MUSIC

Market Uptake Support for Intermediate Bioenergy Carriers

Market uptake of Intermediate Bioenergy Carriers

A Summary for policy makers

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Abbreviations

CHP	Combined Heat and Power
COD	Chemical Oxygen Demand
EGD	European Green Deal
FPBO	Fast Pyrolysis Bio-Oil
HEFA	Hydroprocessed Esters and Fatty Acids
HVO	Hydrogenated Vegetable Oils
IBC	Intermediate Bioenergy Carrier
IBTC	International Biomass Torrefaction Council
ILUC	Indirect Land Use Change
MO	Microbial Oil
PO	Pyrolysis Oil
RED II	Revised Renewable Energy Directive
RES	Renewable Energy Sources
SET (Plan)	Strategic Energy Technology (Plan)
TB(P)	Torrefied Biomass (Pellets)
UCO	Used Cooking Oil

VOC	Volatile Organic Compounds
WP	Wood Pellets

1 Introduction

The MUSIC project, supported by the Horizon 2020 programme of the European Union, aims to facilitate the market uptake of three types of Intermediate Bioenergy Carriers (IBCs), namely pyrolysis oil, torrefied biomass and microbial oil by developing feedstock mobilisation strategies, improved cost-effective logistics and trade centres.

IBCs are formed when biomass is processed to energetically denser, storable and transportable intermediary products analogous to coal, oil and gaseous fossil energy carriers. They can be used directly for heat or power generation or further refined to final bioenergy or bio-based products. IBCs thus contribute to energy security, reduce greenhouse gas emissions and provide a sustainable alternative to fossil fuels in Europe.

IBCs are intermediate products within complex value chains usually based on lignocellulosic feedstock from residues, wastes and energy crops. Potential final uses of IBCs together with their contributions to targets laid down in the Revised Renewable Energy Directive (RED II) are outlined in Figure 1.

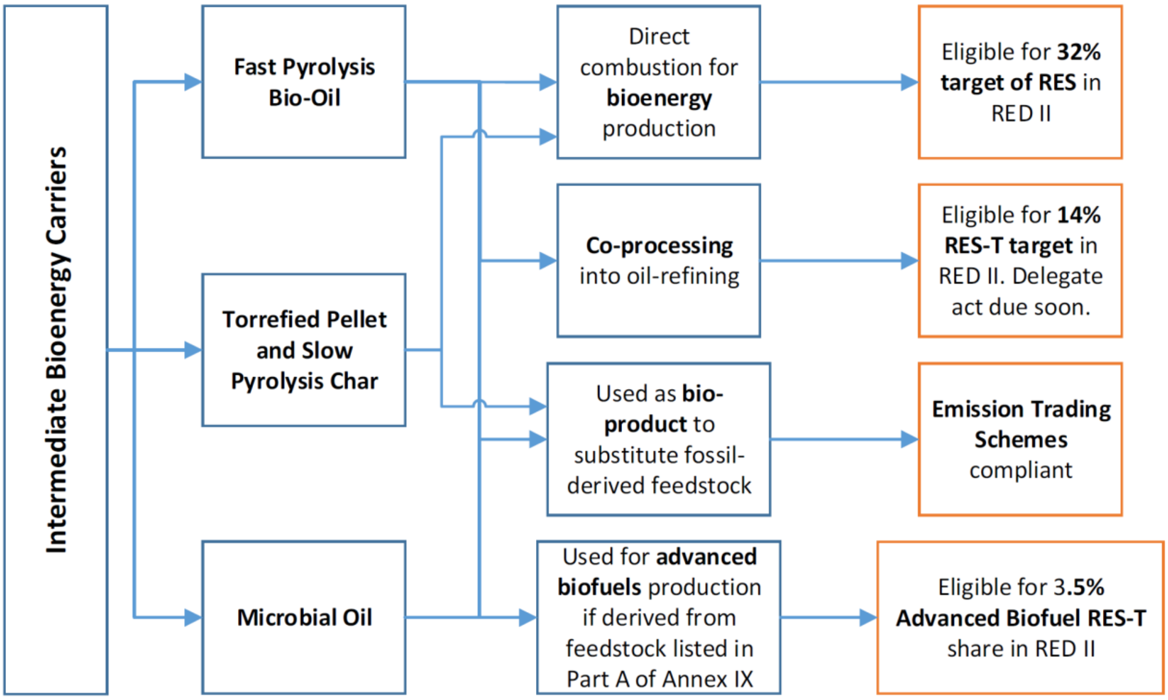


Figure 1: Final uses of the IBCs pyrolysis oil, torrefied biomass and microbial oil and their link to the current legislative framework (Buffi et al. 2020)

IBCs directly combusted for the production of bioenergy (electricity and heat) are eligible for the overall 32% EU target for Renewable Energy Sources (RES) consumption by 2030 provided that the biomass feedstock complies with the sustainability criteria laid down in the RED II. Liquid sustainable IBCs (pyrolysis oil and microbial oil) co-processed in existing oil refineries to produce transport fuels are eligible for the 14% RES target for the European transport sector. Furthermore, transport fuels from IBCs produced from feedstock listed in Part A of Annex IX of the RED II (namely specific selected feedstock for the production of biogas for transport and advanced biofuels) are eligible for the 3.5% sub-target of advanced biofuels.

In order to appropriately address the variety of different application options of IBCs, the following case studies are investigated in the framework of the MUSIC project:

- Torrefied biomass production: Conversion of agricultural residues to IBC for use in district heating plants from DETEPA (Amyntaio Municipal District Heating Operation), Greece
- Pyrolysis oil production: Using renewable feedstock (e.g. residues) from Nordic forest industries to produce pyrolysis oil at Green Fuel Nordic PO plants in Finland and Sweden
- Co-processing microbial oil in ENI's industrial biorefineries in Italy
- Use of torrefied biomass in steel production: Use of torrefied biomass in Arcelor Mittal's steel mills in Europe

For each of the IBCs covered the present "Summary for policy makers: market uptake of Intermediate Bioenergy Carriers" provides an overview on technical solutions, biomass mobilisation, market potential, as well as existing barriers and challenges. Furthermore, recommendations for policy makers are outlined to facilitate the market uptake of IBCs in different end use applications. The paper reflects the knowledge and insights gained from case study development, expert interviews and online workshops held during the first year of project implementation. The content of this paper will be taken up to formulate more extended policy recommendations at the end of the MUSIC project.

