poland	Romania	Spain	UK
-2%	39.82	34.36	36.18	41.33	35.66	38.90	40.16	38.30	42.34	38.92
0,14%	43.67	37.76	39.43	44.60	38.89	42.56	43.88	41.98	46.30	42.01
2%	47.47	41.11	42.64	47.32	42.08	46.16	47.55	45.62	50.21	45.06
4%	52.00	45.11	46.47	51.65	45.87	50.46	51.93	49.95	54.86	48.69
6%	56.96	49.49	50.66	55.36	50.03	55.17	56.72	54.69	59.96	52.67
8%	62.31	54.21	55.18	60.39	54.51	60.24	61.88	59.81	65.45	56.96

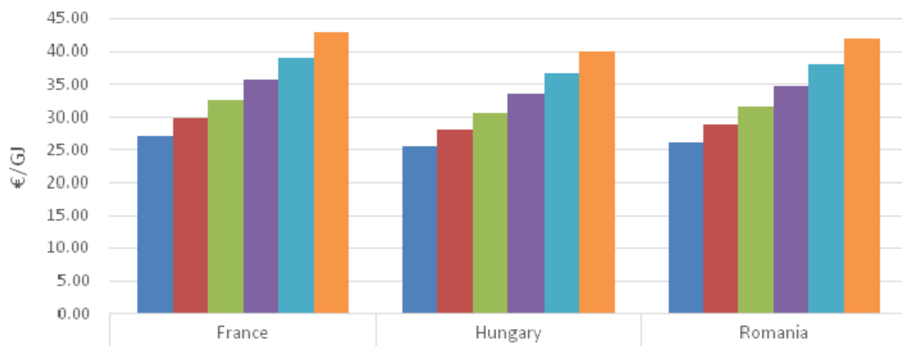
Figure 9 Sensitivity analyses bio FT-diesel from barley straw (see online version for colours)



	Denamark	France	Germany	Poland	Spain	UK
-2%	41.00	29.52	35.40	41.25	33.75	32.77
0,14%	43.58	31.76	37.75	44.97	36.43	34.91
2%	46.12	33.96	40.05	48.64	39.08	37.01
4%	49.14	36.58	42.81	53.02	42.23	39.52
6%	52.46	39.46	45.82	57.81	45.68	42.27
8%	56.03	42.56	49.07	62.97	49.40	45.23

In all scenarios, the same curve of LCOE price was observed. The lowest IR value was –2% and the highest 8%, as expected.

Figure 10 Sensitivity analyses bio FT-diesel from maize straw (see online version for colours)



	France	Hungary	Romania
-2%	27.25	25.59	26.21
0,14%	29.91	28.07	28.89
2%	32.54	30.52	31.53
4%	35.67	33.45	34.68
6%	39.10	36.65	38.13
8%	42.80	40.10	41.85

4.5 Break-even oil price

To assess the competitiveness of bio FT-diesel from wheat, barley, and maize straw in comparison with marine fossil fuel, a correlation cost was used as a benchmark between the average price of crude oil and MGO between 2000 and 2018 (break-even oil average), and the correlation cost between the crude oil price and the MGO price in 2012 alone (break-even oil maximum 2012, when the price of crude oil reached the highest value ever commercialised).

Figure 11 shows the competitiveness of wheat straw bio FT-diesel for the ten potential producer countries. The results indicate the feasibility of the biofuel only if the crude oil is commercialised in a range of 13.58–16.66 €/GJ (break-even oil maximum (2012) and the range of 15.19–18.63 €/GJ (break-even oil average).

Following the same trend of the results in section 3.3, the lowest values were from the Czech Republic, influenced by the low electricity price, and the highest from Spain due to the lower production capacity.

Regarding the barley straw bio FT-diesel (Figure 12), the results show the competitiveness of six potential producers, only if the price of crude oil reaches the value between 11.42–16.18 €/GJ (break-even oil maximum (2012) and 12.78–18.09 €/GJ (break-even oil average).

France has the lowest value influenced by electricity cost, and Poland has the highest influence by the highest TCI, also mentioned in Section 3.3.

The results of the maize straw bio FT-diesel (Figure 13) presented the most competitive price in a range of 10.10–10.76 €/GJ, for Break-even oil maximum in 2012, and 11.29–12.03 €/GJ for the break-even oil average.

Figure 11 Break-even oil price to wheat straw FT biodiesel (see online version for colours)

