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Plating the hot potato: how to make intermediate bioenergy carriers an accelerator to a climate-neutral Europe

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Abstract

Background With sustainable bioenergy in the European energy mix, intermediate bioenergy carriers (IBC) become of growing importance, as they can ensure a more efficient utilisation of biomass feedstocks from agricultural and forest residues. A high potential for market uptake is foreseen for fast pyrolysis bio-oil (FPBO), one of several IBCs. While facing the chicken and egg problem in market entry, the aim of this study was the development of adequate strategies to support market implementation. The case study findings and methodological approach can provide policymakers, industry, and a broader audience with a vision for addressing similar challenges in market adoption of innovations in the bioeconomy and beyond. Therefore, we tested a new PESTEL + I approach and its practical applicability to an IBC value chain.

Results With an adopted PESTEL method, we analysed a promising value chain in which FPBO is produced from sawdust in Sweden and Finland, transported to the Netherlands and upgraded and marketed as a marine biofuel. Our results show that the market uptake of IBCs such as FPBO and subsequently produced biofuels is above all driven by the European Renewable Energy Directive II (RED II). In Annex IX Part A, sawdust is listed as a feedstock for advanced biofuels, which can be double counted towards the 14% renewable energy share goal in the transport sector in 2030. To support the use of advanced biofuels in the maritime and aviation sector, the proposal for revision of RED II 2021 contains a new multiplier (1.2x) for fuels delivered to these sectors, while all other multipliers are deleted. These legal European obligations and implementation into national law of member states create strong incentives for many downstream market actors to use advanced biofuel. However, technological challenges for FPBO use still hamper fast market introduction.

Conclusions Overcoming technology challenges and the creation of long-term validity of guidelines and regulatory framework will create stable market conditions, investment security and finally stimulate long-term offtake agreements between feedstock providers, technology developers and downstream customers. The approach and findings can provide a vision to overcome similar challenges in other bioeconomy innovations' market uptake and beyond.

Keywords Intermediate bioenergy carriers, Advanced biofuel, Bioenergy market uptake, Fast pyrolysis bio-oil, REDII, PESTEL

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Background

It is vital for human society that measures are urgently implemented to mitigate and prevent disastrous global climate change impacts occurring more frequently in Europe and elsewhere [1] and tackle the main reasons such as the widespread use of fossil fuels in the industry [2].

Therefore, several policies and measures are currently being implemented to support the market uptake of renewable energy technologies and mitigate climate change impacts [3–6].

Under the bioeconomy strategy and against the risk of unsustainable biomass use for the natural ecosystem [7–9], the European Union prioritises the use of biomass from residual and waste materials [10]. This means that risks of unsustainable crop cultivation leading to biodiversity loss and soil degradation and primary wood use for bioenergy installations with capacities > 5 MW should be reduced [11]. Advanced intermediate bioenergy carriers (IBCs) can improve the quality of various heterogeneous residues and wastes and therefore contribute significantly to a more sustainable bioeconomy [12]. Biofuels from high iLUC (indirect land use change) risk feedstocks in the transport sector will be gradually reduced starting from 2023 until a complete phase-out in 2030 [11]. Meanwhile, it is still possible to certify biofuels made of POME (palm oil mill effluent) and PFAD (palm fatty acid distillate) as low iLUC risk biofuels countable towards the renewable energy targets. A complete phase-out of palm oil classified currently as high iLUC risk feedstock until 2030 could support increasing market uptake of alternatives such as IBCs.

Meanwhile, in the market environment of some European countries, the implementation of the requirements of the renewable energy directive (REDII) at national and local levels is lagging behind. The reasons for this are slow and inefficient governance processes as well as bureaucracy at local governments and ministries. Uncertainty in a long-term perspective for IBCs can lead to a delay in large-scale investments required for commercial technology upscaling [13, 14].

Transport fuel suppliers are looking for new technologies, renewable feedstocks, and energy carriers to replace fossil fuels and first-generation biofuels within the next decade. According to REDII, in 2018, at least 3.5% of renewable transport fuels shall be provided by advanced biofuels (double counted) [3, 15]. In order to meet those demands, it is necessary to mobilise sufficient feedstocks from sustainable sources. The use of these feedstocks (e.g. wastes and residues from sustainable certified forestry [16, 17] and forest-based industries: bark, branches, thinnings, leaves, needles, tree tops, sawdust, …) prevents adverse indirect land use changes and decline of biodiversity and meets the requirements of the EU LULUCF (Land Use, Land Use Change & Forestry) and other related directives [3, 16–20].

Sawdust is a residue that can be used in many applications [21]. From a waste utilisation perspective, the use of sawdust as a material in, e.g. particle board is preferable, but the availability of sawdust by far exceeds the quantities needed for these applications especially in regions in Northern Sweden and Finland. The use of sawdust for energy can be subdivided into three options: use as direct fuel in biomass burners (combined heat and power plants), use as a feedstock for wood pellets production and use as a feedstock for FPBO. It must be considered that sawdust use for FPBO may reduce available amounts for CHP plants and pelleting industry. The CHP plant operators, however, could easily replace lack of sawdust by increased use of logging residues.

To be economical, sawdust can only be transported approximately 100 km from the sawmill to the end user. Using sawdust as a feedstock for FPBO has the advantage that a liquid can be produced from the sawdust, at locations where the sawdust is abundantly available. A liquid energy carrier like FPBO is in general easier to store, transport and use than raw biomass or solid bioenergy carriers, because of the high energy density of FPBO. As FPBO is a liquid, existing infrastructure can be used in many cases.