2 Torrefied biomass

In recent years, torrefied biomass has gained increasing interest as sustainable energy carrier with the potential to meet the needs of a demanding energy market, as it can provide a solid fuel that meets the needs of coal consumers, able to replace coal directly and without the need for process changes. Torrefied biomass (densified in pellets or briquettes or as powder,) can replace up to 100% of the coal used for steam generation, allowing for instance coal-fired power plants to be converted to biomass power plants, but without the high financial investment required (Nunes and Matias 2020). Furthermore, torrefied biomass may also be used to replace coal as reducing agent in industrial processes such as steelmaking or as process energy source in industries like cement, asphalt, brickworks, minerals calcination etc.

2.1 Technology overview

“Torrefaction can be defined as the thermochemical conversion process of biomass, occurring within a temperature range of 220 to 320°C, at atmospheric pressure, in an oxygen-deficient environment, where the degradation of the constituent hemicellulose occurs with cellulose and lignin remaining” (Nunes and Matias 2020). During this process, volatile organic compounds (VOCs) and water are eliminated which leads to an increase in the solid carbon content and subsequently in the calorific value of the final product. By-products of the process are non-condensable gases like CO_2, CO, and small amounts of methane. Torrefaction increases the energy density and allows the biomass to approach the properties of coal. The following torrefaction technologies can be distinguished:

- Rotary drum reactor
- Fluidized bed reactor
- Moving bed reactor
- Belt and vibrating grate reactor
- Screw conveyor reactor
- Multiple hearth furnace
- Microwave reactor (Cremers et al. 2015).

This thermochemical conversion technology can produce a high-quality biomass fuel allowing efficient combustion (Nunes and Matias 2020, Vos et al. 2020). This technology has significant advantages over other biomass fuels, such as traditional pellets or wood chips:

- The outcome is a product with a higher calorific value per unit mass
- Torrefied biomass is water resistant and does not require physical structures for its storage
- The physical properties of torrefied biomass are similar to those of coal and can therefore be used in the same combustion systems without major modifications

- Torrefied biomass remains a biomass fuel, which contributes to the carbon neutrality of energy production (Nunes and Matias 2020).

The basic torrefaction principle is shown in Figure 2.

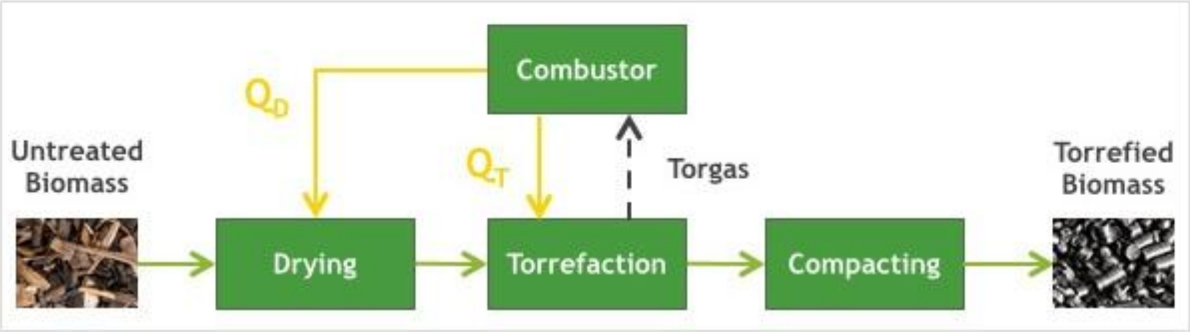


Figure 2: Basic Torrefaction Principle (Vos et al. 2020)

Torrefied biomass is marketed in various forms or shapes, e.g. as powder, pellets, briquettes or granules. This allows a wide range of applications, so that torrefied biomass can be used in different sectors and industries. However, application of torrefied biomass as a substitute for, or co-fired with, fossil solid fuels such as coke, coal or lignite is one of the most promising in the short- and medium-term (Pfeiffer et al. 2020). On the long run one can expect new biomass plants consuming torrefied biomass as well as energy intensive industries (to replace fossil-based fuel and products used in their processes).

The production of hydrogen from the gasification of torrefied biomass is one of the most promising applications. Lopez-Urionabarrenechea et al. (2020) show for instance that the performance of the reforming catalyst improves significantly when treating the vaporised phase of torrefied biomass compared to the vaporised phase of fresh biomass. The hydrogen production shows an increase of 116% (in weight) for torrefied biomass and an increase of 88% (in weight) for fresh biomass. It is expected to allow the development of a new form of mobility based on electrically powered systems, but without the constraints associated to the use of batteries, as it is currently the case (Nunes and Matias 2020). Further areas of application are shown in Figure 3.