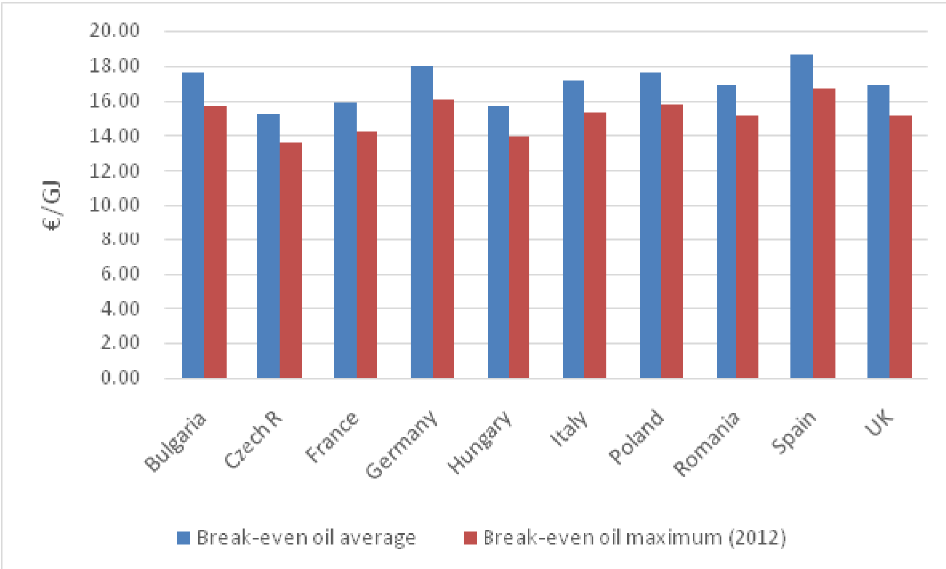
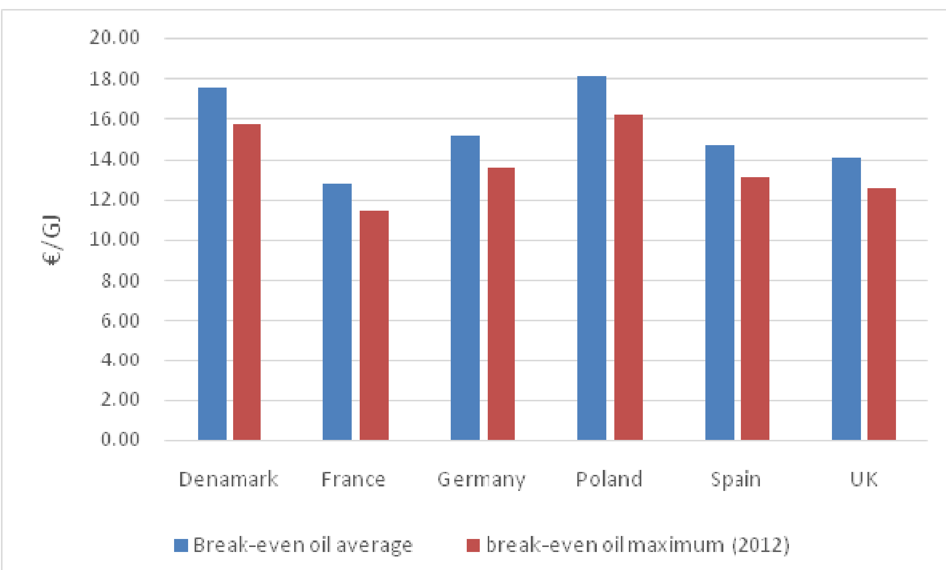


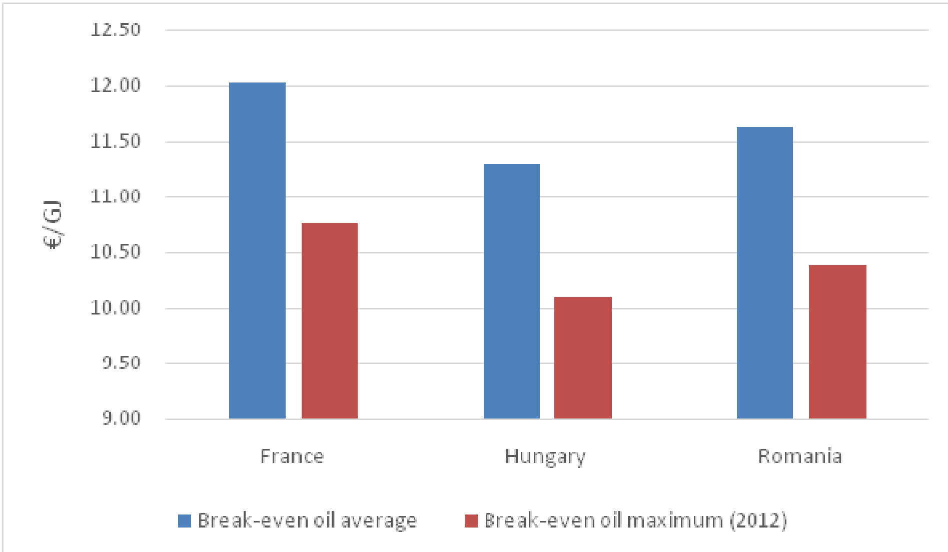
Figure 12 Break-even oil price to barley straw FT biodiesel (see online version for colours)



As in Section 3.3, maize demonstrated the lowest value due to the significantly lower biomass cost.

It is important to mention that, in all cases, the break-even oil average presented higher values than the break-even oil maximum (2012), due to the higher ratio value of the break-even oil average (the price of crude oil and MGO available in Table 10).

