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Replicability Study

WP6 - Task 6.4

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Table of Contents

List of Figures

List of Tables

Abbreviations and acronyms

Acronyms	Meaning
BL2F	Black Liquor to Fuel
CO_2	Carbon Dioxide
EC	European Commission
EU	European Union
GHG	Green House Gases
HTL	Hydrothermal Liquefaction
IHTL	Integrated Hydrothermal Liquefaction
KIT	Karlsruhe Institute of Technology (Germany)
NVG	The Navigator Company (Portugal)
RED II	Renewable Energy Directive
SEI	Stockholm Environment Institute
TAU	Tampere University (Finland)
WWTP	Wastewater Treatment Plant

Glossary

Term	Description
Biofuels	Fuels produced from biological raw materials. Four generations of biofuels are distinguished: • First-generation biofuels are crop-based biofuels as they are commonly derived from food plants, such as biodiesel from oilseed rape and bioethanol from sugar. • Second-generation biofuels are produced from lignocellulose materials derived from whole or parts of plants and trees that are not used for human consumption. These include all biofuels derived from wood and include black liquor-based fuels, lignocellulosic bioethanol and synthetic diesel produced using gasification or the Fischer-Tropsch process. • Third-generation biofuels are those derived from aquatic biomass. • Fourth-generation biofuels, so-called “electro fuels”, include the use of renewable electricity and carbon dioxide as feedstock (Sandquist 2017). Advanced Biofuels, as defined by the European Technology and Innovation Platform, are those “(1) produced from lignocellulosic feedstocks (i.e. agricultural and forestry residues, e.g. wheat straw/corn stover/bagasse, wood-based biomass), non-food crops (i.e. grasses, miscanthus, algae), or industrial waste and residue streams, (2) having low CO_2 emission or high GHG reduction, and (3) reaching zero or low Indirect Land Use Change impact.”(ETIP Bioenergy 2021).
Black Liquor	“Black Liquor” is a by-product of pulp from mills that make products from trees, such as paper. It is currently used to recover cooking chemicals and produce high-pressure steam used in the pulp and paper-making process. It is composed of different ingredients from these processes such as lignin, hemicellulose, sodium hydroxide (NaOH) and sodium sulfide (Na2S). The lignin compound in black liquor can be used to make biofuel.
Renewable Feedstock	Any renewable, biological material that can be used directly as a fuel or converted to another form of fuel or energy product.
Forest Biomass	Forest biomass includes all parts of the tree, not only the trunk but also the bark, the branches, the needles, or leaves, and even the roots (Government of Canada, 2020).

Executive Summary

This study explores the potential and opportunities of three feedstocks (i.e., sewage sludge, sawdust and bark) to produce advanced biofuel in Sweden and Finland. More specifically, it explores the replicability potential of the BL2F (Black Liquor to Fuel) technology with other feedstocks, as BL2F originally uses black liquor for advanced biofuel production.

The report studies the EU, Finnish and Swedish regulations around sewage sludge, bark and sawdust, the advantages and drawbacks of the most widespread usages of these feedstocks, the availability of these feedstocks in Finland and Sweden and the major technological challenges to produce advanced biofuels based on these three feedstocks.

Through the Renewable Energy Directive (RED II), EU regulations allow the use of sewage sludge, bark and sawdust for advanced biofuel production which could contribute to the decarbonisation of the aviation and shipping sectors. These three feedstocks can be used to produce advanced biofuel, replacing or complementing black liquor in the BL2F process for advanced biofuel production.

Bark, followed by sawdust, appears to be the most promising in addition to black liquor for advanced biofuel production within the BL2F process. As bark and sawdust are residues from the forest industry, they both have stronger benefits in terms of logistics, as they can be collected together at pulp mills for the BL2F process. Sewage sludge also presents opportunities for advanced biofuel production in Finland and Sweden due to the challenges and controversies of its usages in other sectors. The limited availability of sewage sludge in Finland and Sweden is however a major brake for the development of sewage sludge-based biofuels in these countries. The cost competitivity of advanced biofuels produced from these three feedstocks yet remains a challenge compared to fossil fuels.

1. Introduction

1.1. Purpose of the report

Black Liquor to Fuel (BL2F) process produces drop-in advanced biofuels for aviation and shipping from black liquor, a side stream of chemical pulping industry. Black Liquor is a by-product of pulp from mills that make products from trees, such as paper. It is currently used to recover cooking chemicals and produce high-pressure steam used in the pulp and paper-making process. It is composed of different ingredients from these processes such as lignin, hemicellulose, sodium hydroxide (NaOH) and sodium sulfide (Na2S). The lignin compound in black liquor can be used to make biofuel. This study explores three other possible feedstocks (i.e., sewage sludge, bark and sawdust) that could be used to replace or to add to black liquor within the BL2F process.

The goals of this replicability analysis are:

- To identify the market potential of sewage sludge, bark and sawdust for the production of advanced biofuels
- To study how the BL2F technology could be replicated with other feedstocks than black liquor and open new possibilities to upscale the project further
- To explore new opportunities for the development of the BL2F technology in Finland and Sweden

1.2. Methodology

1.2.1. Scope of the task

Steps to determine the scope of the task

Several preliminary steps were considered to determine the scope of the task 6.4. A first brainstorming session was organised within the LGI team, which identified two key questions:

1. What other feedstocks could be used within the BL2F process?
2. What other sectors apart from aviation and shipping could be relevant as advanced biofuel end users?

These two questions were discussed with TAU partners to ensure that the study focuses on the most relevant scope for the BL2F project and partners.

The second question was finally dismissed considering the decision from the European Parliament in June 2022 to confirm the phase out of fossil fuel vehicles. This phase out implies the ban of combustion engines by 2035 in several European countries, and prevents e-fuels and biofuels from being used in the road transportation sector (European Parliament 2022).

The focus was therefore drawn on the question "**What other feedstocks could be used within the BL2F process?".** To address this question, several feedstocks were identified based on the RED II Appendix IX (full list in appendix).

The feedstocks were considered to be the most relevant for the BL2F process in terms of technical feasibility, and were prioritised with the partners involved in T6.4 and TAU. Additional insights were collected through one-to-one interviews with project partners in the context of the exploitation task (T6.5) and discussions during the B2LF monthly meeting.

Final scope of the task 6.4

Discussions with T6.4 partners led to the prioritisation of the three following feedstocks

- Sewage sludge,
- Bark,
- and Sawdust

The analysis of bark and sawdust is mostly grouped as they both constitute secondary forest waste residues. A minor section on paper and pulp sludge is included in appendix as it is of interest for several partners.

According to the BL2F market opportunities study (D6.3) published in early 2022, **Finland and Sweden** are among the countries with the most potential for the development of the BL2F technology. A focus is therefore made on these two countries, but information at European level is also included in the report.

1.2.2. Implication of BL2F partners and external stakeholders

The task 6.4 is led by LGI and involves BL2F partners cited in Table 1. An internal kick-off meeting was organised in June 2022 with the partners involved in the task. These partners were involved in the key decisions regarding the scope of the task, as well as the review of the final draft deliverable.

Table 1 BL2F Partners involved in Task 6.4 as contributors

Name of partner	Position	Organisation
Pedro Costa Branco	Research scientist	NVG
Alexandre Gaspar	Industrial scale-up & New Business Development	NVG
Pavel Kukula	Managing Director	Ranido
Yaroslav Kochergin	R&D Project Manager	Ranido
Viswamoorthy Raju	Manager	Valmet
Ekatarina Sermyagina	Researcher	Neste
Tero Joronen	Research scientist/ coordinator of BL2F project	TAU
Babak Arjmand	PhD Student	TAU

Vaihbhav Agrawal	Postdoctoral Research Fellow	TAU
Aino Vettenranta	Specialist	Valmet

To complement the analysis, qualitative interviews were conducted by LGI with sixteen experts. Table 2 lists the seven experts which were interviewed on sewage sludge and Table 3 showcases the nine experts interviewed on sawdust and/or bark.