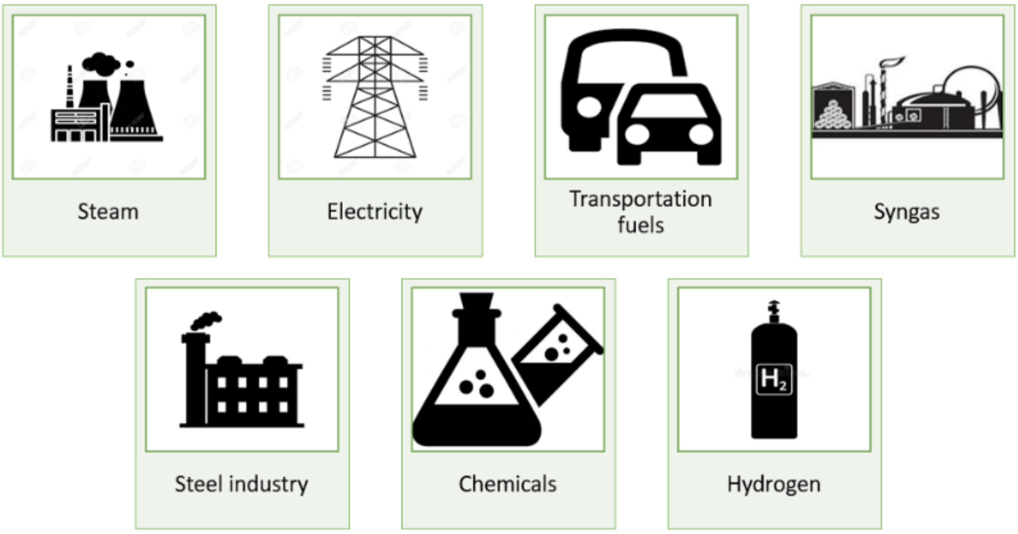


Figure 3: Areas of application (Vos et al. 2020)

2.2 Biomass mobilisation and logistics

The torrefaction of biomass is a promising and much discussed pre-treatment method to reduce the costs of bioenergy chains, in particular logistics costs and emissions caused by logistics. Various studies have shown that the supply chain for fuel pellets made from torrefied biomass is more cost-efficient than for conventional wood pellets. When considering the transport of torrefied biomass pellets (TBP) and wood pellets (WP) from Portugal to North-western European countries (such as Belgium, England, Denmark and Sweden) by sea and comparing their costs, the total costs (production and transport) of one delivered shipload with TBP (€ 8.51/GJ) is slightly lower than for WP (€ 8.68/GJ) due to the about 25% higher energy content of TBP (Godina et al. 2018). A comparative analysis of supply chains for wood pellets and torrefied pellets has shown a reduction in GHG emissions along the supply chain of 11% for TBP, not taking into account the grey energy consumed to establish the infrastructure needed for the handling of wood pellets (Wild and Visser 2018).

According to Stelte (n.d.) unloading and conveying of torrefied biomass is possible using the existing systems in coal power plants. Only minor adaptions in dust suppression systems and in the underloader grabs are required. The outdoor storage of torrefied pellets in a coal storage yard exposes them to sun, rain, wind and frost, which can change the product and lead to emissions such as dust or leachate. Tests on coal storage sites show high organic load (i.e. COD (chemical oxygen demand) values for the leachate, so that ground insulation was required (Stelte n.d.).

Although torrefied biomass was already commercially produced in 2012 (by the company New Biomass Energy) a continuous commercial production of torrefied biomass has just started in Europe with two plants with a capacity of around 100.000 tonnes. Further plants will see commissioning in 2021. Achieved improvements in densification of torrefied biomass did confirm the expected behaviour in logistics and storage even though large volume shipments and storage experience is yet to be gained.

2.3 Market overview and market potential

Torrefaction technologies are also capable of converting low-quality biomass - coming from forestry, agricultural or industrial activities - into biomass-derived fuels which can directly replace coal in electricity generation, especially if it comes from forests which act as carbon sinks. As a pre-processing technology, torrefaction can serve as a basis for the development of other technologies whether for energy production or for biorefineries for green chemicals and biobased materials (Nunes and Matias 2020).

Beyond its use for power generation, torrefied biomass can find application as substitute for fossil fuels in heat production, whether standalone plants for district heating or as a support of industrial processes and a substitution of coal or heating oil in the production processes of some industries. It is anticipated that torrefied biomass has high potential due to commitments of the steelmaking industry to reach carbon neutrality by 2050 (Energy Transitions Commission 2018), existing funding opportunities for the coal and steel industry (European Commission 2020) and the framework of the European Green Deal (EGD) (Pfeiffer et al. 2020).

Figure 4 provides an overview of torrefaction market opportunities, dividing them in three potential opportunity pathways/areas (the conversion technology itself, the solid biomass product and the gaseous biomass product).

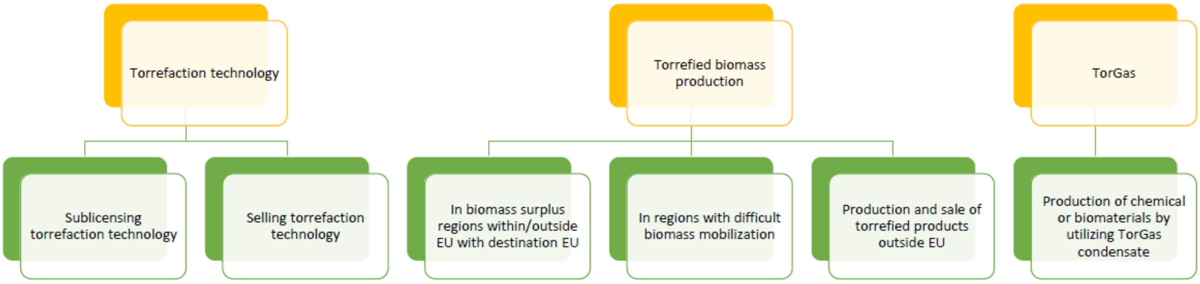


Figure 4: Market opportunities of torrefaction (Vos et al. 2020)

It is estimated that about 50 companies in Europe and North America are involved in the development of torrefaction technologies, with various efforts and at a wide range of involvement and development levels. To date, total cumulative production figures are estimated at 70-120 ktons of torrefied product. The product has been used in coal plants, gasifier(s) and non-industrial facilities, although in very few cases for an extended period of time. Some developers, however, have re-focused on the market for torrefied material: they consider smaller domestic or industrial markets more promising than large scale utilities (Cremers et al. 2015).