"IBCs are created when biomass is processed to energetically denser, better storable and transportable intermediary products." [22]. Some examples are fast pyrolysis bio-oil (FPBO), torrefied biomass and microbial oil (based on fermentation). FPBO (TRL 9) is a versatile product, which can be used for direct energy production, but can also be upgraded to a sustainable transport fuel (TRL 5–6). It is even possible to fractionate the FPBO for use in specific bio-based products, such as modified wood (for construction), bio-based foam resins, and moulding components. The application that is discussed in this paper involves the production of sustainable transport fuel for marine applications (Fig. 1). The use of advanced biofuels in marine application is considered sustainable, and it is one of the ways to increase the environmental sustainability of the marine sector. FPBO is produced by thermochemical decomposition of biomass residues through rapid heating (450–600 ℃) in absence of oxygen. The energy efficiency of the FPBO process is approximately 85%, if the heat that is produced in the production process can be utilised. As to the losses: the pyrolysis process as such does not require much energy, but it is necessary to provide heat to achieve pyrolysis temperatures. This is realised by combusting the char and the permanent gases. Part of this heat is re-used in the process, namely for drying of the biomass. Surplus heat can be transported to external heat consumers, in

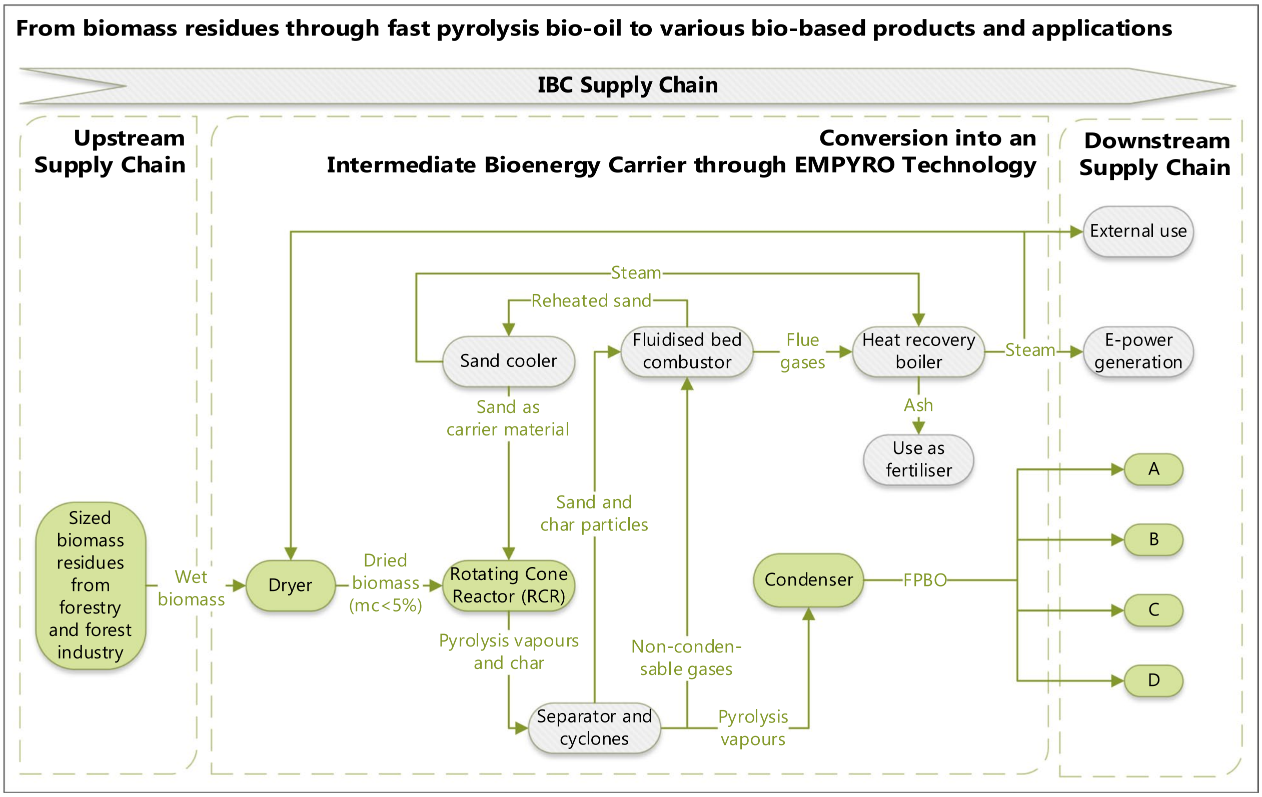

Fig. 1 Potential supply chain of converting forest residues (sawdust) to fast pyrolysis bio-oil (FPBO) [22, 25]

the form of steam. Losses involve (1) stack temperature losses, and (2) cooling down of the pyrolysis oil. More information on FPBO production is summarised by Van de Beld and Muggen [23]. Different types of solid biomass residues (e.g. sawdust, wood chips) can be converted into the homogeneous liquid FPBO energy carrier. The energy density of FPBO with 16–23 MJ/l is about 4–20 times higher than that of raw biomass [22]. Based on recent study results and proposed revised REDII policy targets [11], a market demand for advanced biofuels in the transport sector in the EU was estimated at 121 PJ/yr in 2030 [15]. At a 10% FPBO market share of advanced maritime fuels (biodiesel) in the EU [24], the potential demand could add up to approximately 12 PJ/yr, which corresponds to a capacity of about 50 FPBO production plants (assuming a plant capacity of 240 TJ/yr). Currently, 6 commercial-scale FPBO plants of varying sizes in Northern Europe and Canada provide a capacity of 2.9 PJ/yr [25].

FPBO is a product which can be produced from various locally and sustainably available feedstocks in the EU. Therefore, it can contribute towards reducing dependency on fossil oil and fuel supply chains of which large amounts are imported from non-EU countries. The maritime transport sector can use this bioenergy carrier to reach ambitious total annual greenhouse gas (GHG) emission reduction targets of at least 50% by 2050 compared to 2008 set by the International Maritime Organisation (IMO) [26]. Moreover, the FPBO can be used as a high-energy fuel for firing combined heat and power (CHP) plants during peak demands in the winter period in Northern Europe. In view of the mentioned applications foreseen for FPBO use it was considered essential to analyse and support the market transfer of FPBO as one of the case studies of the EU funded project 'MUSIC—Market Uptake Support for Intermediate Bioenergy Carriers'. It was crucial to get a structured overview of barriers and enablers which were identified in expert interviews in relation to requirements for market uptake of the proposed FPBO value chain (Fig. 1). One barrier for instance is that the production of FPBO in large quantities is not given at the moment, as only two plants with a combined capacity of 920 TJ/yr have been built in Northern Europe (Sweden and Finland) and the actual demand is low. Potential customers such as biofuel refineries still import other—more cost-efficient and directly usable—feedstocks as well as more abundantly available fuels.