Table 2 Sewage sludge experts interviewed in the context of the replicability study

Name of expert	Position	Organisation	Country
Serena Righi	Associate Professor Department of Physics and Astronomy	University of Bologna + ToSynfuel project	Italy
Fabian Stenzel	Business Development	Fraunhofer UMSICHT + ToSynFuel project	Germany
Paula Lindell	Development manager	Finnish Water Utilities Association	Finland
Ari Kangas	Analyst	Finnish Ministry of the Environment	Finland
Suvi-Tuuli Lappalainen	Development Manager	Port of HaminaKotka Ltd	Finland
Linus Dagerskog	Research fellow	Stockholm Environment Institute (SEI)	Sweden
Dr Håkan Jönsson	Professor Emeritus	Swedish University of Agricultural Sciences	Sweden

Table 3 Bark and sawdust experts interviewed in the context of the replicability study

Name of expert	Position	Organisation	Country
Dr Monica Normark	Director Biofuels Technology at KBR and Former CTO Sekab, 2022		Sweden
Kjell Andersson	Policy advisor	Svebio - Swedish bioenergy association	Sweden
Patrick Pitkänen	Director biorefining business development	St1 Biofuels	Finland
Judit Sandquist	Research Scientist	SINTEF-ER	Norway

Name of expert	Position	Organisation	Country
Ursel Hornung	Research Scientist	KIT	Germany
Alexandre Gaspar	Industrial scale-up & New Business Development	NVG	Portugal
Viswamoorthy Raju	Manager	Valmet	Finland
Mats Nordgren	Senior Specialist Pulp Mills	Valmet	Finland
Vesa Helanti	Product Manager Gasification	Valmet	Finland

In addition, LGI participated remotely to the NextGenRoadFuels Event "Turning waste into fuels" in October 2022 in order to learn more about the use of sewage sludge for biofuel production. For the bark and sawdust feedstocks, BL2F partners and external stakeholders were interviewed.

The goal of these interviews was to proceed to a detailed analysis of each selected feedstock to determine the availability, current usages, challenges in current usages, risks, opportunities, and regulations around it, as well as to assess technical feasibility to integrate them in the BL2F process. The content of the interviews were analysed along with desktop research and detailed in the report.

2. Feedstocks and their market potential

In this section, a deeper analysis of sewage sludge, bark and sawdust is conducted. The regulations around the feedstocks, their current usages and the challenges related to advanced biofuel production are explored and linked to the BL2F technology.

2.1. Sewage sludge

Sewage sludge is a mud-like residue resulting from wastewater treatment processes from industrial or municipal wastewater facilities. It is made up of a semi-solid material, mixing organic matter from human waste, food waste particles, micro-organisms, trace chemicals and inorganic solids from products and medicine, together with water bound to these materials.

Sludge can come from industrial facilities (food manufacturers, pulp and paper factories, chemical and fuel factories, etc.) as well as urban and suburban area homes or businesses from washing, bathing, and flushing toilets (Pennsylvania State University 2010).

2.1.1. Regulations around sewage sludge

At European level, the first political decisions related to sustainable sewage sludge management emerged in the 1980's: In 1986, the Sewage Sludge Directive 86/278/EEC on the protection of the environment, and particularly on the soil, was adopted, encouraging the use of sewage sludge in agriculture but ensuring that it does not harm the environment, animals and humans, and defining metal content at EU level. This directive has not been updated or revised since then despite several discussions and consultation processes. It does not longer match current needs related to the amount of pharmaceuticals and microplastics in sewage sludge that were not as relevant at the time (European Commission n.d.).

Regulatory disparities between countries have therefore emerged, for example on limits on the amount of heavy metals and other contaminants for agricultural purposes, not covered by the directive (Dagerskog, Olsson 2020).

The Directive on the treatment of urban wastewater 91/271/EEC was adopted in 1991 to protect the water environment from the adverse effects of discharges of urban waste water and from certain industrial discharges (European Commission n.d.). It introduces controls over the disposal of sewage sludge and forbids the dumping of sewage sludge at sea by 1998.

Finally, since 2018, the Renewable Energy Directive (RED II) authorises the use of sewage sludge for fuel production in Appendix IX[1].

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[1] The Renewable Energy Directive (2018/2001) contains the Annex IX which lists the feedstocks that receive special treatment for the purposes of the RED II transport target.

2.1.2. Current usages of sewage sludge

In the EU, sewage sludge is managed differently depending on each member state respective regulations.

Before being used for specific sectors, sewage sludge must be treated in a certain manner, which may include a combination of thickening, digestion, and dewatering processes (Ambulkar n.d.). Sludge requires treatment to reduce its weight and volume in order to minimise transportation and disposal costs, to reduce the risk it poses to public health, primarily from the pathogenic micro-organism content, to reduce its odour and to improve its stability (Sludge Processing 2020).

The most common treatment methods are digestion and composting.

- Sludge digestion is a biological process in which organic solids are decomposed into stable substances. Digestion reduces the total mass of solids and eases the dewatering and drying process of sludge. In the case of a thermophilic digestion, pathogens are also killed (Ambulkar n.d.).
- Sludge composting is a type of aerobic digestion. Sewage sludge can be combined with other waste materials such as wood chip, straw or green wastes prior to composting to provide a pasteurised product (Sludge Processing 2020).

For example, Figure 1 illustrates the process of sewage sludge treatment for disposal, where the sludge digestion process is used. For other final uses, sludge composting is used instead of digestion.

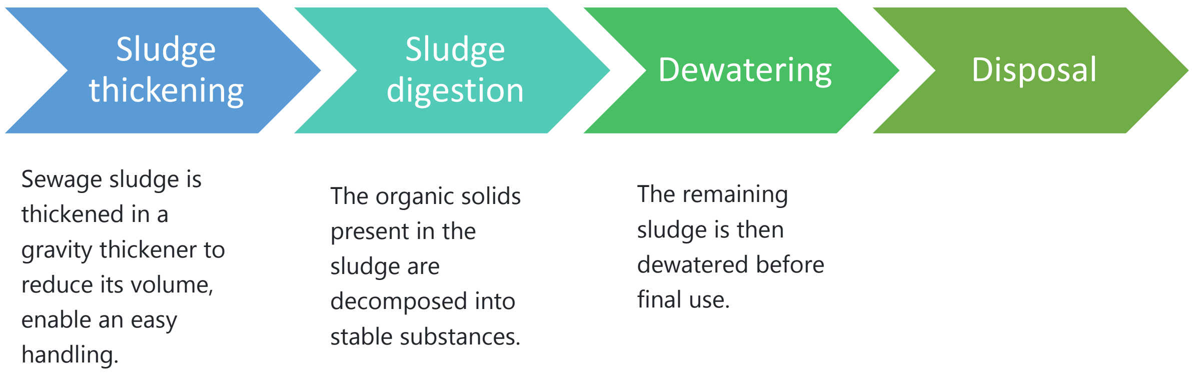

Figure 1 Steps of the sewage sludge treatment process for disposal (Patel 2018)

The most common sewage sludge management strategies in Europe are illustrated in Figure 2 and described below:

- **Agriculture / Green area construction**: The spreading of sludge on farmland is the most common sewage sludge management strategy in the EU: almost half of the sewage sludge produced in the EU-27 is currently used for agricultural purposes. It includes "green area construction", which refers to the use of sewage sludge as soil conditioner or fertilising product.

- **Incineration:** About one fourth of the European sewage sludge is treated by incineration to destroy organic pollutants as well as biological threats.
- **Landfill cover:** Around 8.5% of the sewage sludge is sent to landfill (Campo 2021).
- **Other uses:** Sewage sludge can be used for landscaping and production of building materials:
    - In landscaping, sewage sludge is providing accelerated growth of plants and helping in the reforestation of an area thanks to the nutrients present in sludge.
    - Sewage sludge can be used to produce construction and building materials. It can be used as raw material for the production of eco-cement, bricks and ceramic materials, but also as supplementary admixtures in cementitious materials such as pozzolanic component, fine aggregate or filling material (Świerczek 2018) (Chang, Long, Zhou, Ma 2020).

Figure 2 Most common sewage sludge management strategies in Europe

Figure 3 describes the repartition of sewage sludge management strategies in the EU. The 25% remaining in "Other" includes landscaping and sending to landfill (Dagerskog, Olsson 2020).