2.4 Market uptake barriers and challenges

Despite the advantages of biomass torrefaction, particularly its ability to homogenise different types of raw materials, this technology still has some limitations, particularly in terms of its scalability and the ability of large units to operate continuously, and commercialisation has gone slower than anticipated. Recently, many developments have been realised, especially in terms of process control and stability, which has enabled the production of high-quality products. However, it must be regarded as a technology that can and will further improve, meaning that ongoing funding of research and development is needed (Nunes and Matias 2020). The barriers do not only encompass technological barriers, but also economic barriers and those that affect the whole value chain of torrefaction:

Biomass supply chain barriers

- Security of supply/ (local) resource availability (e.g.due to competition of biomass)
- Transport
- Handling
- Storage and safety issues

Technological barriers

- Challenge of up-scaling from pilot to commercial use (depending on the reactor type)
- Product consistency - wide range of biomass quality
- Operational parameters, such as reactor temperature, residence time etc.
- Limited knowledge on volatiles composition (some developers use these volatiles for heat generation)
- Heavy tars resulting in operational problems
- Little collaboration between academia and industry

Economic barriers

- Logistics costs
- Biomass drying
- Increased process costs compared to coal
- Small production quantities
- Long-term contracting
- Grant and funding landscape (Vos et al. 2020)

Political barriers

- Uneven and/or non-transparent regulatory application of the carbon tax

- Building up of consumer confidence might be hindered by NGOs related to forest preservation, weak naming and labelling (e.g. green coal)

2.5 Policy recommendations

Torrefied biomass is regarded as promising solution to contribute to the decarbonisation of two important sectors of the European economy, namely the energy sector (specifically for the production of electricity and heat) as well as the sector of energy intensive industries (e.g. steel and non-ferrous metal production). Due to its favourable properties in comparison with raw biomass (e.g. heating value, grindability, bulk energy density and hydrophobicity), torrefied biomass can be easily stored, transported and used to replace coal in existing installations and thus avoid or reduce investment needs for retrofitting installations while reducing GHG emissions along the supply chain more efficiently than any other solid biomass.

The following policy recommendations (separated in general and technology-specific recommendations) serve to facilitate the market uptake of torrefied biomass as energy carrier substituting fossil fuels in existing power and combined heat and power (CHP) plants as well as for the decarbonisation of energy intensive industries.

General recommendations

- Torrefaction technologies have reached a high maturity level and commercial solutions are available on the market. Several technology providers (e.g. Torr-Coal) are members of the International Biomass Torrefaction Council (IBTC) dedicated to the promotion of the use of torrefied biomass. However, the current market uptake of torrefied biomass is still limited due to the lack of established full value chains, difficulties to ensure financing as well as the presently higher costs compared to fossil fuels.

- Market uptake of torrefied biomass should be facilitated through the support of further dedicated demonstration projects establishing full value chains in cooperation with technology providers and potential end users from different industrial sectors (such as the Horizon 2020 demonstration project TORERO coordinated by and implemented at the steel company ArcelorMittal).

- Further measures are needed to increase and ensure access to financing for the construction of new torrefaction installations. Bankability of such projects is today often limited by the lack of long-term offtake contracts and the low number of existing reference projects. Opportunities exist in the framework of the European Innovation Fund, one of the world’s largest funding programmes for demonstration of innovative low-carbon technologies, focussing on bringing highly innovative technologies to the market (potentially relevant Horizon Europe call topics: C5-D3-RES-18-2021: Demonstration of large-scale CHP technologies for a shift to the use of biogenic residues and wastes, C5-

D3-RES-34-2022: Efficient and low-emission technologies for industrial use of combustion and gasification systems from low-value biogenic residues and wastes, C5-D3-RES-46-2022: Innovative renewable energy carrier production for heating from renewable energies, C5-D3-RES-56-2021: Market Uptake Measures of renewable energy systems).

- The economic viability of torrefied biomass in comparison with fossil fuels needs to be ensured through the establishment of a mechanism for carbon pricing such as carbon taxes or effective CO_2 emission schemes (e.g. increase of the carbon tax).

- Regional value chains and business cases need to be promoted for the substitution of fossil fuels (e.g. coal) in existing installations, thereby contributing to a just transition process in coal intensive regions. In the short term the use of torrefied biomass in power and heat generation facilities may reduce exposure on the electric grid and support the socially responsible phase-out of coal use.

- Strong safeguards need to be established to ensure the sustainability of future market uptake of torrefied biomass in order to guarantee public acceptance and support of involved industry sectors.

Technology specific recommendations

- The use of torrefied biomass as reducing agent in the steel industry has not yet reached commercial maturity. As this application is regarded as an important component for the decarbonisation of energy intensive industries, further support for R&I initiatives in co-operation with e.g. the steel industry is urgently needed.

- Standards for the use of torrefied material in the steel sector need to be developed to facilitate market uptake in this sector.

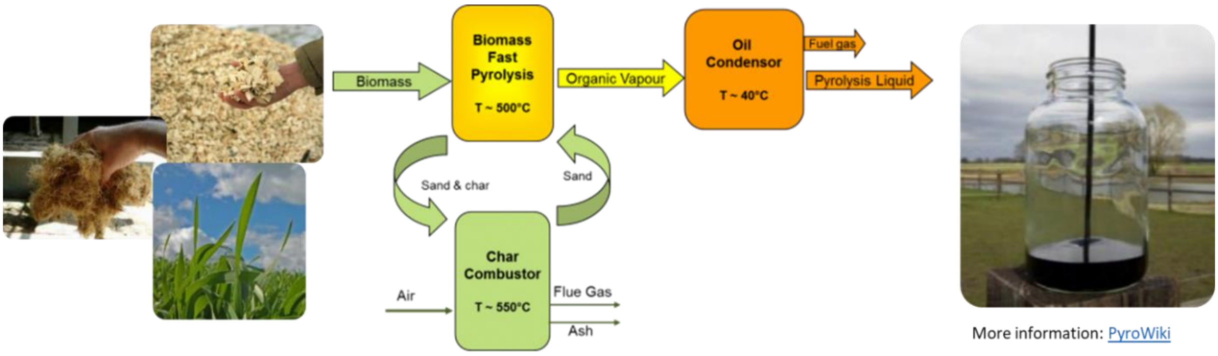
- The use of torrefied biomass as substitute for conventional energy carriers in industrial applications is promising. Support for R&D on direct application and application trials to stimulate a faster transition in industries (cement, minerals, brickwork, etc.) is needed.