To convince potential customers and correctly define market potentials and accelerate the market implementation of IBCs, the whole value chain as well as the complex socio-economic, environmental, and legislative environment needs to be considered. Blümel et al. [27] showed that the adaptation of existing methods for strategic thinking and practice [28] such as PESTLE [29] and PEST [30] is necessary to analyse complex and dynamic value chains and not only single organisations or products. A methodological approach is described to enhance and integrate existing methods and approaches from strategic management. The developed approach with another PESTEL category "Infrastructure (+I)" is particularly helpful to understand the environment of biomass supply chains and to derive strategies for innovations' market uptake [27]. However, the developed framework needs application on a case-study level to verify theoretical findings and support real market uptake of IBCs.

Against this background, the aim of this study is to gather influencing factors and market information with respect to implementation and strategic development of an innovative FPBO value chain (Fig. 1). This may help to overcome similar challenges as well as assist with further innovative bioenergy value chains.

Methods

Approach

Our approach used the strategic management method "PESTEL+I" that has not yet been applied to an IBC value chain. PESTEL analysis is a useful tool for assessing the market uptake of a supply chain concept because it allows for a comprehensive evaluation of the external factors that may impact the success of the concept. This includes political, economic, social, technological, environmental, and legal factors, which can all influence the demand for and acceptance of the concept in the market [31].

In addition, PESTEL analysis can be used to identify potential trends and changes in the external environment that may impact the supply chain in the future. This information can help to plan the market uptake for potential disruptions and make necessary adjustments to the supply chain in order to remain competitive and efficient [32]. This information can be used to develop strategies that address these factors and ensure a stable and efficient supply chain. Adaption of the PESTEL+I method applied in the research process is described in detail by an affiliated article by Blümel et al. [27].

Relevant market players or stakeholders were identified via internet research and snowball sampling in a three-step process. Within the research process, stakeholders directly involved in the MUSIC project were asked for recommendations from additional experts in their network to supplement the list of relevant players [33]. In a first step, different categories of stakeholders such as upstream (feedstock providers), conversion (technology companies, producer companies, research) and downstream users (refineries, transport sector) were defined in stakeholder factsheets [34]. Some stakeholders not directly involved in the observed value chain belonged to additional categories such as service provider, policy and society. Secondly, actual stakeholders in the case study regions of the MUSIC project were determined by the case study partners by preparing a series of maps of regional bioenergy settings [35]. In a third step, the identified players were included in a compiled stakeholder list [36].

The potential supply chain of the case study involves the conversion of forest residues (sawdust) to FPBO and its usage for replacement of fossil fuels in combined heat and power plants (A), the co-processing (5% max.) in fluid catalytic cracking (FCC) units in existing fossil refineries to produce advanced biofuels (e.g. biodiesel) for the marine transport sector (B), the upgrading in a stand-alone unit (stabilisation and hydrodeoxygenation) to advanced marine or aviation biofuel (C), and the fractionation in a biorefinery into pyrolytic lignin, sugars and small organics for the production of bio-based materials and chemicals (D) (Fig. 1).

An overview of macro-environmental factors was collected during the first stakeholder engagement workshop in the frame of the MUSIC project. During the workshop, the PESTEL+I categories (political, economic, social, technological, environmental, legal, infrastructural) [27–30], the code scheme and the related codes definitions (Table 1) as well as the suitability for the analysis of the FPBO value chain was discussed and adjusted in exchange with multiple stakeholders and experts. The collected factors were then further specified in interviews and coded by using a "Computer Assisted Qualitative Data Analysis Software" (CAQDAS, NVivo) [37]. The coding and classification of factors was independently conducted, repeated by different persons and discussed between researchers to generate inter-coder reliability [38]. Data triangulation (use of different data collection methods) as a common practice in case study research, was applied to create validity, uncover inconsistencies and to verify information [39–43]. This involved the collection of data from multiple sources (stakeholder engagement workshops, online surveys, reports, peer-reviewed literature), using multiple methods of analysis, and involving multiple researchers in the coding process. This helped to ensure that the findings are not influenced by any single perspective or bias.

The qualitative code structure to extract important information relevant for the FPBO value chain (Table 1)

Table 1 Code book for a structured qualitative PESTEL + I analysis for the IBC market uptake [27]

Category	Subcode	Definition
PESTEL		Strategic management method to analyse the macro-environment of an organisation or product (or supply chain). The method distinguishes in several groups of influencing factors. This category contains all coded segments from the subcategories
	Political and Legal (P, L)	Every political and legal factor such as the role of state/governments (inter-governmental and governmental organisations, but also standard-setting bodies and further institutions), action plans, strategies, taxation, governmental subvention/subsidies, consumer incentives, trade barriers
	Economic (E)	Economic factors comprise aspects such as the availability of resources, costumer needs as well as competitiveness and prices of technologies or products (CAPEX—capital expenditure, OPEX—operational expenditure)
	Social (S)	Cultural or demographic factors such as changes in social thinking, consumer convenience or campaigns of non-governmental organisations
	Technological (T)	Technological innovations such as different technologies, cost comparisons of plants, product life cycles as well as research and development
	Environmental (E)	Environmental or "green" issues such as GHG emissions, environmental pollution, impact on biodiversity or the comparison to fossil fuels
+ I	Infrastructural (I)	Logistics and transport options. Examples can be railway network, road infrastructure or storage. (in the results section included in PESTEL factors, indicated here with symbol + I)
Market uptake support for IBCs		Within these categories, barriers and enablers for the market uptake support of IBCs are coded. The identification of these factors is seen as the basis for further strategic analysis
	Barriers	All factors which hinder the market uptake of IBCs, e.g. disadvantages in politics or competitors
	Enablers	All factors which support the market uptake of IBCs, e.g. technology advantages or subsidies

was developed deductively, mainly based on the previously mentioned PESTEL + I framework [27, 29]. Specific words, phrases and text sections were related to the defined PESTEL categories and codes. In order to assess the effect of the identified factors on the value chain implementation process, they have also been coded as barriers or enablers regarding IBCs' market uptake.

Data collection

The data about the macro-environment of the market value chain were gathered through semi-structured interviews with experts obtained from a stakeholder network (Table 2) [30] and literature review. A standard list of questions was prepared for each of the main stakeholder groups (upstream, conversion, downstream users). In the first instance, we interviewed the MUSIC project partners in order to then use snowball sampling [30] to identify further potential interviewees. The market players collected previously [35] were requested for an interview via e-mail or phone. Further, the standard questionnaire was structured, adjusted and personalised for each interviewee to gather as much specific information as possible. In total, 15 semi-structured, qualitative interviews were conducted (Table 2).