Figure 13 Break-even oil price to maize straw FT biodiesel (see online version for colours)



4.6 Potential ports and carbon accounts according to region

According to the United Nations Conference on Trade and Development (UNCTDA, 2019), the container port throughput accounted for 111 million of the twenty-foot equivalent (MTEU), corresponding to 15% of the world port activities (Figure 14). The data from the International Council on Clean Transportation (ICCT, 2013) presented the average carbon intensity of the cargo ships of 150 gCOeq/TEU-NM. This data showed that European shipping activity was responsible for around 27 Mton of consumed HFO and 84 Mton of CO_2respectively emitted by the container cargo ships.

Table 15 HFO replacement in European ports

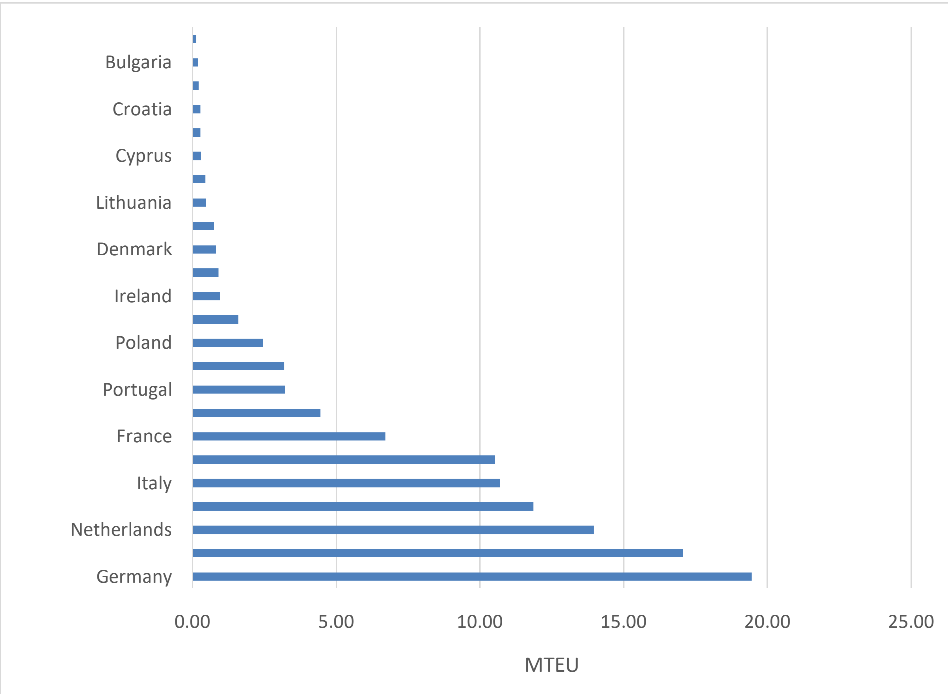
Countries	*Mton of HFO*	*Mton bio FT-diesel*	*Replacement factor*
Germany*	4.59	1.36	0.30
Spain	4.03	0.96	0.24
Italy	2.52	0.17	0.07
UK	2.48	0.80	0.32
France	1.58	2.27	1.44
Poland	0.58	0.74	1.28
Denmark	0.19	0.27	1.39
Romania**	0.18	1.75	9.89
Bulgaria	0.05	0.14	5.58
Total	16.20	8.47	0.52

Notes: The Czech Republic production was allocated to Germany as there is no seaport in the country. The Hungary production was allocated to Romania as there is no seaport in the country.

Table 15 displays the HFO oil consumed per country according to their TEU activity, the bio FT-diesel potential of all crops, and the biofuels replacement factor of each country (correlation bio FT-diesel production and consumed HFO).

The Bio FT-biodiesel potential could replace around 52% of the HFO consumed by the container ships in Europe (Table 15).

Figure 14 European port activity (see online version for colours)



Source: UNCATSTAT (2019)

Romania and Bulgaria had the highest replacement factor (Table 15) as their ports have a low TEU activity and, consequently, low fuel consumption in comparison with other ports such as Germany, Italy, and Spain.

Countries such as France, Poland, Denmark, Romania and Bulgaria could sell their surplus production as an alternative, which could increase the final cost of the Bio FT-Diesel at the ports.

5 Conclusions

The EU, more than any other region, has sought alternatives to make the maritime transport sector less carbon-intensive. Europe has one of the busiest maritime activities in the world (UNCTAD, 2019), which makes it the second-highest GHG emitter in the global maritime transport sector.

Numerous studies worldwide have suggested clean fuel alternatives, such as hydrogen, solar, and wind resources but liquid fuel still represents a greater impact on the maritime sector decarbonisation.

This study was important to show how the lignocellulosic resources from crops combined with the FT route can represent a vast potential for exploration toward the European maritime sector's energy independence.

Wheat was found to be the most important crop in EU countries (138 Mha), followed by barley (56.5 Mha) and maize (69.5 Mha). Nevertheless, only 15%, 15.7%, and 6.9% of planted wheat, barley, and maize areas, respectively, could be explored feasibly.

Around 28 plant units of the crops studied corresponded to approximately 36 GW of installed capacity, capable of producing 8.47 Mton of bio FT-diesel annually and reducing 10% of the consumption of HFO on the European continent. The study pointed out 11 countries with a high potential for biofuel production due to their large crop areas.

Countries such as France, Poland, Denmark, Romania, and Bulgaria would have surplus production of bio FT-diesel, which could then potentially be commercialised with other European countries.