- The establishment of value chains and optimised conversion processes for torrefied biomass from feedstock such as short rotation coppice (e.g. poplar) cultivated on marginal or abandoned land such as former lignite mining areas shall be promoted. In addition, the promotion of raw materials from the agricultural sector (agrobiomass or by-products) would support a circular economy approach and rural development.

3 Pyrolysis oil

3.1 Technology overview

Fast pyrolysis is a process in which organic materials are rapidly (≈2 sec) heated to 450 - 600 °C in the absence of air. Under these conditions, the structure is broken down and organic vapours, pyrolysis gases and charcoal are produced. In a next step, the vapours are condensed, and pyrolysis oil is formed. For good oil quality quick condensation of the formed vapours is important. Typically, 60-75 wt.% of the feedstock is converted into oil (Vos et al. 2020) (see Figure 5).



More information: PyroWiki

Figure 5: Fast pyrolysis process (Vos et al. 2020)

For achieving maximum yield and high quality of the oil rapid heat transfer is essential. This can be done by using small, homogeneous feedstock particles (approx. 3mm) with a moisture content of less than 10% and a carrier material for enhancing heat transfer (e.g. sand). The sand is heated during the combustion of char in a combustor. The energy generated during the combustion can be used to power the plant or to produce process heat for other applications. The quality of the pyrolysis oil is influenced by factors, such as type of reactor used, operating conditions and other feedstock properties, like ash content (Vos et al. 2020). Some advantages of pyrolysis oil compared to raw biomass are the following:

- Pyrolysis oil is easier to store, transport and use than raw biomass
- Biomass residues with diverse properties are converted to a homogeneous liquid
- Energy density of pyrolysis oil is 4-20 times higher than of raw biomass
- Pyrolysis oil contains significantly less minerals than raw biomass leading to lower emissions during combustion
- Pyrolysis oil can be upgraded to transport fuels, chemicals and materials (Vos et al. 2020).

The final product of the process is fast pyrolysis bio-oil (FPBO), a dark brown, acid and viscous liquid which can be used in different forms, e.g. as bioliquid for energy purposes, feedstock to be processed to advanced biofuels, feedstock for co-processing or production of chemicals and materials (Buffi et al. 2020).

3.2 Biomass mobilisation and logistics

Currently there are a few FBPO plants in operation or under development in Europe, operating in different settings. Biomass mobilisation and pyrolysis oil logistics highly depend on the local conditions. In Finland, a FBPO plant is in operation at Fortum's combined heat and power (CHP) plant in Joensuu. Fortum uses small-size woody biomass coming from wood thinning as raw material. The wood is harvested, chipped at the roadside and transported to the plant. It can also be transported as logs and chipped at the plant terminal. In the Netherlands, the energy utility Twence owns and operates the Empyro pyrolysis plant in Hengelo that was developed by BTG Bioliquids. Twence uses residues from wood pellet production that are brought to the plant with a pellet truck that pneumatically feeds the residues to the storage vessel. In Sweden, the Pyrocell plant, located at Setra's Kastet sawmill in Gävle at the east coast, is under development (BTG Bioliquids technology, start-up in 2021). The plant will transform sawdust into pyrolysis oil, for further processing into renewable diesel and petrol at Preem's refinery in Lysekil. In Finland, the first Green Fuel Nordic pyrolysis plant is under development in Lieksa, in the east of the country (BTG Bioliquids technology, start-up in 2020), also using sawdust from a nearby sawmill.

When operating biomass pyrolysis plants, to secure operational flexibility and to reduce feedstock supply risks, it can be beneficial to have multiple feedstock suppliers and/or multiple storage facilities. In general, a PO plant will be more economically viable when build as near as possible to the feedstock to avoid costly transportation of a low value material. Either way the transport modality (e.g. train, truck, ship) should be chosen according to the amount of biomass, the distance and the resulting transport costs (Vos et al. 2020).

3.3 Market overview and market potential

Markets for products from biomass pyrolysis are emerging and technology providers are moving from demonstration to commercial scale. This is partly because pyrolysis is the simplest and most cost-effective option for converting biomass into advanced biofuels, chemicals and other products. Pyrolysis can be used to process a wide range of materials and there are many sources of low-value materials such as agricultural residues, forestry by-products or even burnt trees (Bauer 2017).

Already today, PO can be considered as an economic solution to replace oil or natural gas. Ensyn (Canada) supplies heat to hospitals, whereby fossil oil is replaced, Twence (Netherlands) sells pyrolysis oil to replace natural gas to produce high-pressure steam at a dairy plant and Fortum replaces heavy fuel oil with pyrolysis oil in two of its plants in Finland (Lee Enterprises n.d.).

Production costs depend heavily on the local availability, feedstock (pre-treatment) costs, plant scale, type of technology etc. Studies indicate that pyrolysis oils can be produced for between 75 and 300 EUR/t oil (4 to 18 EUR/GJ), assuming feedstock costs between 0 and 100 EUR/t (0 to 1.9 EUR/GJ) (EUBIA n.d.). Preference is given to areas with reliable feedstock sources within a close radius of a potential plant site. As such, pyrolysis of biomass can create an economic boost to rural areas, whereby locations with an existing forest industry have a high potential. This makes the technology also attractive for new markets in e.g. Asia and Africa that have an increased interest in using local resources, inter alia for the local power generation in areas without grid infrastructure. Markets for biomass pyrolysis products are emerging, particularly in Asia, Europe, Canada, and California. And even though power production is the main application today, agricultural uses and chemical production are growing in importance. Further development for improved methods for upgrading the pyrolysis products to chemicals might help pyrolysis process economics (Bauer 2017).