Moreover, the PESTEL + I approach was supplemented by two further strategic management methods, namely a SWOT analysis and a TOWS matrix: the enablers and barriers collected for the IBCs market uptake were identified and allocated to a SWOT analysis (strengths, weaknesses, opportunities, and threats) (Table 3). In a TOWS matrix, external threats (T) and opportunities (O) were matched with internal weaknesses (W) and strengths (S) to develop strategies for market uptake (Table 3). The combination of the two methods makes it possible to identify all important hindering and enabling factors (SWOT) but also provides strategies for actions (TOWS) to overcome barriers and take advantage of opportunities to point out pathways for the implementation of the value chain.

Case study

A value chain of converting woody biomass (sawdust, forest residues) into IBCs such as FPBO to produce biofuels or biochemicals in a Northern European region was the main object of investigation integrated into the framework (Figs. 1 and 2). The company BTG Bioliquids (Enschede, the Netherlands) could serve as an example to illustrate how different factors affect the value chain. Since 2015, a commercial pyrolysis plant (EMPYRO) built by BTG Bioliquids in Hengelo, the Netherlands, and sold to the local utility company Twence in 2018, converts 5 tonnes/hour of biomass into FPBO on a 24/7 basis [44]. The FPBO is used in a boiler to produce heat at a dairy plant in Borculo, the Netherlands. A similar plant was delivered to Finland, for Green Fuel Nordic (GFN) in 2020 [45]. Sawdust serves as the raw material for FPBO production, and steam released in the process is used internally for drying the biomass. When the feedstock is already dry, surplus steam is available for external users. With this first plant in Lieksa, Finland, GFN will produce

Table 2 List of expert interviews

ID	Date	Stakeholder category (SC)	Country	Expertise, experience, function
N1	12.08.2020	Policy	Sweden	Many years of experience in the forestry sector; expertise on (upstream) supply chain management; strategy development in regard to a European bioeconomy
N2	10.07.2020	Service provider	Netherlands	Many years of professional experience in bioenergy conversion technologies and market analyses
N3	16.07.2020	Service provider	Netherlands	Working on bioenergy conversion technologies, life cycle assessments and market analyses in the bioenergy sector
N4	07.07.2021	Service provider	Netherlands	Many years of experience in the chemical industry; business development for bioenergy; buyer experience
N5	17.06.2020	Service provider	Netherlands	Expertise on issues related to logistics/transport of bioenergy carriers; knowledge of requirements regarding maritime application of biofuels
N6	17.06.2020	Service provider	Netherlands	-„-
N7	12.07.2021	Downstream	Finland	More than 20 years of experience in the pulp and paper and forest industry; technology expert for pyrolysis plant regards planning and research and development
N8	12.08.2020	Downstream	Finland	Many years of experience in international business, especially working on strategic planning and feasibility studies in the bioenergy sector
N9	19.10.2021	Downstream	Finland	Senior expert in large-scale international biofuel business and management
N10	27.08.2021	Downstream	Sweden	Experience in investor relations and project financing, especially for renewable fuels projects; Experience in advanced biofuel production
N11	04.11.2021	Upstream	Sweden	Many years of experience in biofuels/biorefineries, etc.; evaluating many different technologies to convert sawdust and other residues from industries
N12	26.11.2021	Upstream	Sweden	Chief forester; Experience in forest management
N13	18.05.2020	Downstream	Sweden	Broad spectrum of expertise, e.g. on business development and international purchasing; lobbying activities; comprehensive knowledge of political and legal issues on EU level
N14	15.07.2021	Upstream	Sweden	Expertise in the bioenergy sector; especially bioenergy policy at EU level and Swedish policy on bioenergy
N15	26.07.2021	Downstream	Germany	Expertise in sustainable development; expert on fuel quality and represented in various standard-setting bodies

20 million litres of FPBO per year that will be used for various offtake customers in Finland and Europe. Additional plants may follow in Finland. BTG Bioliquids also sold a commercial FPBO production plant to Pyrocell in Sweden, which started operating in September 2021. The FPBO produced is co-processed in a fluidised catalytic cracker (FCC) of Preem's Lysekil refinery to produce gasoline fuels [46]. Altogether to date (06/2022), 4 fast pyrolysis plants have been established in Europe (Empyro, GFN, Pyrocell, Fortum [47]) and 2 plants in Canada (Kerry Group, Cote North) [48, 49].

Results

Political factors—enablers (strength—S, opportunities—O)

(S1) Sawdust as a forest residue is included in RED II Annex IX Part A (o), which is a list of eligible feedstocks for the production of advanced biofuels [3].

(S2) Advanced biofuels are considered double their energy content when counting towards the 14% minimum proportion of all renewable energy in the transport sector until 2030 [3] and to reach the sub-target energy share of advanced biofuels (double counted) of 3.5%. Advanced maritime and aviation fuels can be multiplied 1.2× towards the mentioned targets. A proposal for a revision of REDII suggested by the EC in 07/2021 presented even more ambitious targets of a 28% share of renewables in the transport sector and a sub-target share for advanced biofuels of 2.2% without double counting [11].

(O1) A changing political environment worldwide highlights the need for alternative fuel and energy sources to contribute to a more resource-independent Europe and towards reducing fossil fuel imports. Biofuels can play an important role while increasing crop-based biofuels, production will not be accepted because of the risk of adverse land use change impacts. Advanced biofuels such as FPBO made from forest residues can provide a sustainable and environmentally friendly option to fill the gap.