France was found to have the greatest area of crops in this study (23.9% of the 11 countries) and is, consequently, the most important producer of bio FT-diesel (2.27 Mton annually) in Europe.

When the economic factors were applied using an average IR of the last ten years (0.14%) the LCOE of bio FT-diesel had a cost of 42.11 €/GJ for wheat straw, 38.23 €/GJ for barley straw, and 28.96 €/GJ for maize straw. The maize straw had the lowest cost due to the lower cost of biomass and electricity. The sensitive valuation regarding the IR variation showed the same trend of LCOE.

Countries with lower-capacity industries such as Spain, Poland, and Denmark, had high LCOE influenced by the low biofuel production capacity.

The competitiveness (break-even oil cost) of the routes would vary according to each feedstock used. The bio FT-diesel would become a viable option only if the crude oil reaches high prices of commercialisation.

The high investment cost of the biomass to the bio FT-diesel route remains an obstacle. The low technological development of production needs more investments and R&D to bring effective yields, yet there are still no maritime engine biofuel standards in place as there are for bio ethanol and biodiesel for road vehicles in Europe, the USA, and Brazil. Furthermore, the low value of fossil fuel makes the competition unfair for advanced biofuel routes. Measures such as carbon pricing and split incentives for producers and consumers could make this route more accessible toward maritime decarbonisation in the future.

The study proved to be pertinent as it successfully identified potential regions with a large harvesting area that could become great precursors for a transition to a maritime transport sector based on renewable fuel sources.

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 Europe Union (EU), under the grant number PD/BD/142848/2018.

References

Acomi, N. and Acomi, O.C. (2014) 'Improving the voyage energy efficiency by using EEOI', *Procedia – Social and Behavioral Sciences*, Vol. 138, pp.531–536, Elsevier B.V., DOI: 10.1016/j.sbspro.2014.07.234.

Altieri, M.A. (1999) 'The ecological role of biodiversity in agro ecosystems', *Agriculture Ecosystems & Environment*, Vol. 74, Nos. 1–3, pp.19–31, doi: 10.1016/S0167-8809(99)00028-6..

Ančić, I. and Šestan, A. (2015) 'Influence of the required EEDI reduction factor on the CO2 emission from bulk carriers', *Energy Policy*, Vol. 84, pp.107–116, DOI: 10.1016/j.enpol.2015.04.031.

Andrews, A. and Logan, J. (2008) 'Fischer-Tropsch fuels from coal, natural gas, and biomass: background and policy', in *CRS Report for Congress*, p.34.

Balcombe, P. et al. (2019) 'How to decarbonise international shipping: options for fuels, technologies and policies', *Energy Conversion and Management*, October 2018, Vol. 182, pp.72–88, DOI: 10.1016/j.enconman.2018.12.080.

Bannon, E. (2015) 'Shipping emissions 17% of global CO2, making it the elephant in the climate negotiations room', *Transport & Environment* [online] https://www.transportenvironment.org/press/shipping-emissions-17-global-co2-making-it-elephant-climate-negotiations-room (accessed 1 February 2020).

Bouman, E.A. et al. (2017) 'State-of-the-art technologies, measures, and potential for reducing GHG emissions from shipping – a review', *Transportation Research Part D: Transport and Environment*, The Authors, Vol. 52, pp.408–421, DOI: 10.1016/j.trd.2017.03.022.

CEIC (2020) *European Union Long Term Interest Rate* [online] https://www.ceicdata.com/en/indicator/european-union/long-term-interest-rate (accessed 5 February 2020).

CEPCI (2019) *Chemical Engineering Plant Cost Index* [online] https://www.chemengonline.com/site/plant-cost-index/ (accessed 7 February 2019).

Damartzis, T. and Zabaniotou, A. (2011) 'Thermochemical conversion of biomass to second generation biofuels through integrated process design – a review', *Renewable and Sustainable Energy Reviews*. Elsevier Ltd, Vol. 15, No. 1, pp.366–378, DOI: 10.1016/j.rser.2010.08.003.

Douvartzides, S.L. et al. (2019) 'Green diesel: biomass feedstocks, production technologies, catalytic research, fuel properties and performance in compression ignition internal combustion engines', *Energies*, Vol. 12, No. 5, DOI: 10.3390/en12050809.

EIA (2020) *Petroleum & Other Liquids, U.S energy Information Administration – European Brent Spot Price* [online] https://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=pet&s=rbrte&f=a (accessed 6 February 2020).

Eurostat (2018) *Agriculture, Forestry and Fishery Statistics 2018 Edition Eurostat* [online] https://ec.europa.eu/eurostat/documents/3217494/9455154/KS-FK-18-001-EN-N.pdf/a9ddd7db-c40c-48c9-8ed5-a8a90f4faa3f (accessed 10 March 2020).

Exchange Rates (2020) *Currency Rates* [online] https://www.exchangerates.org.uk/GBP-EUR-exchange-rate-history.html (accessed: 5 February 2020).

FAO (2019) *Food and Agriculture Data*, Faostat [online] http://www.fao.org/faostat/en/#home (accessed: 20 February 2020).