3.4 Market uptake barriers and challenges

Increased market uptake of pyrolysis oils will require further research and innovation on advanced technological equipment and processes to increase carbon yields and reduce production costs. At current fossil carbon prices, pyrolysis products are often more expensive than fossil-based alternatives.

In order to enhance competitiveness of pyrolysis oils, investments for improving products and processes is needed as well as an accompanying monetarisation of environmental benefits offered. Such credits can either be direct subsidies, carbon tax, governmental regulations, or preferably a willingness by end users to pay higher prices for environmentally beneficial products (Bauer 2017).

3.5 Policy recommendations

Pyrolysis oils are believed to become a crucial element of the European bioeconomy. It is an intermediate product with superior properties (e.g. energy density, homogeneity) which can serve several industries and applications, such as combustion (least effective/basic application), conversion to biofuels or as basis for chemical products. Pyrolysis oil will furthermore play a crucial role as (co-)feed in (bio-)refineries for the production of transport fuels.

The following policy recommendations (separated in general and technology-specific recommendations) serve to facilitate the market up-take of pyrolysis oil as energy carrier and feedstock for bio-based products in the framework of the future European bioeconomy. Today, commercial prospects for pyrolysis oil are better than for torrefied biomass, specifically underlined through increasing interest from large oil companies. Nevertheless, future large-scale market uptake will benefit from a conducive policy and regulatory framework as well as dedicated support activities and schemes.

General recommendations

- Market uptake of pyrolysis oil should be facilitated through the support of further dedicated demonstration projects establishing full value chains in cooperation with technology providers and potential end users. In the framework of the MUSIC project a value chain case study will be investigated using renewable feedstock from Nordic forest industries to produce pyrolysis oil in Finland and Sweden and upgrading it to advanced drop-in marine biofuel in the Netherlands. Opportunities may exist in the framework of the planned Horizon Europe call topic C5-D3-RES-47-2022: Demonstration of complete value chains for advanced biofuel and non-biological renewable fuel production (further potentially relevant Horizon Europe call topics: C5-D3-RES-18-2021: Demonstration of large-scale CHP technologies for a shift to the use of biogenic residues and wastes, C5-D3-RES-46-2022: Innovative renewable energy carrier production for heating from renewable energies, C5-D3-RES-56-2021: Market Uptake Measures of renewable energy systems).

- Dedicated measures are needed to increase and ensure access to financing for the construction of pyrolysis oil installations. Bankability of such projects will benefit from mandates laid down in legislation, subsidies and green credits as well as the commercial proof of technology (namely operating commercial pyrolysis units).

- The economic viability of pyrolysis oil in comparison with fossil fuels needs to be ensured through the establishment of a mechanism for carbon pricing such as carbon taxes or effective CO_2 emission schemes.

- Effective incentive schemes need to be established that provide long-term support for the production and use of PO on European and Member State level.

- PO value chains add value to the forest industry by valorising waste streams and by-products of their processes. Thus, forest industries can supply a valuable biomass feedstock to PO value chains instead of using it internally, mainly for less efficient energy production.

- Biomass for PO production must be extracted from regions with positive forest trends instead of importing biomass from countries where negative trends of deforestation are observed.

- Pyrolysis oil is a highly suitable feedstock for co-refining in fossil refineries. Clear rules and regulations need to be developed on European level to verify and value the “green content” of fuels produced in co-refining units.

- Pyrolysis oil upgrading to bio-based materials, thus replacing fossil-based materials, may serve to ensure public acceptance of PO technology and to strengthen the competitiveness of PO producers.

Technology specific recommendations

- Pyrolysis technology is already proven on commercial scale and several plants are operational (e.g. the Fortum plant in Joensuu, Finland and the Empyro plant in Hengelo, The Netherlands) or under construction (e.g. the Green Fuel Nordic plant in Lieksa, Finland and the PyroCell plant in Gävle, Sweden. However, similarly to torrefied biomass the current market uptake of pyrolysis oil is still limited due to the lack of established full value chains, difficulties to ensure financing as well as the presently higher costs compared to fossil fuels.

- Support is currently still required for pyrolysis technology development enabling the use of economically promising feedstocks, such as certain residues from forestry operations, from wood processing and from the agricultural sector.

- Continued RD&D support is also needed for higher-value applications including (a) co-feeding of PO in FCC units of fossil refineries (b) stand-alone conversion of PO into advanced (marine) transport fuels (c) PO as substitute for fossil feedstock in biomaterials (e.g. Bio4Products project).

- The energetic use of pyrolysis oil should be regarded as interim solution (to establish functioning value chains) until material use (e.g. through upgrading in bio-refineries) for bio-based products becomes an economically viable pathway. Therefore, all policy measures supporting the establishment of the European bio-based economy will serve to support the market uptake of pyrolysis oils. European Member State governments such as The Netherlands are currently preparing policies to phase out certain energetic uses of biomass (e.g. direct combustion) in favour of biomass feedstock use for bio-based products.

4 Microbial oil

Microbial oil (MO) is produced by oleaginous yeasts from cellulosic sugars derived from lignocellulosic biomass, and it consists of 100% triglycerides (i.e. lipids) as conventional vegetable oils. Average MO yields of around 14.wt % of biomass feedstock input have been reported (Davis et al. 2013). The produced MO can be used like conventional vegetable oils for biodiesel industry or biorefineries. MO is storable, can be easily transported and fed to energy conversion systems. Its energy density is 15 to 25 times higher than wheat straw or wood chips (Buffi et al. 2020). At present, the MO production technology is not fully commercial yet. However, MO can be perfectly introduced in advanced biofuel chains, as both upstream (lignocellulosic sugars) and downstream (conversion of lipids to HVO/HEFA) is fully industrialised, being existing plants able to produce respectively, thousands tons (upstream) and hundred thousand to million tons (downstream) of products per year.