Table 3 TOWS matrix with strategies for the market uptake of FPBO produced from forest residues in Scandinavian countries, transport to the Netherlands and upgrade to marine biofuels

External factors	Internal factors	
	S (Internal Strength)—enablers: (S1) Sawdust included in RED II Annex IX Part A (S2) FPBO enables biomass transport to low biomass countries (+I) (S3) FPBO conversion reduces transport cost (+I) (S4) Fast pyrolysis increases bulk density (+I) (S5) sixfold increase of the energy density of biomass (+I) (S6) Large abundance of sawdust in Northern EU (+I) (S7) Currently a hazard assessment classification of FPBO is prepared (S8) REACH registration of FPBO enables trade and import in EU	W (Internal Weakness)—barriers: (W1) Investment discouraged by few commercial-scale plants (+I) (W2) High CAPEX and OPEX for pyrolysis plants (W3) Low energy content pyrolysis oil compared to fossil fuels (+I) (W4) Limited amount of skilled labour is available in remote areas (+I) (W5) Missing infrastructure, which needs to be built by skilled labour (+I) (W6) Heating of storage tanks required in cold regions (+I) (W7) Continuous stirring of FPBO required during storage (+I) (W8) Acidic character of the FPBO causes corrosion, metal content interferes with catalysts during upgrading in Fluid Catalytic Cracker (W9) Classification and certification process not finalised
O (External Opportunities)—enablers: (O1) Changing politics support biofuels compensation of fossil imports (O2) Advanced biofuels counted double their energy content (O3) Rising fossil fuel prices, legislative incentives such as CO_2 tax, ETS system and blending quota for advanced blended fuels in transport sectors will create markets (O4) Decline of the pulp and paper industry in the North creates unused feedstock potential (+I) (O5) FPBO industry creates new value chains for regional companies and the local forest industry (+I) (O6) Creation of regional employment opportunities, support rural development and local resources use (+I) (O7) Upgraded FPBO (FCC and/or deoxygenation) could serve demand for sustainable aviation ad maritime fuels	S1,2,3,4 × O1,4,5: International stakeholders and industry should form associations to promote forest residues use for advanced biofuel production and inter industrial sector communication S1,2 × O1,2,3: Feedstock quality and advancing biofuel production technology opens up new markets for the biomass that is converted into FPBO S1,2 × O1,2,6,7: EU markets will increasingly demand alternative fuels if blending quotas are implemented. This opportunity should be explored. Germany could become a sales market for biofuels made from FPBO S1,2 × O6: Further investigate technological possibilities along with certification processes to upgrade FPBO to advanced sustainable aviation fuels S4 × O5: Forestry industry/refineries should invest increasingly in the installation of a FPBO plant because they could use their own resources of own plants nearby, establish regional value chains, reduce dependence on imports S4,5 × O3,6: Additional feedstock types should be exploited: looking for adequate partners should be one of the first steps; e.g. (a) from wood and waste chains; (b) first thinning ground, raw wood; (c) remnants of natural disasters and similar	W1,4,5 × O1,2,3: Increase organisation of bilateral talks, workshops of feedstock providers and other stakeholders in the value chain W1,2,4,5 × O6,7: Missing long-term operation of only 6 FPBO plants indicates investment insecurity. Incentives can only be provided by further nationally initiated funding programmes; FPBO must be included in new business concepts combined with other renewables W4,5,6,7,8 × O2,3: Producing advanced biofuels nearby the FPBO plant and exporting the final fuel to other countries may be the easier option compared to exporting FPBO as an intermediate W1,2 xO4,5: Therefore, it needs to be elaborated if FPBO-based biofuels may have a competitive advantage over biofuels based on residues of palm oil production in terms of costs in the future W2,4,5 × O7: Construct FPBO plant near planned green hydrogen production sites and other industrial installations (pulp mills, refineries) to use synergies

Table 3 (continued)

External factors	Internal factors	
T (External Threat)—barriers: (T1): Political uncertainty: RED II and III adjustments and regulatory discontinuity of measures, slow or missing national implementation (T2): POME part of RED II Annex IV, part A, will serve demand (T3) In the Netherlands from 2025 onwards blending fossil maritime and aviation fuels with biofuels may not be possible anymore (T4) Currently, prices for renewable advanced biofuels made from FPBO higher than other biofuels (T5) NGOs and environmental lobbyists campaigning against woody resources use for energy application (T6) Decreasing public appreciation of usage of woody feedstocks for biofuels (T7) Supply of sawdust from sustainably managed forests must be regularly audited and certified	S1,6×T1: National implementation of RED II is key and has to be promoted as well as national sub-quota for biofuels blending S1,6×T1,7: Creation of a long-term database, which continuously provides information about the availability of sustainable forestry feedstock, based on reliable data and controlled by independent institutions S1,2,3×T5,6,7: Prevailing misunderstanding of different biofuel generations; campaigns are needed in which it is clarified that (a) advanced biofuels do not compete with food production chains, (b) feedstock used has to undergo certification processes, (c) assessment of the biofuels life cycle is made, (d) biodiversity issues are considered	W6,7,8×T2: Further R&D activities on FPBO quality, adapt characteristics according to the requirements of the engines that represent the most promising application field (e.g. eliminate metal content because already small contents are problematic for FCC units in refineries) W3,6,7,8×T2: FPBO quality determines application, always investigate the best fitting purpose in order to reach the highest value, clearer allocation of specific feedstock to specific applications/processes, e.g. lower quality FPBO could serve as a fuel for CHP plants in Sweden W3,6,7,8×T1,2: ASTM standardisation requirements, currently prevent the application of FPBO in SAF—> Further R&D activities on FPBO, adapt characteristics according to the requirements of plane engines W1,2,4,5×T4: Further R&D activities on plant operation, which lead to an increase in the process efficiency and therefore, (a) makes the plant operation also profitable and economic at smaller scale (output less than 25,000 t/yr) and (b) converge prices for advanced biofuels and conventional fuels