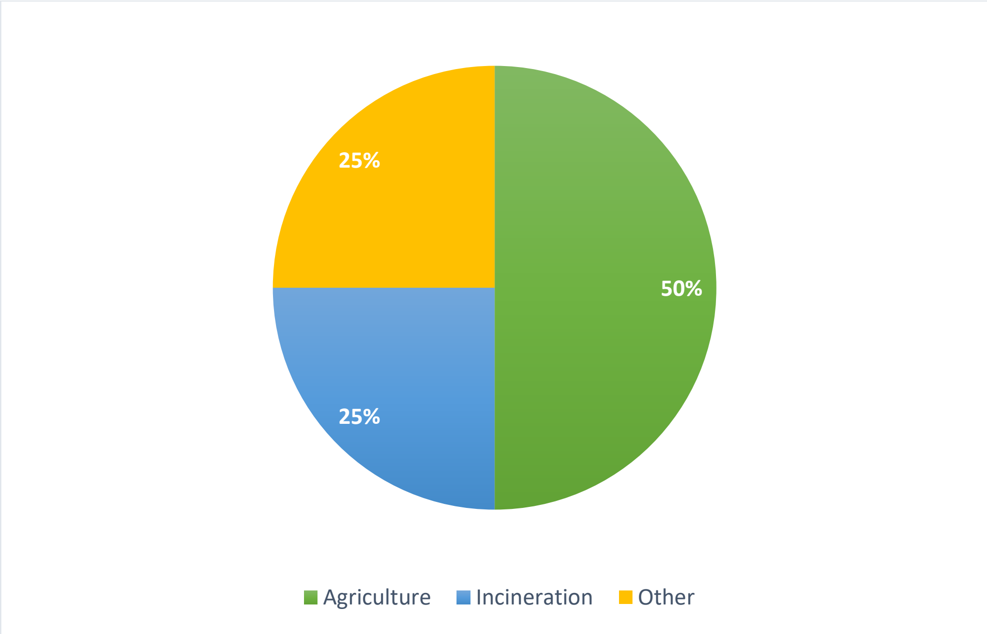

Figure 3 Sewage sludge management strategies in the EU (Dagerskog, Olsson 2020)

Each EU country has its own combination of sludge management strategies. While the types of applications can vary from the respective characteristics of each region (Righi 2022). Figure 4 illustrates the most common sewage sludge management strategies in each country. The most common strategy that is highlighted is however not the only sewage sludge management strategy in these countries.

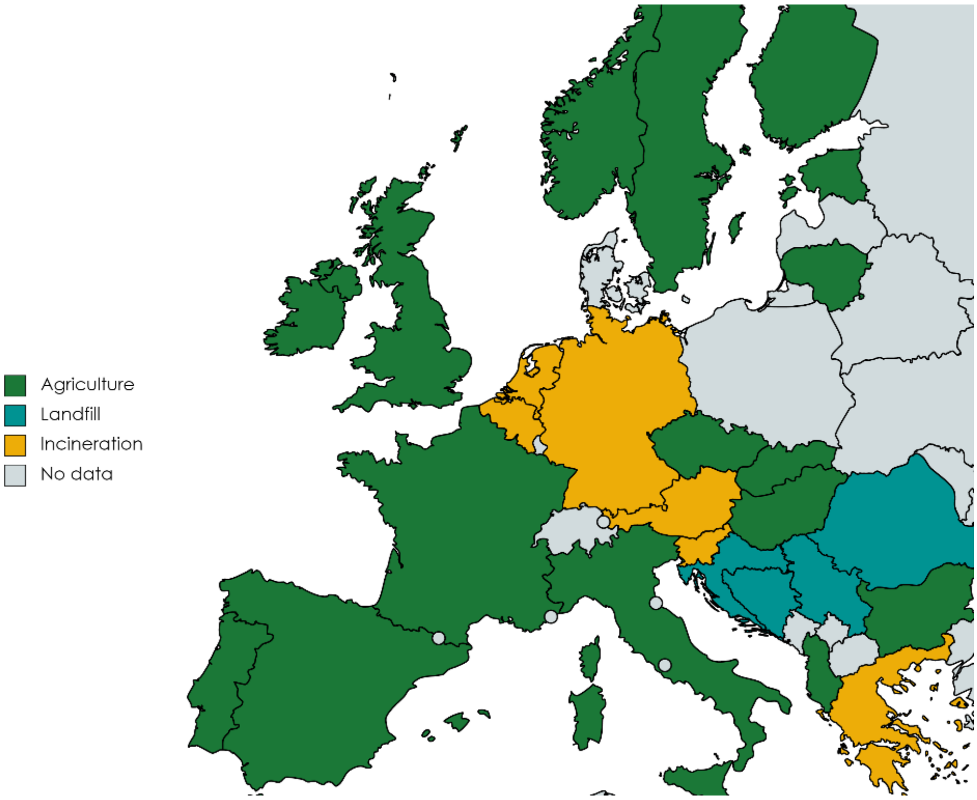

Figure 4 Most dominant sewage sludge management strategy in European countries, data retrieved from (Eurostat 2015, 2017)

The advantages and drawbacks of each of the applied sewage sludge management strategies are then studied in order to compare and determine the opportunities and levers for the use of sewage sludge in advanced biofuel production.

Use of sewage sludge in agriculture

Sewage sludge may be spread on agricultural land to valorise it as a soil conditioner and fertiliser. As sludge may contain toxic industrial chemicals, its direct use on land where crops are grown for human consumption is not recommended.	
Advantages	**Drawbacks**
• Sewage sludge can be used as biogenic **fertiliser for agriculture because it contains nutrients** such as phosphorous (P), nitrogen (N), potassium (K) and carbon (C) which are critical elements for plant growth. • In terms of regulations, the use of sewage sludge for agriculture purposes is allowed in most EU countries as it is the most common treatment in most countries. Its use is however regulated.	• While the use of sewage sludge in agriculture is allowed in Finland and Sweden, there are **food industry related prohibitions** on its use in agriculture. • The potential negative impacts of heavy metals, hormones, microplastics, pathogens, medical residues and other pollutants in sludges could have an **impact on human health and on the environment** (detailed below). • **Heavy metals** are highly present in sewage sludge including Cadmium (Cd), Chromium (Cr), Copper (Cu), Nickel (Ni), Lead (Pb), Zinc (Zn) and Mercury (Hg) that originate from industrial wastewater, runoff, and corrosion within the sewage system. Such high concentrations can cause health and environmental damage (Tytla, Widziewicz-Rzońca 2021; Zhang, Wang, Wang 2017). • **Hormones and medical residues**: An emerging issue is the presence of micropollutants including pharmaceutical compounds, hormones, fragrances and personal care products that are continually discharged to sewer systems but that cannot be fully eliminated by current sludge treatment. The

	unknown toxicity, teratogenicity and carcinogenicity of these substances associated with lack of monitoring and control measures impose a significant hazard risk on the public health (Hagström 2021; Nassiri Koopae, Abdollahi 2017). • **Microplastics**: The explosion of plastic use in the last decades at both domestic and industrial level has caused an increased quantity of microplastic in sewage sludge. Plastic contamination of terrestrial ecosystems and arable soils pose potentially negative impacts on several soil functions (Rolsky, Kelkar, Driver, Halden 2020). • **Pathogens:** Sewage sludge commonly contains high amounts of human pathogenic bacteria excreted in faeces. These might contaminate soil-grown fresh products and pose a health risk for both humans and animals (Major, Schierstaedt 2020). • In terms of **societal acceptance**, the use of sewage sludge in agriculture remains a very controverted and polarised issue due to these potential negative impacts on health and soil.

Incineration of sewage sludge

Incineration of sewage sludge completely evaporates the moisture and converts the organic solids into inert ash, which can then be disposed of.	
Advantages	**Drawbacks**
• In countries with important incineration capacity available (exceeding the sewage sludge volume), incineration is the cheapest option (Righi 2022).	• Incineration emits substances such as dioxins, furans, NOx (oxides of nitrogen) and SO_2 (sulphur dioxide) that impacts mainly on **human**

- Incineration allows the **elimination of all harmful substances** present in sewage sludge without the fear of contaminants ending up in the environment. - In the case of mono-incineration of sewage sludge, phosphorus (P) can be effectively recovered from sewage sludge ash (SSA) by applying wet chemical extraction techniques. As phosphorus is one of the most common nutrients in fertilisers, it can then be reused for agriculture. - If the energy is recovered and reused, the energy and heat produced (e.g., electricity, fuel for heating), can lighten the environmental impact of incineration.	**toxicity and ecotoxicities** (Pradel, Reverdy, Richard, Chabat 2014). - The co-incineration of sewage sludge in waste incineration plants and coal-fired power plants does not allow the valorisation of phosphorus (Gutjahr, Müller-Schaper 2018). - Apart from phosphorous, incineration does not allow the valorisation of other nutrients (e.g., potassium, nitrogen) present in sewage sludge. - Incineration is not very widespread in Finland and Sweden. It requires the use of existing incineration plants or large investments.

Landfilling

The landfilling of sewage sludge consists in burying dewatered sludge underground in a sanitary landfill.	
Advantages	**Drawbacks**
Disposal is usually the cheapest route for sewage sludge management in countries where it is allowed.	- Landfilling does not allow the valorisation of energy and nutrients present in sewage sludge. *Sewage sludge is a resource, not a waste. It contains nutrients and we have to exploit it."* (Righi 2022). - Dumping sewage sludge in the ocean or sea is the most impacting landfilling scenario as it leads to freshwater eutrophication (Pradel, Reverdy, Richard, Chabat 2014).

A focus is made on the current uses and regulations in Finland and Sweden. In each of these countries, the use of sewage sludge is closely linked to the regulations around it.