Florentinus, A. et al. (2012) *Potential of Biofuels For Shipping*, Ultrecht, Netherlands.

Geerlings, J.J.C. et al. (1999) 'Fischer-Tropsch technology – from active site to commercial process', *Applied Caralysis*, Vol. 186, Nos. 1–2, pp.27–40, doi: 10.1016/S0926-860X(99)00162-3.

GlobaPetrolPrices.com (2020) *Retail Energy Price Data* [online] https://www.globalpetrolprices.com/countries/ (accessed 5 February 2020).

Gousi, M. et al. (2017) 'Green diesel production over nickel-alumina co-precipitated catalysts', *Applied Catalysis A: General*, Vol. 536, pp.45–56, Elsevier B.V., DOI: 10.1016/j.apcata.2017.02.010.

Holmgren, K.M. et al. (2015) 'Perspectives on investment cost estimates for gasification-based biofuel perspectives on investment cost estimates for gasification-based biofuel production systems', *Chemical Engineering Transactions*, September, Vol. 45, pp.427–432, DOI: 10.3303/CET1545072.

Holmgren, K.M. (2015) *Investment Cost Estimates For Gasification-Based Biofuel Production Systems*, Stockholm, Sweden [online] https://www.ivl.se/download/18.7e136029152c7d48c202a1d/1465298345076/B2221.pdf (accessed 6 May 2020).

Hsieh, C-W.C. and Felby, C. (2017) *Biofuels for the Marine Shipping Sector – An Overview and Analysis of Sector Infrastructure, Fuel Technologies and Regulations*, Copenhagen-Denmark [online] http://task39.sites.olt.ubc.ca/files/2013/05/Marine-biofuel-report-final-Oct-2017.pdf (accessed 22 April 2020).

ICCT (2013) *Consumers, Shipping, and Our Carbon Footprint* [online] https://theicct.org/blogs/staff/consumers-shipping-and-our-carbon-footprint (accessed 5 February 2020).

IEA (2018) *Commentary: International Maritime Organization Agrees to First Long-Term Plan to Curb Emissions* [online] https://www.iea.org/newsroom/news/2018/april/commentary-imo-agrees-to-first-long-term-plan-to-curb-shipping-emissions.html, (accessed: 10 March 2020).

International Maritime Organization (IMO) (2011) *Resolution MEPC* [online] http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Documents/TechnicalandOperati onal Measures/Resolution MEPC.203(62).pdf.

International Maritime Organization (IMO) (2014) *Third IMO Greenhouse Gas Study 2014*, London [online] file:///C:/Users/HP/OneDrive/Favoritos/doutorado/Doutorado/Conferencias2019/EFS2019/Regulationsinforce/GHG3Executive Summary and Report.pdf.

International Maritime Organization (IMO) (2018) *Adoption of the Initial IMO Strategy on Reduction of GHG Emissions from Ships and Existing IMO Activity Related to Reducing GHG Emissions in the Shipping Sector*, London, p.27 [online] https://unfccc.int/sites/default/files/resource/250_IMOsubmission_TalanoaDialogue_April2018.pdf (accessed 10 June 2020).

International Maritime Organization (IMO) (2019) *Special Areas Under MARPOL* [online] http://www.imo.org/en/OurWork/Environment/SpecialAreasUnderMARPOL/Pages/Default.aspx (accessed 15 March 2020).

IRENA (2016) *Innovation Technology Outlook for Advanced Liquid Biofuels*, International Renewable Energy Agency (IRENA) [online] http://www.irena.org/-/media/Files/IRENA/Agency/Publication/2016/IRENA_Innovation_Outlook_Advanced_Liquid_Biofuels_2016.pdf (accessed 5 May 2020).

Johansson, D., Berntsson, T. and Franck, P.Å. (2014) 'Integration of Fischer-Tropsch fuel production with a complex oil refinery', *International Journal of Environment and Sustainable Development*, Vol. 13, No. 1, pp.50–73, DOI: 10.1504/IJESD.2014.056413.

Johnson, H. et al. (2013) 'Will the ship energy efficiency management plan reduce CO2 emissions? A comparison with ISO 50001 and the ISM code', *Maritime Policy and Management*, Vol. 40, No. 2, pp.177–190, DOI: 10.1080/03088839.2012.757373.

Lapuerta, M. et al. (2010) 'Potential for reducing emissions in a diesel engine by fuelling with conventional biodiesel and Fischer-Tropsch diesel', *Fuel*, Vol. 89, No. 10, pp.3106–3113, DOI: 10.1016/j.fuel.2010.05.013.

Machado, L.R. (2014) *Dimensionamento De Sistema De Corte, Carregamento E Transporte Do Eucalipto*, Master thesis – Escola de Economia de São Paulo da Fundação Getúlio Vargas – FGV-EESP.

Meerman, J.C. et al. (2012) 'Performance of simulated flexible integrated gasification polygeneration facilities, part B: economic evaluation', *Renewable and Sustainable Energy Reviews*, Vol. 16, No. 8, pp.6083–6102, DOI: 10.1016/j.rser.2012.06.030.