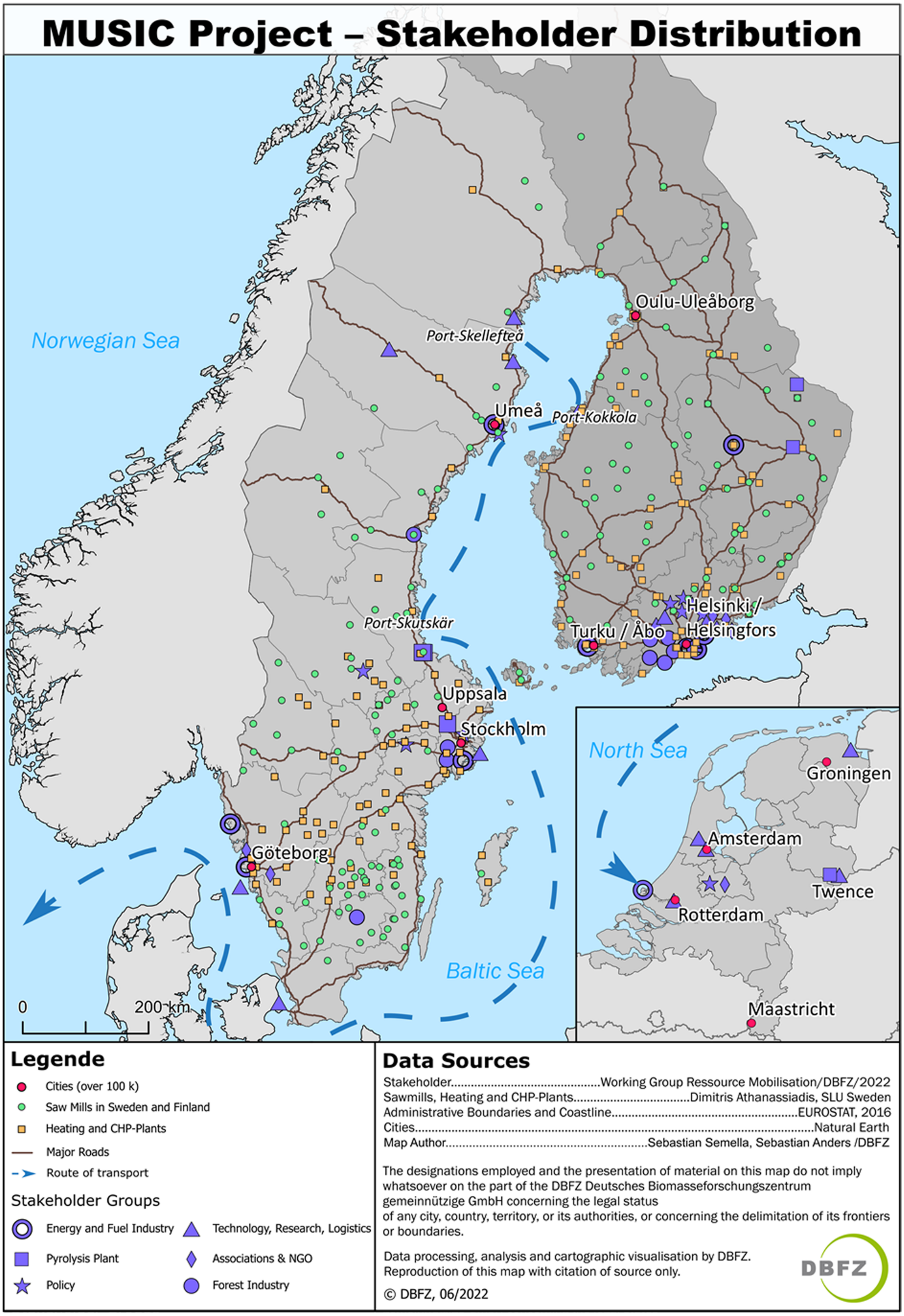

Fig. 2 Stakeholders of a value chain converting sawdust to FPBO and marine biofuel [22, 25]

Political factors—barriers (weakness—W, threat—T)

(T1) There are uncertainties caused by a lagging REDII implementation at a national level with an unclear outcome in terms of the detailed reinforcement measures in each EU member state.
(T2) The use of low-cost palm oil production residues (palm oil mill effluent (POME)) for advanced biofuels and other non-food feedstocks of scale (palm fatty acid distillate (PFAD), animal fats, used cooking oil (UCO)) for advanced and waste-based biofuels production, however, is still permitted by RED II. The classification of PFAD in REDII, Annex IX Part A or Part B depends on national legislations in each of the EU countries. In Finland, for example, PFAD is classified as a residue usable as a feedstock for advanced biofuels [50, 51]. As those options are readily available, they already take up large shares, such as in the case of UCO and PFAD in Germany [51]. The residues mentioned above are likely to first meet the demand of customers because of their low price, availability without high investment costs and handling characteristics. Today, potential investors may not support FPBO upscaling because of more cost-efficient alternatives still available on the market.
(T3) In the Netherlands from 2025 onwards, the generation of so-called HBEs (hernieuwbare brandstof eenheden=renewable fuel units) by blending fossil maritime and aviation fuels with biofuels may not be supported anymore.

Economic factors: enablers (strength—S, opportunities—O)

(S3) FPBO conversion reduces transport costs compared to bulky biomass such as sawdust (+I).
(O2) FPBO as an IBC enables cost-efficient and climate-friendly transport of energy resources from regions with abundant resources and low energy demand to countries with low biomass availability and high energy demand (e.g. energy consumption inland waterways and domestic maritime transport per year is in Sweden 3.8 PJ, and in Germany 9.7 PJ [15].
(O3) Rising fossil fuel prices, legislative incentives such as rising CO_2 prices and an increasing quota for low carbon fuels in transport sectors in Germany and other EU member states in the near future could close the price gap between fossils and advanced biofuels made from intermediate bioenergy carriers such as FPBO.

Economic factors: barriers (weakness—W, threat—O)

(W1) Investment and purchase of large volumes of FPBO is discouraged by recent inadequate production capacities of only 6 commercial-scale plants in the EU (the Netherlands, Sweden, and Finland) and Canada with a total capacity of 180,000 kt/yr which equals approximately 2.9 PJ [25] (+I).
(W2) CAPEX and OPEX for pyrolysis plants are mostly high and such high capital investment requires a certain security and reliable forecast of market profits and price stability, which is not given at the moment.
(T4) Currently, prices for renewable advanced biofuels made from FPBO estimated at 1750 €/t [23] would be in the range of prices of conventional biofuels (e.g. SME biodiesel 1500–1600 €/t, FAME biodiesel 1700–1800 €/t, [52] and more than double the current fossil fuel prices. The political instability in Europe leads to heavily fluctuating and rising biomass feedstock and material costs resulting in unstable biofuel market price developments.
(W3) The lower energy content of pyrolysis oil of about 18–20 GJ/ton [22] compared to fossil crude oil with 40–46 GJ/tonnes leads to higher transportation and storage costs for FPBO (+I).

Social factors: enablers (strength—S, opportunities—O)

(O4) In the past decades the pulp and paper industry from Northern Sweden and Finland has moved further south and closer to larger cities, which created an economic and social decline in some Northern areas (+I).
(O5) The construction of FPBO production and upgrading units in these remote regions of Northern Sweden and Finland will create new value chains and markets for regional companies and the local forest industry (+I).
(O6) The new biofuel industry and related value chains will create new employment opportunities, support rural development and infrastructure and help to protect the climate if certified sustainable and ecologic forest and feedstock management practices are implemented (+I).