Finland

In Finland, sewage sludge mostly goes to agriculture or green area construction. A very small amount of sewage sludge is used as a landscaping for old landfill areas, and an even smaller portion goes to incineration as there are only 2 plants for incineration amounting for less than 1% of total (Kangas 2022). Combined treatment of digestion and composting is the most common method of sludge treatment in Finland, as shown in Figure 5.

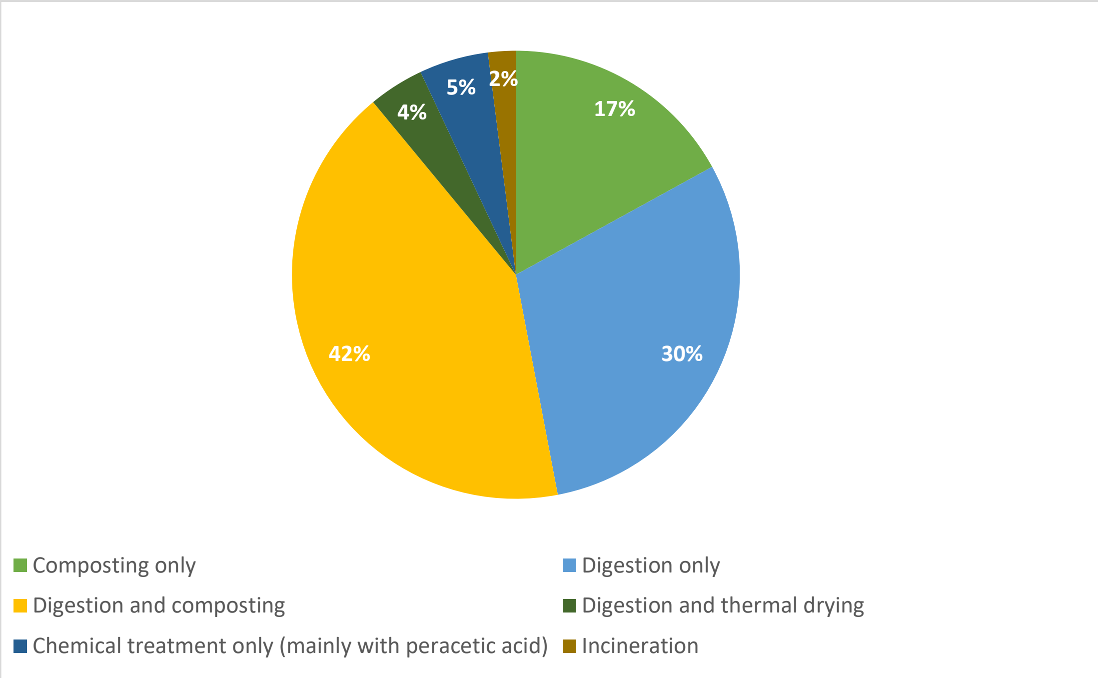

Figure 5 Contributions of sludge treatment methods to total sludge in 2020 (Vesilaitosyhdistyksen 2020)

In 2019 and 2020, 47% of sewage sludge went to agriculture, 40% to green area construction and 7% landscaping (Figure 6).

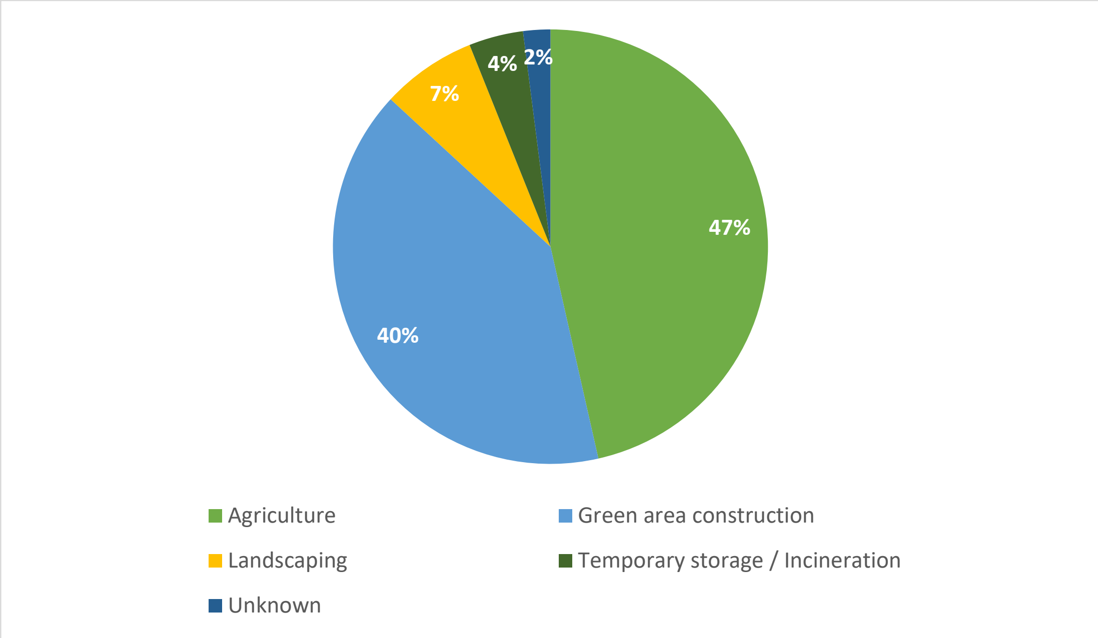

Figure 6 Proportional shares of sludge recovery methods in 2019 and 2020 (Suomen Vesilaitosyhdistys ry 2020)

The use of sewage sludge in agriculture is however a contentious and polarised issue in Finland, due to the potential negative impacts on human health and soil. The use of sewage in agriculture is regulated by the Ministry of Agriculture and Forestry: in the article 11 a of the Fertiliser Regulation (Lannoitevalmisteasetus 12/12, 11 a §), it states that only treated sludge may be used in agriculture and limits the permitted levels of harmful substances in agricultural land, the maximum annual load of sludge application to agricultural land and the permitted pH values for agricultural land (Frank-Kamenetsky 2018; Waterworks Association 2013).

Several development projects are ongoing and looking for new options for sewage sludge treatment and nutrient recovery. The Finnish Water Utilities Association (FIWA) encourages the use of new solutions to manage sewage sludge (Toivikko 2020).

Sweden

In Sweden, a large proportion of sewage sludge is used for topsoil production and covering landfills. About a third (34%) of sewage sludge is spread on farmland annually as agricultural input (Ekane, Barquet, Rosemarin 2021), followed by green area construction (25%) and landfill cover (17%) (Bioenergitidningen.se 2021) (Figure 7).

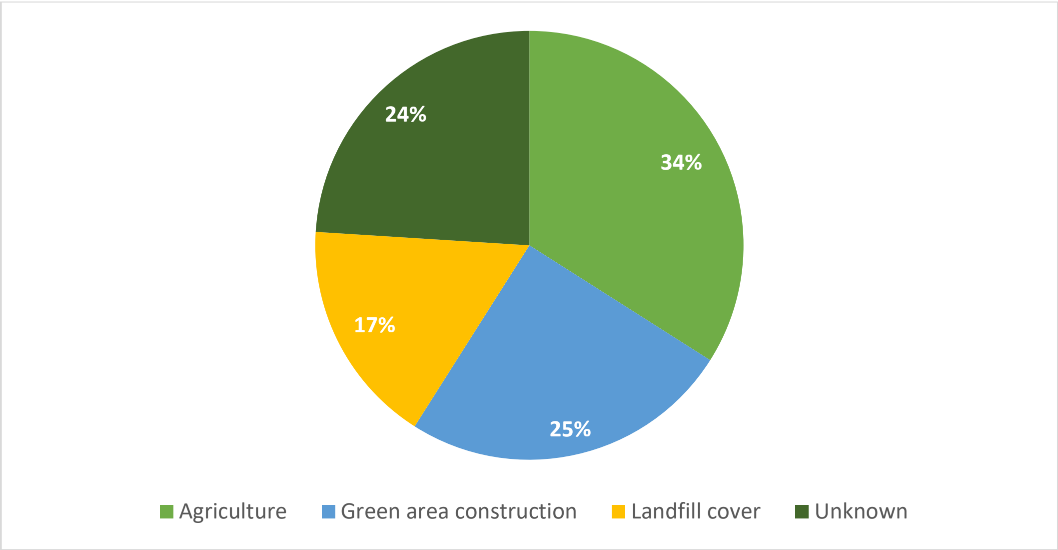

Figure 7 Proportional shares of sludge recovery methods in 2021 (Bioenergitidningen.se 2021; Ekane, Barquet, Rosemarin 2021)

Among other uses which proportion was undetermined, a part has been used for covering old mining sites and re-establishing biodiversity.