Meerman, J.C. et al. (2013) 'The techno-economic potential of integrated gasification co-generation facilities with CCS Going from coal to biomass', *Energy Procedia*. Elsevier B.V., Vol. 37, pp.6053–6061, DOI: 10.1016/j.egypro.2013.06.534.

Nebraska Department of Agriculture (NDA) (2020) *Corn Stalk Bale Price* [online] https://nda.nebraska.gov/promotion/hay/sellers.pdf, (accessed 5 February 2020).

National Energy Technology Laboratory (NETL) (2010) *Cost and Performance Baseline for Fossil Energy Plants, Volume 1: Bituminous Coal and Natural Gas to Electricity*, US Department of Energy (DOE), DOI: 2013 DOE/NETL-2010/1397.

PigWorld (2020) *Straw Prices for the Week Ending*, 31 May [online] http://www.pig-world.co.uk/news/weekly_bhsma_straw-prices.html (accessed 5 February 2020).

Pimentel, D. and Kounang, N. (1998) 'Ecology of soil erosion in ecosystems', *Ecosystems*, Vol. 1, No. 1, pp.416–426, doi: 10.1007/s100219900035.

Portugal-Pereira, J. et al. (2015) 'Agricultural and agro-industrial residues-to-energy: techno-economic and environmental assessment in Brazil', *Biomass and Bioenergy*, April, Vol. 81, pp.521–533, DOI: 10.1016/j.biombioe.2015.08.010.

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*, PhD thesis – Universidade Federal do Rio de Janeiro - Rio de Janeiro - Brazil.

Ship and Bunker (2020a) *Global 20 Ports Average* [online] https://shipandbunker.com/prices/av/global/av-g20-global-20-ports-average#IFO380 (accessed 8 May 2020).

Ship and Bunker (2020b) *Global 20 Ports Average* [online] https://shipandbunker.com/prices/av/global/av-g20-global-20-ports-average#MGO (accessed 8 May 2020).

Silva, F.F.d.S. (2017) *Avaliação da Torrefação e Densificação de Residuos Agrícolas no Brasil*, Tese de Mestrado – Universidade Federal do Rio de Janeiro – Brazil.

Swanson, R.M. et al. (2010) *Techno-Economic Analysis of Biomass-to-Liquids Production Based on Gasification Scenarios*, ACS National Meeting Book of Abstracts.

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 and Bioenergy*, November 2018, Vol. 123, pp.134–148, Elsevier Ltd., DOI: 10.1016/j.biombioe.2019.02.018.

Trading Economics (2020) *Naphta* [online] https://tradingeconomics.com/commodity/naphtha (accessed 5 February 2020).

UNCATSTAT (2019) *Country Profile* [online] https://unctadstat.unctad.org/countryprofile/en-GB/index.html (accessed 10 February 2019).

UNCTAD (2019) *UNCTADSTAT, Maritime Transport* [online] https://unctadstat.unctad.org/wds/ReportFolders/reportFolders.aspx (accessed 15 July 2019).

UNCTDA (2018) *Review of Maritime Transport – 2017*, Geneva, Switzerland, ISBN: 978-92-1-112928-1.

UNCTDA (2019) *Review of Maritime Transport 2019*, New York, New York, USA, ISBN: 978-92-112858-8.

Wetterlund, E. (2012) *System Studies of Forest-Based Biomass Gasification*, PhD thesis, Universidade de Linkoping, Sweden.

Wight, J.P. et al. (2012) 'Management effects on bioenergy sorghum growth, yield and nutrient uptake', *Biomass and Bioenergy*, Vol. 46, pp.593–604, Elsevier Ltd., DOI: 10.1016/j.biombioe.2012.06.036.

Notes

1 $3.6 \cdot 10^6$ represents the conversion GJ/h = 3.6/MW.

2 1 square kilometre (km^2) = 0.785 millions of hectares (Mha).

3 The potential number of plant units found was limited by the total biomass energy available within a 50 km radius from the crops (area where a plant would be installed). Thus, the number of plants was obtained by dividing the total area available of the most producers per 50 km radius (0.750) (equation 5).

4 1 GJ corresponds to 0.16 BOE.

Acronyms and abbreviations

CEPCI	Chemical engineering plant cost index
EEDI	Energy efficiency design index
EU	Europe Union
FAO	Food and Agriculture Organisation
FT	Fischer Tropsch
gCO_2eq	Grams of carbon dioxide equivalent
GHG	Greenhouse gases
GJ	Gigajoule
HFO	Heavy fuel oil
ICE	Internal combustion engine
IMO	International Maritime Organisation
IR	Interest rate
MARPOL	International convention for the prevention of pollution from ships
MBOE	Million barrel of oil equivalent
MEPC	Marine environment protection committee
Mha	Million hectares
MTEU	Million twenty-foot equivalent unit
NM	Nautical mile
PJ	Petajoule
SEEMP	Ship efficiency energy management plan
TPES	Total primary energy supply

Appendix A

Figure 15 Wheat, barley, maize, rice, and soybean production in eu-28/2018 (see online version for colours)