4.1 Technology overview

The MO production process, as shown in Figure 6, is similar to lignocellulosic bioethanol production. More precisely, both the biomass smart cooking section (i.e. biomass pre-treatment) and the hydrolysis section (cellulose is conversion to sugars) are almost identical in the two processes. The main differences can be found in the sugar fermentation section. There, the MO production process requires the use of different yeast strains, as well as a prior lignin separation from the feedstock stream, as a solid residue. Moreover, an additional intermediate step before fermentation is required to increase the sugar concentration of the remaining sugars-water solution. The downstream final sections differ as well between the two processes, namely a distillation section for ethanol and an oil extraction section for MO production, respectively.

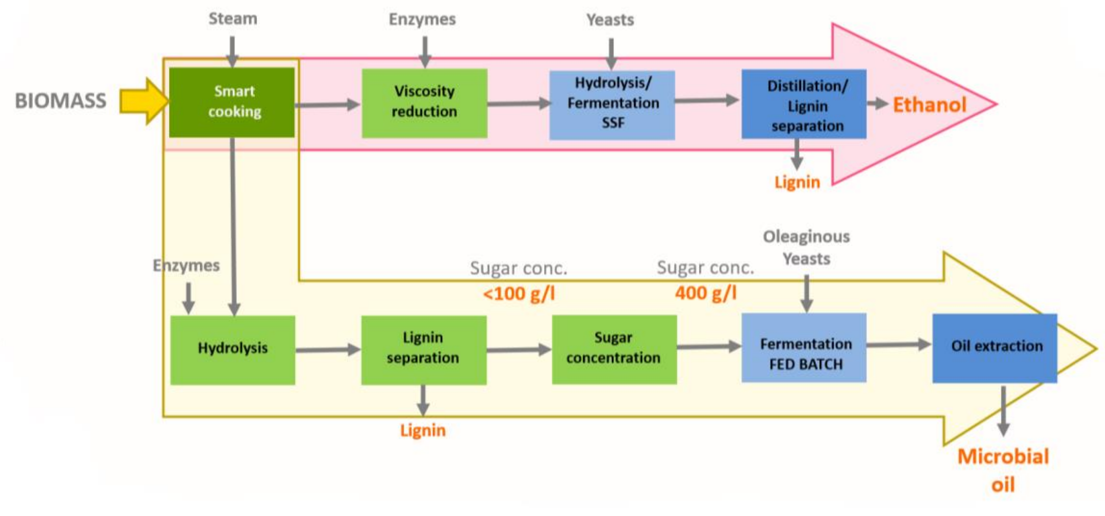


Figure 6: Main differences between lignocellulosic ethanol (light red route) and microbial oil production processes (light yellow route) (Vos et al. 2020)

Lignin and remaining solid materials can be burned to produce electricity and heat to be used within the IBC plant or transferred to other customers.

Due to its chemical composition, MO is well suited as feedstock for the hydrotreating process, producing Hydrotreated Vegetable Oil (HVO) fuels such as renewable diesel. HVO could also be further processed to obtain bio-based aviation fuels, under the ASTM-certified HEFA (Hydroprocessed Esters and Fatty Acids) production pathway (ASTM International, formerly known as American Society for Testing and Materials, is an international standards organization that develops and publishes voluntary consensus technical standards).

Renewable diesel produced from e.g. MO has several advantages compared to conventional, ester-type biodiesel fuels, such as:

- Meeting conventional diesel fuel requirements,
- Reduced NOx emission,
- Less storage stability problems and deposit formation,
- Better cold properties.

4.2 Biomass mobilisation and logistics

Currently, the technology readiness level (TRL) of the microbial oil fermentation step is at 4-5, thus lower than torrefaction and pyrolysis, and MO is not yet commercially produced. Biomass mobilisation and logistics for MO production shows strong similarities with the lignocellulosic ethanol chain. In fact, agricultural residues such as wheat straw and corn stover may be used as feedstock, as well as forestry residues (hardwood or softwood) and energy crops such as Arundo donax.

The high energy density of MO compared to raw biomass suggests a logistics system where the IBC plant is placed closer to the feedstock production areas than to the bio-refinery where the HVO diesel or jet fuel (SAF, Sustainable Aviation Fuel) is produced. This helps to reduce the overall transportation costs of the raw, low-value materials. The following two different scenarios are possible:

1. Energy crops: Initial biomass harvesting, densification and collection in strategic points for drying/storage, and transport to IBC plant;
2. Agro and forest residues: Collection, pre-treatment and transport to IBC plant.

Such short chain biorefineries, fed by lignocellulosic biomass instead of vegetable oils from distant origins, promote local value chains within the future European bioeconomy. Finally, multiple feedstock suppliers and/or multiple storage facilities are beneficial to secure operational flexibility and to reduce feedstock supply risks (Vos et al. 2020).

4.3 Market overview and market potential

Today, the main feedstock for the production of biodiesel for the European market are vegetable oils. Lipids are consolidated feedstock for commercial HVO biorefineries, with palm oil considered one of the best feed, due to its lower cost and related lower H_2 consumption. The RED II directive sets a cap for such food- and feed-based biofuels that could contribute for a maximum of a 7% share to the total final energy consumption of EU road and rail transport sectors. RED II also defined targets to reduce the consumption of high ILUC-risk feedstock - such as palm oil - to produce biofuels, starting in 2023 and reaching a complete phase out by 2030. Some HVO producers, however, either already cut the use of palm oil, or have announced to do this by 2023.

MO production, integrated in existing large scale HVO installations,has a very large potential as a substitute for vegetable oils and food-related lipids. Thus, MO are attracting growing interest as this process could largely benefit from synergies with two major advanced biofuels commercial technologies such as HVO and lignocellulosic ethanol.