As in Finland, the use of sewage sludge in agriculture is a very contentious and polarised issue in Sweden, due to the potential negative impacts on human health and soil. There is a lot of resistance from consumers and the food industry, fearing that the impurities contained in the sludge could re-enter the food chain and cause health issues. Environmental organisations also give resistance, urging to protect soils from contamination. For example, in 2022 the Swedish association "Doctors for the Environment" (*Läkare för miljön*), that advocates for a ban on the spreading of sewage sludge on productive agricultural land, demanded either the labelling of food grown on sludge-free land or food grown on toxic land in order to allow the transparency of the products for consumers (Hagström 2022).

In Sweden, the use of sewage sludge for agricultural purposes started in the 1960s, while the first regulations only emerged in the 1980s. Figure 8 illustrates the evolution of the sewage sludge regulations between the 1960's and 2008.

Figure 8 Timeline of sewage sludge regulations in Sweden since the 1960's

- In the 1960's, sewage sludge for agricultural reuse was seen as a low-cost solution to the problem of disposal, with the advantage of bringing benefits to farmers.

- In the 1980's, public guidelines emerge on the use of sewage sludge for agricultural purposes: discussions on the potential risks related to other contaminants started, especially on heavy metals and organic micropollutants.
- Established in 2008 by the Swedish Water & Wastewater Association and other national stakeholders, the REVAQ system, a joint certification programme for wastewater treatment plants is introduced to set limits on key contaminants in sludge destined for agricultural reuse and improving sludge quality (Juhanson, Malmström, Pell, Hallin 2021).

The REVAQ system recommends that only sludge from REVAQ-certified treatment plants meeting quality standards should be used on farmland. This represents about 45% of all sludge produced in Sweden. Several limitations however remain, despite the introduction of REVAQ. For example, Swedish flour mills will not accept grain that has been fertilised with sewage sludge for fear of consumer backlash, and crops fertilised with sludge cannot be certified as organic (Svenskt Vatten 2013). Furthermore, the current REVAQ guidelines do not cover emerging contaminants such as pharmaceuticals and microplastics. (Dagerskog, Olsson 2020)

Given the uncertainty of being able to reach increasingly strict quality requirements and finding farms willing to receive the sludge, incineration is likely to become a dominant practice (Dagerskog 2022). Consumers and food industry are mostly supporting the incineration of sewage sludge and recovery of phosphorous ashes.

In 2018, the Swedish government initiated the inquiry "Pollutant-free and circular recovery of phosphorous from sewage sludge" to propose a complete ban on land application of sewage sludge with the goal of reducing soil pollution and increasing the utilization of nutrients in sewage sludge (Government Offices of Sweden 2018). The intention with the 2018 inquiry was to end the conflicts between stakeholders and increase sewage sludge recycling reliability by the introduction of new technology. In 2020, the inquiry suggested two pathways, one to ban all land application, and one where agricultural land use should continuously be allowed (Burgman 2022).

The country is struggling with ways to deal with sewage sludge. Research is needed and ongoing on alternative sanitation systems that are designed for resources recovery in Sweden.

"*Regulations should focus on resource recovery from the whole sanitation system and also go beyond the narrow focus on phosphorous, and realise that also nitrogen, potassium, sulphur and organic matter are valuable to recover from sustainability point of view.*" (Dagerskog 2022)

2.1.3. Availability and procurement of sewage sludge

The EU produces around 10 million metric tonnes of sewage sludge every year (Dagerskog, Olsson 2020). Sewage sludge is generated in proportion to the population and its properties are almost constant. Germany is the highest sludge producer in the EU, with about 2,200,000 tonnes of dry matter[2] annually (Turlej, Banas 2018).

The potential of sewage sludge-based biofuels, in other words, the quantity of advanced biofuel that can be produced with sewage sludge in one specific location, partly depends on the amount of sludge produced by each wastewater treatment plant (WWTP). The bigger the cities, the more sewage sludge will be available in one location.

The highest biomass and biofuel potential of sewage sludge is available in centralised urban areas with a significant population and large-scale wastewater treatment systems. As a result, the theoretical potential of sewage sludge is particularly large in Western European urban areas. In major European cities such as Berlin, London, Madrid and Vienna, the biofuel potential is around 10,000 – 19,000 tonnes (Batteiger 2017). Figure 9 shows the European countries with the most populous cities. Sweden and Finland are among the countries with the fewest cities with more than 100,000 people: 10 in Sweden and 6 in Finland.

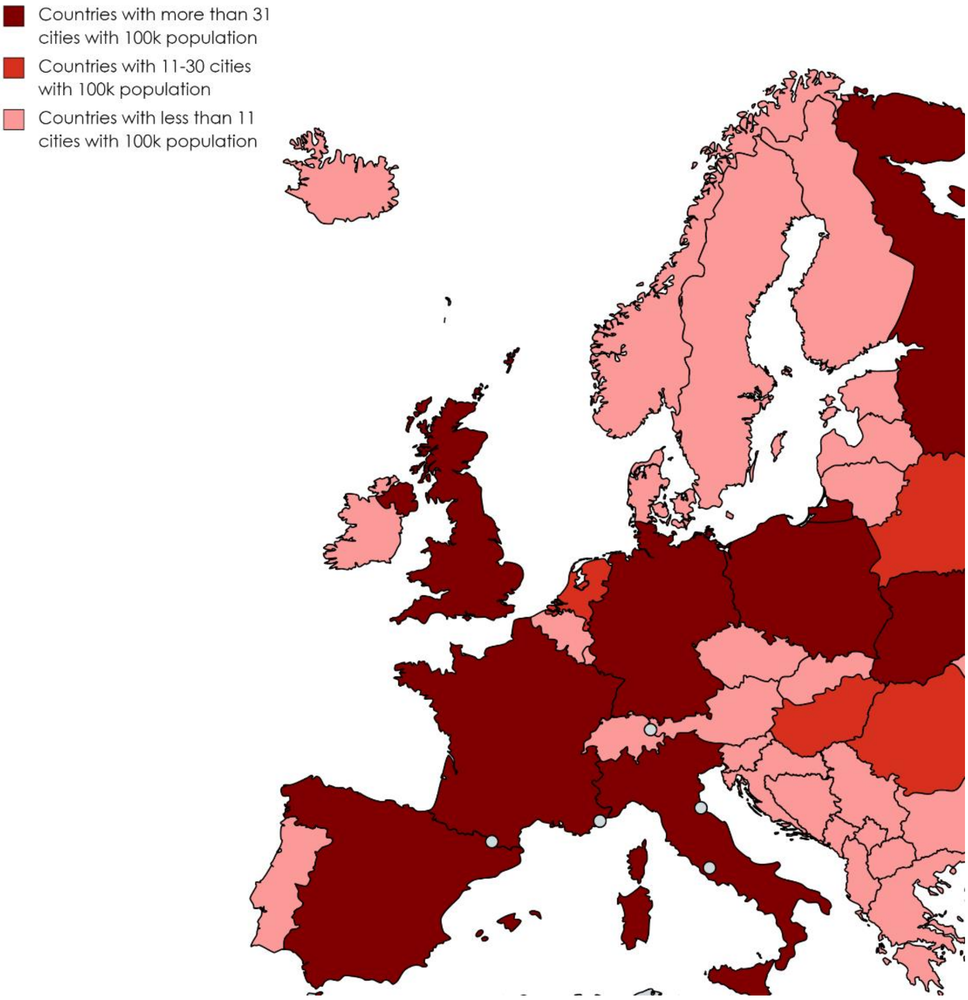

Figure 9 Number of cities over 100,000 people across European countries (Data retrieved from World Population Review, 2022)

[2] « Dry matter » refers to sewage sludge after the dewatering process. Dewatered sludge, in most cases, may contain up to 70% water, despite its solidified state.

Finland and Sweden are therefore not the most promising countries in Europe in terms of sewage sludge availability.

In comparison, countries such as the UK or Germany, count around 100 cities with more than 100,000 population each, making them more promising countries for sewage-sludge based biofuels.

The availability of sewage sludge does not only depend on the amount of sewage sludge produced, but also on the amount that can be procured for the production of advanced biofuels. The nature, capacity and localisation of wastewater treatment plants are therefore crucial elements to consider studying the economic feasibility of sewage sludge-based biofuels.

Wastewater treatment plants are usually decentralised and located outside of cities in big industrial areas. Their dimensions can vary from 10k person eq. to 100k person eq. As the amount of sludge produced is lower in smaller cities, it is necessary to collect and assemble them together to reach a big enough amount to feed a biofuel system.