Countries	Wheat								Barley							
	Tonnes	*ha*	*Ton/ha*	*50km*	*40km*	*30km*	*20km*	*10km*	*Tonnes*	*ha*	*Ton/ha*	*50km*	*40km*	*30km*	*20km*	*10km*
Austria	1,37E+06	2,93E+05	4,68	NO	NO	YES	YES	YES	6,95E+05	1,39E+05	4,99	NO	NO	NO	YES	YES
Belgium	1,65E+06	1,96E+05	8,44	NO	NO	NO	YES	YES	3,20E+05	4,22E+04	7,6	NO	NO	NO	NO	YES
Bulgaria	5,83E+06	1,21E+06	4,81	YES	YES	YES	YES	YES	4,38E+05	1,04E+05	4,22	NO	NO	NO	NO	YES
Croatia	7,44E+05	1,38E+05	5,38	NO	NO	NO	YES	YES	2,28E+05	5,10E+04	4,46	NO	NO	NO	NO	YES
Cyprus	1,81E+04	8,49E+03	2,13	NO	NO	NO	NO	NO	1,87E+04	1,03E+04	1,81	NO	NO	NO	NO	NO
Czechia	4,42E+06	8,20E+05	5,39	YES	YES	YES	YES	YES	1,61E+06	3,25E+05	4,95	NO	NO	YES	YES	YES
Denamark	2,65E+06	4,26E+05	6,23	NO	NO	YES	YES	YES	3,49E+06	7,95E+05	4,38	YES	YES	YES	YES	YES
Stonia	4,50E+05	1,55E+05	2,91	NO	NO	NO	YES	YES	3,47E+05	1,38E+05	2,51	NO	NO	NO	YES	YES
Finland	4,95E+05	1,78E+05	2,78	NO	NO	NO	YES	YES	1,34E+06	4,05E+05	3,3	NO	NO	YES	YES	YES
France	3,58E+07	5,23E+06	6,84	YES	YES	YES	YES	YES	1,12E+07	1,77E+06	6,33	YES	YES	YES	YES	YES
Germany	2,03E+07	3,04E+06	6,67	YES	YES	YES	YES	YES	9,58E+06	1,62E+06	5,91	YES	YES	YES	YES	YES
Greece	1,07E+06	4,04E+05	2,65	NO	NO	YES	YES	YES	3,45E+05	1,29E+05	2,67	NO	NO	NO	YES	YES
Hungary	5,25E+06	1,03E+06	5,1	YES	YES	YES	YES	YES	1,14E+06	2,44E+05	4,67	NO	NO	NO	YES	YES
Ireland	5,07E+05	5,80E+04	8,74	NO	NO	NO	NO	YES	1,22E+06	1,85E+05	6,61	NO	NO	NO	YES	YES
Italy	6,93E+06	1,82E+06	3,81	YES	YES	YES	YES	YES	1,01E+06	2,62E+05	3,85	NO	NO	NO	YES	YES
Latvia	1,43E+06	4,17E+05	3,43	NO	NO	YES	YES	YES	3,06E+05	1,18E+05	2,59	NO	NO	NO	NO	YES
Lithuania	2,84E+06	7,73E+05	3,67	NO	YES	YES	YES	YES	6,20E+05	2,26E+05	2,74	NO	NO	NO	YES	YES
Luxembourg	7,84E+04	1,30E+04	6,04	NO	NO	NO	NO	NO	3,47E+04	6,00E+03	5,77	NO	NO	NO	NO	NO
Malta	1,22E+04	2,40E+03	5,08	NO	NO	NO	NO	NO	2,19E+03	5,24E+02	4,17	NO	NO	NO	NO	NO
Netherlands	9,85E+05	1,12E+05	8,82	NO	NO	NO	NO	YES	2,53E+05	3,60E+04	7,04	NO	NO	NO	NO	YES
Poland	9,82E+06	2,42E+06	4,06	YES	YES	YES	YES	YES	3,05E+06	9,76E+05	3,12	YES	YES	YES	YES	YES
Portugal	6,77E+04	2,70E+04	2,51	NO	NO	NO	NO	NO	4,96E+04	2,05E+04	2,42	NO	NO	NO	NO	NO
Romania	1,01E+07	2,11E+06	4,8	YES	YES	YES	YES	YES	1,87E+06	4,22E+05	4,43	NO	NO	YES	YES	YES
Slovakia	1,93E+06	4,03E+05	4,78	NO	NO	YES	YES	YES	4,87E+05	1,24E+05	3,92	NO	NO	NO	NO	YES
Slovenia	1,22E+05	2,78E+04	4,38	NO	NO	NO	NO	NO	8,81E+04	2,10E+04	4,19	NO	NO	NO	NO	NO
Spain	7,99E+06	2,06E+06	3,87	YES	YES	YES	YES	YES	9,13E+06	2,57E+06	3,55	YES	YES	YES	YES	YES
Sweden	1,62E+06	3,73E+05	4,35	NO	NO	YES	YES	YES	1,09E+06	3,61E+05	3,03	NO	NO	YES	YES	YES
UK	1,36E+07	1,75E+06	7,75	YES	YES	YES	YES	YES	6,51E+06	1,14E+06	5,72	YES	YES	YES	YES	YES
Total	1,38E+08	2,55E+07	5,41						5,65E+07	1,22E+07	4,61					