Social factors: barriers (weakness—W, threat—T)

(W4) There is a shortage of skilled labour in remote areas (+I).
(W5) Missing infrastructure, which needs to be built by skilled labour (+I).
(T5) Several NGOs and environmental protection lobbyists are strongly campaigning at an EU and national level against the further exploitation of woody resources for energy application. In particular, large international NGOs (e.g. Greenpeace, IUCN) can strongly influence the political positions of important groups, decision-makers and the public through information and communication campaigns. Statements are justified by research results describing a decline of biodiversity and CO_2 storage capacity in intensively managed forests compared to unmanaged forest stands [9]. In contrast to that, some studies describe more nuanced results of management intensity, species composition and close-to-nature forest management concepts [53–55].
(T6) Decreasing public acceptance of usage of woody feedstocks for biofuels production.

Technological factors: enablers (strength—S, opportunities—O)

(S4) Fast pyrolysis increases bulk density (BD) (sawdust 280 kg/m^3 to FPBO 1,200 kg/m^3) (+I).
(S5) Sixfold increase in the energy density by fast pyrolysis of biomass compared to sawdust (+I).
(O7) Complete deoxygenation of FPBO by hydrogenation yields HPO, which can be blended directly with common fuels such as diesel. Therefore, it could serve—in some cases after further distillation—as a feedstock for sustainable aviation fuels or maritime fuels.

Technological factors: barriers (weakness—W, threat—T)

(W6) Heating of storage tanks is required in cold regions and seasons to keep the temperature of FPBO > 0°C (+I).
(W7) Continuous stirring of FPBO is required to keep a homogeneous quality (+I).
(W8) To prevent corrosion, stainless steel should be used as the storage tank material because of the acidic character of the FPBO (+I).

Environmental factors: enablers (strength—S, opportunities—O)

(S6) Sawdust and other forest residues were estimated to be available in abundance in Northern Sweden and Finland [56, 57]. In Northern Sweden, an estimate showed that about 320,000 raw tonnes (t/yr) could be potentially available from several sawmills near the cities of Piteå and Sundsvall. A number of about 12 sawmills in Lieksa (North Karelia), Lisalmi (North Savo) as well as in Kainuu regions in Finland could potentially provide approx. 263,000 raw tonnes (t/yr) of sawdust for FPBO production [25] (+I).

Environmental factors: barriers (weakness—W, threat—T)

(T7) Supply of feedstocks such as sawdust from sustainably managed forests must be regularly audited and certified.

Legal factors: enablers (strength—S, opportunities—O)

(S7) A hazard assessment classification of FPBO is carried out as a prerequisite for registration at IMO. FPBO could thereafter be listed in the Marine Environment Protection Committee (MEPC.2/Circular) with validity in all countries [58].
(S8) FPBO is registered in the system for Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) and therefore the production and import of fast pyrolysis liquid in the European Union is permitted.

Legal factors: barriers (weakness—W, threat—T)

(W9) Several standardisation processes and guidelines define the market framework for FPBO and derived fuels. The ISO 8217:2017 [59] and the IMO guidelines [60] are setting the quality standards and benchmarks for fuels used in ships and the marine sector. FPBO as a flammable liquid will be likewise classified as a hazardous substance with additional costly safety measures. Guidelines defining the transportation/shipping of fuels are set by the Economic and Social Council (ECOSOC) Committee of Experts on the Transport of Dangerous Goods. The IMO is responsible for maritime transport and the

Intergovernmental Organization for International Carriage by Rail (OTIF) for rail transport.

Discussion

The results of our analysis highlighted some important enablers for the FPBO market uptake in a potential value chain consisting of sawdust conversion to FPBO near Nordic sawmills, transport to Swedish and Finnish Baltic sea ports, shipping to the Netherlands and finally upgrading to maritime biofuels there. The transport sector, including the marine and aviation sector, is committed to reaching sustainability targets [61–64]. In order to achieve the EU target of a 55% reduction in total emissions by 2030 and a 90% reduction in transport emissions by 2050 [64], FPBO-based advanced biofuel from sustainable raw materials (sawdust) could contribute to a medium-term solution for climate-neutral maritime transport in Europe [25]. Replacing propulsion technologies and systems in transport fleets with electric and fuel cell systems will take decades and will require very large investments that most shipping companies and airlines will not be able to afford immediately. Therefore, sustainable low carbon aviation and marine fuels of high energy density made from FPBO could represent a cost-efficient and fast intermediate solution for these important sectors.

Large amounts of woody residues (wood chips, sawdust) in specific regions of scarcely populated Northern Europe with low energy demand could be processed in Sweden and Finland to FPBO [25] and transported to regions further south (the Netherlands, Germany) where renewable biomass resources are limited, and energy demands are high. In the context of policy initiatives to reduce dependence on fossil fuel imports [64], market opportunities are created for the European forestry and advanced biofuels industry. This represents an alternative to crop-based biofuels and strengthens the regional energy supply of the EU.

Of concern is the competition of an increasing number of biofuel companies each preferring its own technology pathways and targeting similar feedstocks such as sawdust and other woody residues. Following the circular (bio-)economy strategy, other industry sectors such as the chemical industry, the recycling or the construction sector are also eyeing up these feedstocks, which may lead to reduced sawdust availability, rising feedstock prices, overuse, and unsustainable exploitation practices. The European Commission has published a report providing an overview of the EU bioeconomy strategy progress [65]. Bioeconomy value chains and products can be assessed and monitored in regard to their environmental and social consequences by using sustainability indicators [66–70].

While estimates of available biomass potentials were made [71–73], current usage and resulting mobilisable potentials for specific usage paths are not yet clearly defined in EU member states. The industry may, therefore, import these feedstocks from countries outside of the EU. This will again jeopardise the efforts for a change to a climate neutral, resource-efficient, and independent European society and economy.

However, the most important policy-driven market opportunity remains the double counting of advanced biofuels made from forest residues to reach renewable energy shares in the European transport sector. This incentivises the market uptake and investment in advanced biofuels by fuel companies to reduce the currently large share of conventional biofuels and related crop-based feedstocks in the EU. The abatement costs to reach greenhouse gas reductions and renewable energy shares could thus effectively be halved under specific regulatory conditions and at full achievement of the subquota (e.g. Germany) [74].