The demographic structure of countries and therefore their capacities of wastewater treatment plants in the country are key factors to consider. If the population is spread across small villages, meaning that the wastewater treatment plants have smaller capacities, it is more difficult to collect significant amounts for full capacity process (Stenzel 2022). A key challenge is to ensure the obtention of sufficient material to use to fully feed the process. **In case there is not enough sewage sludge, the process of converting sewage sludge into biofuels cannot be economical.**

Additionally, sludge must be transported from wastewater treatment plants to biofuel production plants, increasing transportation costs and generating CO_2 emissions.

In terms of economics, a fee must be paid to the wastewater treatment plant (WWTP) for the procurement of sewage sludge. The gate fee is payment that treatment facilities charge waste disposers to accept their waste sludge (transport, dewatering of the sludge, final disposal). The amount of the fee depends on the capacity of treatment in the country (Stenzel 2022).

Finally, another challenge is that the treatment of sewage sludge is different from one WWTP to another and can result in primary or secondary sewage sludge. Different treatments lead to different carbon content, hence different potential for biofuels production (Righi 2022).

Finland and Sweden

In 2021, Finland produced **160,000 tonnes of sewage sludge dry matter per year** (Kangas 2017). Figure 10 illustrates the production of sewage sludge across Finland.[3] The production of sewage sludge is mostly focused on the south of the country in correlation to the population distribution.

[3](Vesilaitosyhdistyksen 2020)

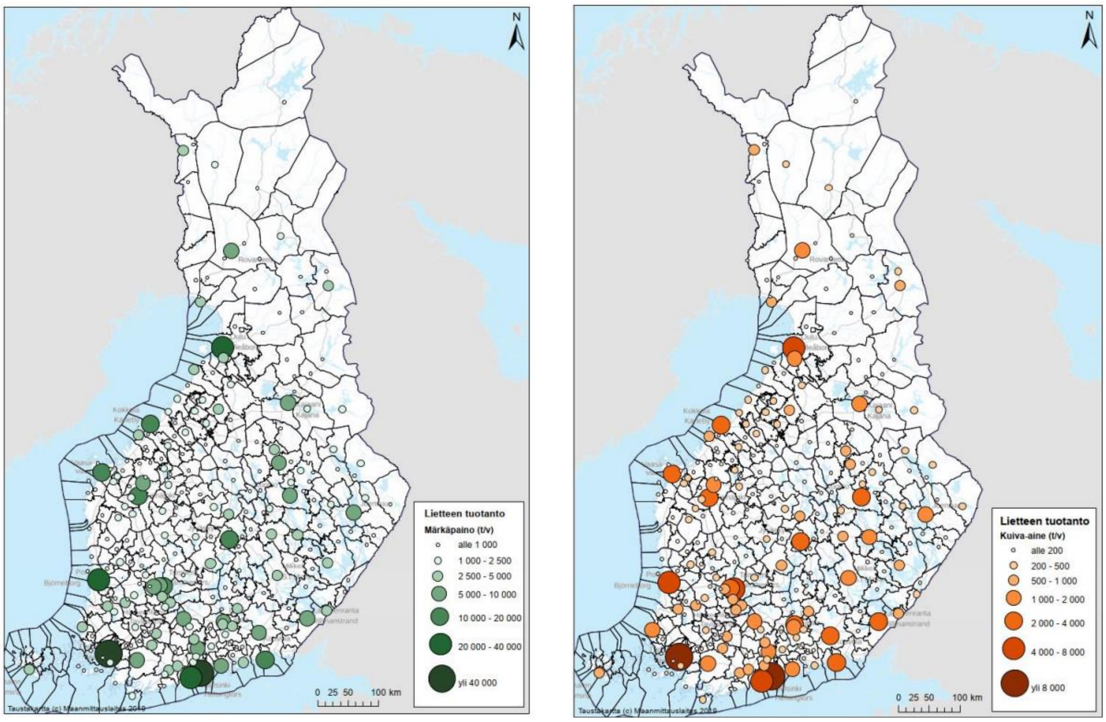

Figure 10 The production of sewage sludge in Finland in wet weight (left) and dry weight (right)

The average sludge transport distance to the treatment unit in the areas of medium-capacity units is about 50 km for the entire country. This number goes up to 110 km for high-capacity units (Vesilaitosyhdistyksen 2020).

In Sweden, over **200,000 tonnes** of sewage sludge (dry matter) are produced each year (Ekane, Barquet, Rosemarin 2021), ca. one eleventh of the sewage sludge produced in Germany and one fiftieth of the total European production.

Finland and Sweden are therefore countries with limited availability of sewage sludge in comparison with other European countries and altogether represent less than 4% of the total production.

2.1.4. State of the art: Benchmark of biofuels based on sewage sludge

Sewage sludge can be used to produce energy, including advanced biofuel. The use of sewage sludge for biofuel production is however quite uncommon in Europe. Four projects, including EU projects, described in Table 4, were identified on this market segment across Europe.

Table 4 Organisations involved in the production of sewage sludge based biofuels

Name of the organisation	Description
Steeper Energy	This Canadian start-up aims to transform sewage sludge and waste for the **production of sustainable biofuels like renewable diesel or jet fuel** using **hydrofaction®, a proprietary implementation of HTL** which applies supercritical water as a reaction medium for the conversion of biomass directly into a high-energy density renewable biocrude oil. The organisation is involved in the EU project Nextgenroadfuels and has pilot facility in Denmark (Steeper Energy n.d.).
Tosynfuel	TosynFuel is a European H2020 project which aims to produce **synthetic fuels and green hydrogen** from organic waste biomass, mainly sewage sludge. In this process, **Thermo-Catalytic Reforming (TCR)** is applied. It is a thermo-chemical process, based on intermediate pyrolysis followed by a post-reforming step. The obtained bio-oil has a low water, oxygen and acid content. It can be used as a co-feed in refineries (Stenzel 2022).
HyFlexFuel	HyFlexFuel is a European H2020 project which aims to demonstrate the compatibility of **HTL-based fuels production** with a diverse biomass feedstock portfolio that includes algae and waste streams, such as sewage sludge (HyFlexFuel 2021).
The Baltic Sea Action Group (BSAG)	In Finland, The Baltic Sea Action Group (BSAG) is collaborating with multiple companies, including Gasum, on the new Ship/t Waste Action project. The initiative turns sewage from ships into **biogas that will be used as fuel by the heavy-duty (marine) transport sector** (Bioenergy Insights 2021; Lappalainen 2022).

While these stakeholders produce biofuels based on sewage sludge, they will not be considered as competitors since several options are required for the decarbonisation of the transport sector and are therefore complementary rather than competing. These initiatives instead show that there is potential for the use of sewage sludge for fuel production, especially with HTL.

Additionally, several organisations and research projects are involved in the valorisation of nutrients present in sewage sludge.

2.1.5. Technological challenges of sewage sludge for biofuel production

High water content of sewage sludge

The high-water content in sewage sludge (93-99%) is the main hurdle, as it requires significant dewatering demand and drying before being used for any application (Stenzel 2022). This implies an important use of thermal energy (and electrical to a lesser degree) for drying. High energy demand results in notable emissions if natural gas is used as energy source. Using wood gasification, solar drying or off-heat from industry or other combustion processes will reduce CO_2 emissions significantly; particulate matter is yet higher in wood gasification. CO_2 emissions depend on the treatment used for dewatering, drying and thickening sludge. After the dewatering process, the water content of sewage sludge is still above 70% (TreaTech 2021).

Due to its very low organic content, the **low heating value**, linked to the high-water content of sewage sludge is also a challenge, as sewage sludge requires transport and handling of a lot of mass with little energy in it (Stenzel 2022). Although sewage sludges are good energy carriers, the high-water content lowers the useful effect of heat. The heating value of raw sludge is about 17 MJ/kg; about 15 MJ/kg for activated sludge, and 11 MJ/kg for stabilised sludge (Ostojski 2017).

The geographical location of the plant is a factor for easier dewatering process: In warmer countries (e.g., Spain, Southern Italy, Greece) as the dewatering process is faster, less emissions are generated. As it is not the case for Finland or Sweden, the source of energy is very important to limit CO_2 emissions (IRENA 2018) (Righi 2022).

Contaminants in sewage sludge

Lots of contaminants and impurities are present in sewage sludge, i.e., sulphur, nitrogen, heavy metals, hormones, microplastics, medical residues, organic contaminants and pathogens which are partly transferred into the liquid biofuel and require post treatment (Stenzel 2022).

Nitrogen is problematic in combustion and must be removed by upgrading, which can be challenging due to resistant nitrogen compounds. The sludge can go through a chemical treatment or an enzymatic pre-treatment (Alegria, Zimmerman 2022).

The metal concentration of sludge creates a limitation for the feasible ways to exploit sludge (Righi 2022).