Countries	Maize								Rice								Soybean							
	Tonnes	*ha*	*Ton/ha*	*50km*	*40km*	*30km*	*20km*	*10km*	*Tonnes*	*ha*	*Ton/ha*	*50km*	*40km*	*30km*	*20km*	*10km*	*Tonnes*	*ha*	*Ton/ha*	*50km*	*40km*	*30km*	*20km*	*10km*
Austria	2,13E+06	2,10E+05	10,15	NO	NO	NO	YES	YES									1,84E+05	6,76E+04	2,73	NO	NO	NO	NO	YES
Belgium	4,43E+05	5,40E+04	8,21	NO	NO	NO	NO	YES																
Bulgaria	3,48E+06	4,45E+05	7,82	NO	NO	YES	YES	YES	6,34E+04	1,10E+04	5,76	NO	NO	NO	NO	NO	4,55E+03	2,32E+03	1,96	NO	NO	NO	NO	NO
Croatia	2,42E+06	2,35E+05	10,27	NO	NO	NO	YES	YES									2,45E+05	7,71E+04	3,18	NO	NO	NO	NO	YES
Cyprus	NO	NO	NO	NO	NO	NO	NO	NO												NO	NO	NO	NO	NO
Czechia	4,89E+05	8,19E+04	5,98	NO	NO	NO	NO	YES									2,53E+04	1,52E+04	1,66	NO	NO	NO	NO	NO
Denamark	3,59E+04	5,33E+03	6,74	NO	NO	NO	NO	NO																
Stonia																								
Finland																								
France	1,27E+07	1,42E+06	8,91	YES	YES	YES	YES	YES	7,33E+04	1,34E+04	5,48	NO	NO	NO	NO	NO	4,00E+05	1,54E+05	2,60	NO	NO	NO	YES	YES
Germany	3,34E+06	4,11E+05	8,14	NO	NO	YES	YES	YES									5,90E+04	2,40E+04	2,46	NO	NO	NO	NO	NO
Greece	1,21E+06	1,13E+05	10,63	NO	NO	NO	NO	YES	2,23E+05	3,04E+04	7,34	NO	NO	NO	NO	NO	9,49E+03	3,37E+03	2,82	NO	NO	NO	NO	NO
Hungary	7,96E+06	9,44E+05	8,44	YES	YES	YES	YES	YES	1,20E+04	3,02E+03	3,96	NO	NO	NO	NO	NO	1,78E+05	6,30E+04	2,83	NO	NO	NO	NO	YES
Ireland	NO	NO	NO	NO	NO															NO	NO	NO	NO	NO
Italy	6,18E+06	5,91E+05	10,45	NO	YES	YES	YES	YES	1,51E+06	2,30E+05	6,59	NO	NO	NO	YES	YES	1,14E+06	3,27E+05	3,49	NO	NO	YES	YES	YES
Latvia																								
Lithuania	8,76E+04	1,34E+04	6,54	NO	NO	NO	NO	NO																
Luxembourg	5,65E+02	9,10E+01	6,21	NO	NO	NO	NO	NO																
Malta																								
Netherlands	8,49E+04	9,43E+03	9,01	NO	NO	NO	NO	NO																
Poland	3,86E+06	6,45E+05	5,99	NO	YES	YES	YES	YES									1,03E+04	5,45E+03	1,89	NO	NO	NO	NO	NO
Portugal	7,14E+05	8,34E+04	8,56	NO	NO	NO	NO	YES	1,61E+05	2,94E+04	5,47	NO	NO	NO	NO	NO								
Romania	1,87E+07	2,44E+06	7,64	YES	YES	YES	YES	YES	4,34E+04	8,25E+03	5,25	NO	NO	NO	NO	NO	4,66E+05	1,69E+05	2,76	NO	NO	NO	YES	YES
Slovakia	1,52E+06	1,79E+05	8,47	NO	NO	NO	YES	YES									1,05E+05	4,53E+04	2,31	NO	NO	NO	NO	YES
Slovenia	3,50E+05	3,71E+04	9,45	NO	NO	NO	NO	YES									5,33E+03	1,76E+03	3,04	NO	NO	NO	NO	NO
Spain	3,84E+06	3,22E+05	11,92	NO	NO	YES	YES	YES	8,08E+05	1,05E+05	7,7	NO	NO	NO	NO	YES	4,25E+03	1,48E+03	2,87	NO	NO	NO	NO	NO
Sweden																								
UK																								
Total	6,95E+07	8,25E+06	8,43						2,90E+06	4,30E+05	6,74						2,88E+06	9,56E+05	3,02					

Appendix B

Table 16 Equipment capacities according to straw productivity of each country

Country	*Wheat straw equipment capacity (S) (MWth)*	*Country*	*Barley straw equipment capacity (S) (MWth)*	*Country*	*Maize straw equipment capacity (S) (MWth)*
Bulgaria	460	France	2,829	France	1,571
Czech Republic	697	Germany	2,424	Hungary	1,976
France	806	Poland	516	Romania	1,542
Germany	799	Spain	1,537		
Hungary	828	UK	3,292		
Italy	547	Denmark	1,761		
Poland	516				
Romania	533				
Spain	420				
UK	960				