4.4 Market uptake barriers and challenges

Microbial Oil still needs high levels of investments in research and development due to its current low TRL of 4-5 and at the same time could suffer from the so-called “chicken and egg situation”: an operational reference plant is important to persuade reluctant investors, but at the same time such a reference plant is quite unlikely to be funded, since investment security is not granted.

Beside the techno-economic challenge of scaling up the plant from pilot to fully commercial, other important challenges are found within the biomass supply chain. Here the use of agricultural residues for the MO process can lead to new revenue streams for farmers and improve the storage and transport worthiness of these residues (after processing) (Pfeiffer at al. 2020). However, in order to exploit the potential of MO, upstream supply logistics need to be further developed: several small- and medium-sized producers would have to be gathered together in order to reach the critical mass of feedstock needed by the IBC plant. Moreover, logistics costs should be carefully defined, also taking into account geographical characteristics of the production areas.

4.5 Policy recommendations

Microbial oils (produced by oleaginous yeasts from cellulosic sugars derived from lignocellulosic biomass) as potential feedstock for the development of a European biobased economy are presently at early stages of development. Microbial oils can thereby be of specific interest for the fossil refineries sector for their transition towards a low-carbon economy. Fossil refineries need sustainable lipid feedstocks in large quantities to replace crude oil. Furthermore, facilities producing HVO (Hydrogenated Vegetable Oils) biodiesel in existing refineries (such as ENI in

Porto Marghera, Total in La Mede, PREEM in Gothenburg and Neste Oil in Porvoo) will be regulated to reduce their use of food crop based bio-oils (such as palm oil) and to complement feedstock such as Used Cooking Oil (UCO) and other waste oils which are not available in sufficient quantities.

The following policy recommendations serve to support the market up-take of microbial oils as sustainable feedstock in biorefineries.

- Dedicated support for technology development, demonstration and pilot scale operation for the production and use of microbial oils is required to move this promising technology from the present TRL 4-5 to TRL 8-9 in the coming years.

- The European research and innovation programme for the period 2021-2027 (Horizon Europe) should include calls for Research and Innovation Actions (RIA) targeting improved microbial oil production processes (with respect to yield, production costs, environmental impacts).

- Horizon Europe should include dedicated Innovation Actions (IA) to demonstrate microbial oil production and use at industrial facilities (potentially relevant Horizon Europe call topic: C5-D3-RES-19-2021: Demonstration of cost-effective advanced biofuel technologies utilizing existing industrial plants).

- Initiatives of European industrial actors to benefit from the European Innovation Fund should be promoted and supported.

- As initial use of microbial oils is anticipated as co-feeding feedstock in fossil refineries, a European definition for determining the sustainability of biofuels from co-feeding is needed to facilitate market uptake. Clear rules, including a calculation formula to derive the “green content” of fuels need to be established with respect to “green transport fuels” that also contain fossil-based fuels.

- The promotion of advanced biofuels laid down in the RED II through its dedicated subtarget for advanced biofuels may serve to promote microbial oil production from initial feedstock listed in Annex IX Part A of RED II.

- Finally, all policy measures serving to transform the European economy into a sustainable bioeconomy will create market opportunities for sustainable feedstock such as microbial oils produced from sugars derived from lignocellulosic biomass.

5 Conclusion

Intermediate Bioenergy Carriers (IBCs) such as pyrolysis oil, torrefied biomass and (in medium or long term) microbial oil may significantly contribute to the decarbonisation of the European economy and the successful transition towards a sustainable future circular and bio-based economy. Thereby, IBCs may serve to replace fossil fuels in the energy sector (for power and heat production), the transport sector (for advanced biofuels production), within energy intensive industries as well as for the production of bio-based materials.

Promising applications of IBCs include the substitution of fossil fuels in existing power and CHP plants (torrefied biomass and pyrolysis oil), the co-feeding with crude oil in refineries (pyrolysis oil, microbial oil) for the production of advanced biofuels and bioproducts, as well as the replacement of coal as reducing agent in the steelmaking process.

Therefore, it is recommended to appropriately integrate IBCs in roadmaps and action plans of the European Green Deal and its associated call “Building a low-carbon, climate resilient future: Research and innovation in support of the European Green Deal”. Specifically, IBCs may benefit from the following call topics:

- LC-GD-2-1-2020: Innovative land-based (and offshore) renewable energy technologies and their integration into the energy system (inviting Research and Innovation Action (RIA) proposals to bring solutions to TRL 4-5)
- LC-GD-3-2-2020: Demonstration of systemic solutions for the territorial deployment of the circular economy (inviting Innovation Action (IA) proposals to bring circular solutions to TRL 6-7)

Furthermore, IBC based solutions shall be addressed in the framework of the European research and innovation programme for the period 2021-2027 (Horizon Europe). Potential calls promoting technology development and market uptake of IBCs include:

- Pyrolysis technology development enabling the use of lower quality and thus cheaper feedstock such as waste wood and agricultural residues.
- Technology development for the use of torrefied biomass in energy intensive industries.
- Technology development targeting improved microbial oil production processes
- Demonstration projects establishing full value chains for torrefied biomass and pyrolysis oil in cooperation with technology providers and potential end users.
- Demonstration of microbial oil production and use at industrial facilities.

Finally, Intermediate Bioenergy Carriers are integral part of the SET Plan Implementation Plan of the SET Plan Implementation Working Group (IWG) 8 on Bioenergy and Renewable Fuels for Sustainable Transport and stated as important component in the framework of the recently published Input Paper for the 14th SET Plan Conference 2020 "Making the SET Plan fit for the EU Green Recovery" - The SET Plan contribution to the Offshore Renewable Energy strategy:

“Intermediate bioenergy carriers, e.g., bio-oils, torrefied pellets produced in modular small units near-shore from local biomass residues and wastes can also store off-shore generated renewable energy and used in a flexible way to stabilize the electricity grid or supply renewable energy to heat, cool and transport in downstream central production units.”

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