Technical feasibility of using sewage sludge in the BL2F process

The small particulate size and wet appearance of sewage sludge make it possible to mix it with black liquor. While the water content of sewage sludge is a drawback in several valorisation strategies, it can be an advantage for the IHTL approach.

The biggest challenges related to the integration of sewage sludge in the BL2F process are related to the contaminants present in sewage sludge: the high amount of nitrogen and heavy metals are unfavoured products in HTL oil. Salt separation is expected to extract most of the nitrogen present in the sewage sludge, as the nitrogen is mainly present in the aqueous phase

(Fan, Meyer, Gong, Krause, Hornung, Dahmen 2022) and expected to appear in the extracted salt and aqueous phase. The majority of heavy metals (70%–98% of Zn and Cu, 71%–99% of Pb, 87%–98% of Cd and 20%–75% of As) are concentrated in the solid product of HTL (Li, Lu, Zhang, Liu 2018). The verification of these requires further studies.

There exists a lot of literature on the subject of sewage sludge and HTL, which has proved that the IHTL approach has several benefits in sewage sludge applications (Badrolnizam, Elham, Hadzifah, Husain, Hidayu 2019; HyFlexFuel 2021; Mishra, Mohanty n.d.; Morales, Pesante, Vidal 2015).

In Tampere (Finland), a new sewage wastewater treatment plant is under construction, where sewage sludge is burnt. As a low level of utilisation is expected, this could be an opportunity to convert this sewage sludge to HTL products. As the size of the HTL plant is limited, smaller scale units should however be considered.

2.1.6. Summary: Potential of Sewage sludge-based biofuels

Based on the analysis, evaluation grade given on a scale from 1 to 3 to each of the main factor studied. The evaluation represents the complexity for sewage sludge biofuels to enter the market. The following evaluations are assigned:

- **Easy** → *All or most criteria are filled to allow an optimal market for the feedstock*
- **Medium** → *Part of the criteria are filled to allow an optimal market for the feedstock*
- **Complex** → *None or few of the criteria are filled to allow an optimal market for the feedstock*

Table 5 evaluates the potential of sewage sludge-based biofuels based on the results from the study.

Table 5 Evaluation of the potential of sewage sludge-based biofuels in Finland and Sweden

Factor determinant to the success of sewage sludge-based biofuels	Evaluation	Rational
Availability of the feedstock	**Complex**	Finland and Sweden are countries with limited availability of sewage sludge in comparison with other European countries.
Logistics	**Complex**	As the wastewater treatment plants are smaller in Finland and Sweden due to the smaller size of the cities, the distance between the wastewater treatment plant and the biofuel plant will be longer.
Competition between sectors	**Easy**	The use of sewage sludge for advanced biofuel production presents several advantages in comparison with other uses (agriculture, incineration, disposal).

		In the first place, it allows the valorisation of the sludge (i.e., for energy production) unlike landfill and incineration. "*Since sewage sludge is contested, it might be good if can be used for more things, add value to what can be done with sludge*" (Dagerskog 2022). *"The organic part could be used for biofuels, and nutrients like phosphorus and nitrogen could be recovered and used for fertilisers."* (Stenzel 2022). Challenges related to the presence contaminants of pharmaceuticals, plastics and phosphorous in sewage sludge for agricultural purposes are the key drivers for alternative technologies in Finland and Sweden. Sewage sludge could be an opportunity for the biofuel industry.
Cost competitivity of sewage sludge-based biofuels	**Complex**	The cost of the process to produce sewage sludge-based biofuels will be higher than other sewage sludge disposal methods. The process must be improved to be more economical. As sewage sludge is a cheap raw material, it however represents an opportunity for sewage sludge-based biofuels: companies doing digestion and composting and producing fertilising products pay a fee to sewage sludge producers to use the sewage sludge (Kangas 2022).
Regulations around sewage sludge-based biofuels	**Easy**	The use of sewage sludge for biofuel production is allowed by the RED II directive and could be a solution to the controverted issue of using sludge for agriculture purposes.
Technical feasibility of integrating sewage sludge in the BL2F process	**Medium**	The integration of sewage sludge in the BL2F process is technically feasible without significant modifications to the process.
Societal perception of sewage sludge-based biofuels	**Medium**	In a study conducted by the Tosynfuel project, sewage sludge is the second raw material that is considered the most sustainable by consumers to produce

		synthetic fuels after agricultural wastes (Claret i Carles 2020). However, the controverted debate on sewage sludge in agriculture in the public space, it is uncertain how sewage sludge-based biofuels will be perceived.
Environmental impact of sewage sludge-based biofuels	**Easy**	Advanced biofuels are needed for the decarbonisation of the aviation and maritime sectors. In the short term, electrification is not an option for these sectors, meaning that this is an advantage for biofuels (Stenzel 2022).

In summary, the major opportunities and threats of sewage sludge-based biofuels are the following:

Major opportunities are:

- Advantage of advanced biofuel production compared to other uses
- Favourable regulations around sewage sludge-based biofuels
- Technical feasibility of integrating sewage sludge in the BL2F process
- Positive environmental impact of sewage sludge-based biofuels
- Positive societal perception of sewage sludge-based biofuels

Major threats are:

- Limited availability of sewage sludge in Finland and Sweden
- Inconvenient logistics between WWTP and biofuel plants in Finland and Sweden
- Low cost competitivity of sewage sludge-based biofuels
- The contamination of heavy metals and nitrogen in the sludges

2.2. Bark & Sawdust

Since the 1970s, Finland and Sweden have been working constantly in lowering their dependence on imported fossil fuels and, instead, to take advantage of the two countries large forests. Consequently, the forest industry in Finland and Sweden has become prominent, becoming the main source of bioenergy. As illustrated in Figure 11 and Figure 12, 141 TWh and 99 TWh of biomass were consumed in 2020 in Sweden and Finland respectively, accounting for around one third of the countries' total energy used, with wood fuels being the most important source of renewable energy (Statistics Finland 2021; The Swedish Energy Agency 2022).

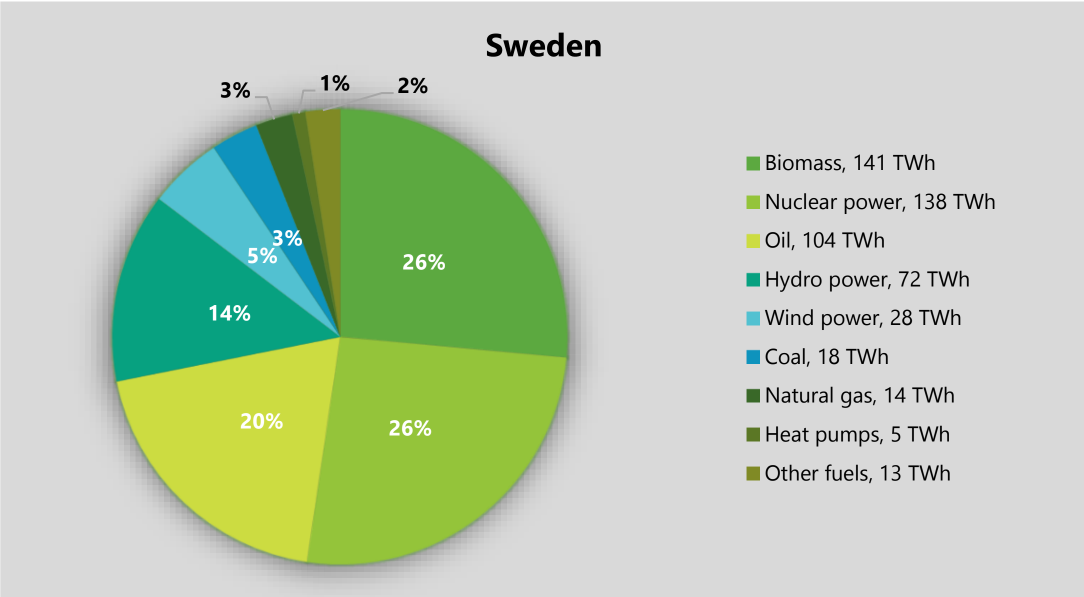

Figure 11 Sweden's energy use in 2020, data retrieved from The Swedish Energy Agency 2022