Besides the availability of large amounts of suitable woody residues in the targeted production locations, the phase-out of palm oil as a high iLUC-risk biofuel feedstock is another important factor, which may lead to long-term agreements between the forest industry, biofuel refineries and FPBO-producing companies. However, some barriers still currently prevent the rapid uptake of FPBO technology, such as technological issues in the biofuel production process in FCC in refineries and adjustments to present logistic fuel transport and storage infrastructures. Several standardisation processes and guidelines define the market framework for FPBO and derived fuels. The ISO 8217 and the IMO guidelines are setting the quality standards and benchmarks for fuels used in ships and the maritime sector [59, 60]. Guidelines defining the transportation/shipping of fuels are likewise set by the IMO [58].

Prerequisites such as hazard classification and standardisation processes required for direct market application of FPBO are still ongoing and preventing customers from the immediate uptake of the technology into their production processes.

Some of the barriers mentioned (T: external threats, W: internal weaknesses, Table 3) for a successful market uptake of IBCs seem to create a chicken and egg problem or vicious cycle, which obviously seems to hamper the comparably new value chain and a fast FPBO market uptake. The large production capacities and available volumes of FPBO demanded from potential customers are not yet in place. On the other hand, the construction of these large facilities is not possible without major investments requiring long-term commitments by all partners.

Political uncertainty and the delayed national implementation of REDII in European states regarding reliable long-term legislation for sustainable biomass feedstock use at the moment still hinders potential investments.

The abundance of low-cost imported palm oil residues which are listed in the RED II annex IX Part A [3] as a sustainable feedstock is another factor, which makes it unnecessary and less economic for potential big customers to use FPBO made from sawdust for biofuel production. Nevertheless, the implementation of a gradually increasing quota for advanced biofuels in the transport sector of some European countries such as Germany (target minimum share 0.2% in 2022 and 2.6% by 2030) [74] could open up profitable market shares also for FPBO-based advanced biofuels made from residues of certified sustainably managed forests.

An adopted PESTEL + I approach was applied successfully in our analysis to support strategy development for IBC market implementation [27]. The results gathered give a broad overview of enabling and hindering factors for the proposed FPBO value chain at a certain point in time, so we were taking a "snapshot" as a basis for policy recommendation. The limitations of the method are further detailed by Blümel et al. [27]. Constant fluctuations of material and feedstock costs and subsequent price changes are subject to recent and future market changes, which could not be fully reflected by the current approach. To take these changing environments into account it would be necessary to further adjust the PESTEL + I method in a more dynamic and automated procedure. With that, forecasts and scenarios for value chains and strategic recommendations could be better adapted to real market environments and challenging geopolitical and climatic changes in the future.

Conclusion

Intermediate bioenergy carriers such as FPBO made from residues from sustainably managed forests represent a promising regionally available resource for advanced biofuels. Introduction of IBC value chains can support the creation of new employment opportunities and infrastructure development in Northern Sweden and Finland. This will also reinforce social and cultural progress and sustainable development of local communities in these remote and largely forested regions. A qualitative structured investigation of the market environment by using the adopted PESTEL + I approach of Blümel et al. [27] showed that technology challenges in upscaling and ongoing certification and standardisation processes currently slow down the speed of the market uptake of FPBO technology. According to our findings, future research is needed to develop procedures to avoid FPBO contamination resulting from low quality input feedstock which may create issues in subsequent upgrading processes. Another important field of research which needs further exploration is the upscaled production of sustainable aviation fuels from FPBO at reasonable costs to make it competitive in Europe and other markets. Nevertheless, the national implementation of European directives on the use of energy from renewable sources will soon provide investment security for the accelerated market transfer of IBC technologies. Germany for instance has recently introduced a national sub-quota for advanced biofuels in the transport sector. These and other incentives such as the increasing CO_2 price under the Emission Trading System of the EU could lead to a fast development and upscaling of supply chains and create a profitable and stable market. Subsequently, increasing innovative and competitive pressure may rapidly solve prevailing technological and logistical challenges of FPBO. A balance of supply and demand will create another advanced sustainable biofuel source at scale, which contributes to a climate-neutral transport sector in Europe. The involvement of stakeholders and the results gathered using the PESTEL + I methodological approach can provide a broad audience with a vision for addressing the challenges of IBC market introduction, but also for social and policy innovation in the bioeconomy and beyond.

Abbreviations

BTG	Biomass Technology Group
BD	Bulk density
CAPEX	Capital expenditures
CHP	Combined heat and power
DBFZ	Deutsches Biomasseforschungszentrum gGmbH
EC	European Commission
ECOSOC	Economic and Social Council
LULUCF	Land use, land use change and forestry
FAME	Fatty acid methyl ester
FCC	Fluid catalytic cracking
EU	European Union
€/t	Euro per tonne
FPBO	Fast pyrolysis bio-oil
GFN	Green Fuel Nordic
GHG	Greenhouse gas
GJ	Gigajoule
HBEs	Hernieuwbare Brandstofeenheden = Renewable Fuel Units
HPO	Hydrotreated pyrolysis oil
+I	Infrastructure
IBC	Intermediate bioenergy carrier
iLUC	Indirect land use change
IMO	International Maritime Organisation
ISO	International Organisation for Standardisation
kg/m^3	Kilogramme per cubic metre
kt/yr	Kilotonnes per year
mc	Moisture content
MEPC	Marine Environment Protection Committee
MUSIC	Market Uptake Support for Intermediate Bioenergy Carriers
NGO	Non-Governmental Organisation
OPEX	Operational expenditures
OTIF	Intergovernmental Organisation for International Carriage by Rail
PESTEL + I	Political, Economic, Social, Technological, Environmental, Legal and Infrastructural Factors

PFAD	Palm fatty acid distillate
POME	Palm oil mill effluent
PJ	Petajoule
RCR	Rotating cone reactor
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals
REDII	Renewable Energy Directive II
SLU	Swedish University of Agricultural Sciences
SME	Soybean Oil Methyl Ester
SWOT	Strengths, Weaknesses, Opportunities, Threats
TJ	Terajoule
t/yr	Tonnes per Year
TOWS	SWOT backwards
UCO	Used cooking oil

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