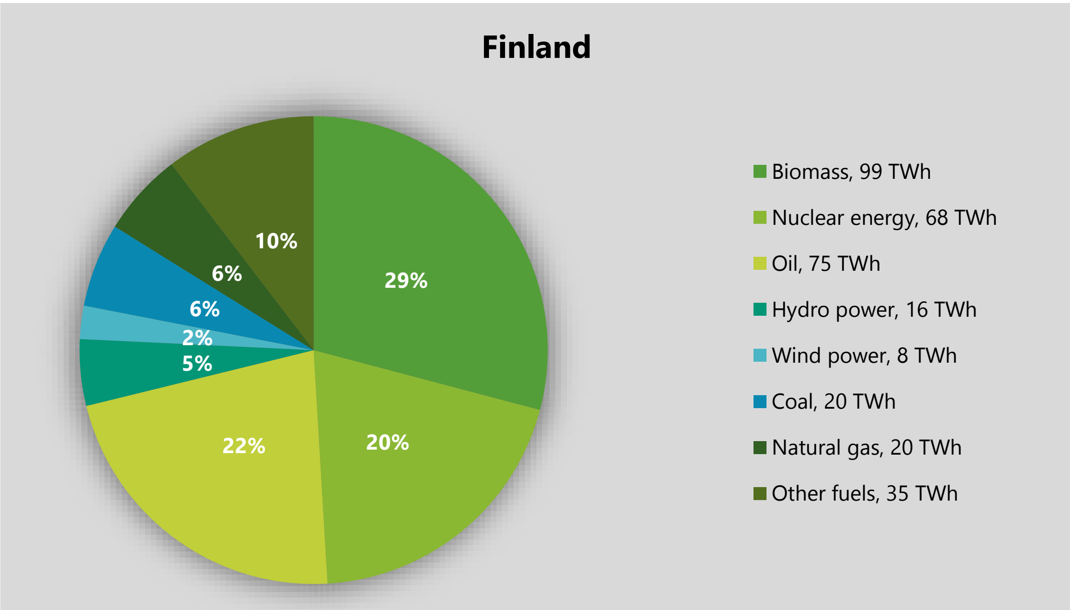

Figure 12 Finland's energy use in 2020, data retrieved from Statistics Finland 2021

The solid biofuels standard (EN ISO 17225-1:2014) divides wood fuels into 3 sub-categories:

- Woody biomass from forests and plantations, and other virgin wood
- By-products and residues from the wood processing industry
- Used wood

Sawdust and bark are two main by-products of the wood industry and are usually under-utilised and considered as low value materials.

2.2.1. Bark & sawdust analysis

Environmental benefits of bark- & sawdust-based biofuels

Several environmental benefits are associated with the production of advanced biofuels from bark and sawdust. Biofuels derived from secondary forest residues have a CO_2 emissions reduction up to 90% potential in comparison with fossil fuels. Advanced biofuels have in fact the highest emissions reduction potential of all studied decarbonisation measures for shipping and aviation sectors (IRENA 2019).

Social perception of bark- & sawdust-based biofuels

However, despite the environmental benefits, the production of advanced biofuels from wood is often negatively perceived by society since it is thought to be contributing to unsustainable forest management and deforestation in Europe. In September 2022, debates questioning the sustainability of wood biomass led to a proposal suggesting the exclusion of forest biomass from the RED II directive in a RED III amendment. This debate was urged by associations claiming that forests were not renewable and that producing biofuel from wood can accelerate forest depletion (World Bioenergy Association 2022).

Future potential for wood-based biofuels

With the European Union seeking carbon neutrality by 2050 as well as aiming to become more energy-independent from fossil fuels (the war between Ukraine and Russia has highlighted this need), there is clear opportunity for the market development of wood-based biofuels. Despite disengaging from first generation biofuels, the European Commission is pushing for the development of advanced biofuels.

However, these advanced biofuels can only supply a small part of the fuel market share and cannot completely substitute all the fossil fuels currently consumed in Europe. In the future, transportation will consist of a blend of different options: advanced biofuels will have a significant role to play, as well as electrification, hydrogen, and e-fuels (Gaspar 2022).

2.2.2. Bark

Bark is the outer part of a tree and typically accounts for 10% of the wood log. It is a side stream of wood processing and is generally considered a low-value waste material.

2.2.2.1. Regulations around bark

The European Renewable Energy Directive RED II supports the use of residual forest biomass. The directive includes in its Annex IX a list of all feedstocks from which a produced biofuel is considered advanced (available in Appendix). As bark figures in this list, it is considered as suitable feedstock for advanced biofuels production.

2.2.2.2. Current usages of bark

In the EU, bark is mainly used in fuel boilers in forestry plants and heating stations for electricity and steam production. However, although less common, other strategies are also adopted to manage this side-stream. The most common bark usages in Europe are illustrated in Figure 13:

- **Combustion:** At forestry plants, bark is burned in boilers to create steam and/or electricity which will then either be used to meet the energy needs of the plant itself or sold to the grid. For example, in pulp and paper mills, the steam produced from burning bark is usually needed to dry paper, and in sawmills, it can be used to dry sawn wood products.
- **Gasification:** A common solution in modern pulp and paper mills where bark is used as a feedstock in gasification to produce combustible gas for the lime kiln (Helanti 2022).
- **Bark pelletisation:** Bark can also be used to produce pellets which can be stored in bags and transported for domestic heating.

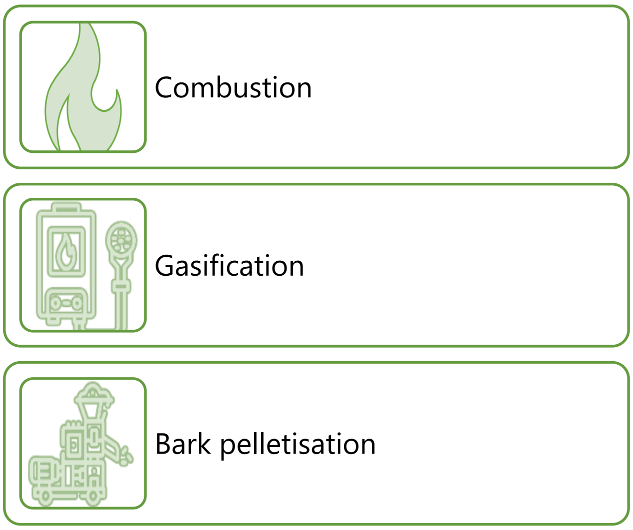

Figure 13 Most common bark usages in Europe

So far, the most typical use of bark in Finland is burning for energy production (Ministry of agriculture and forestry of Finland 2019). Similarly, Sweden mostly use bark for heating purposes.

The advantages and drawbacks of each of the most common bark uses are then studied in order to compare and determine the opportunities and levers for the use of bark in advanced biofuel production.

Combustion

Bark combustion in boilers to produce heat and electricity.	
Advantages	**Drawbacks**
• Bark combustion provides a low-cost solution to meet the needs of pulp mills and sawmills in heat and electricity. • Excess heat produced can be used for district heating.	• Bark combustion has a low economic return. • The high ash content of bark generates problems related to fouling and corrosion.

Gasification

Gasification converts the organic biomass into combustible gas.	
Advantages	**Drawbacks**
• High energy conversion (thermal efficiency above 90%).	• Gasifiers require to be fed with low moisture feedstocks for optimal performance. Consequently, with usually high moisture content, bark must be dried using heat or a mechanical bark press in order to be suitable for gasification. This alone consumes around 10% of the total energy produced.

Bark pelletisation

Pelletisation transforms bark into pellets that can be later used for heating purposes.	
Advantages	**Drawbacks**
• Easy to handle, use and transport. • High energy content. • Environmentally friendly energy form.	• Must be milled and dried. • Bark-derived pellets typically have higher ash content, less clean burning. • Bark-derived pellets typically have lower endurance for long-term storage.

2.2.2.3. Availability of bark in Europe

Within the EU-27 countries, there are approximately **23 million metric tonnes of tree bark** available as an untapped lignocellulosic side-stream (InnoRenew CoE 2021). The potential of bark-based biofuels mostly depends on the amount of bark available at pulp mills and sawmills. The more developed the forest industry is in a specific country, the more bark will be available. Having well established forest industries, Finland and Sweden can be considered as countries with high bark availability.

Finland

The yearly amount of wood consumed by Finnish forest industry is around 72 million cubic meters. About **7 million cubic meters** or 3 million tonnes of bark are derived as by-product of this forest industry (Ministry of agriculture and forestry of Finland 2019).

Sweden

In Sweden, the total supply of bark is estimated to be around **7.5 million cubic meters** per year. The largest point sources of bark are the pulp mills, of which there are currently 21 while the number of sawmills is around 100, also generating bark. The share of bark from pulp mills is about 51% while the share of bark from sawmills is about 49% (Börjesson 2021).

2.2.2.4. State of the art: Benchmark of biofuels based on bark

Bark can be used to produce bioenergy, including advanced biofuel. The use of bark for biofuel production is however quite uncommon in Europe; only some laboratory-scale projects were conducted (Table 6).

Table 6 Projects involved in the production of bark-based biofuels

Name of the project	Feedstock	Description
SSUCHY (EU Horizon 2020 project)	Birch bark	In this work, birch (*Betula pendula*) bark was converted to hydrocarbons suitable for use in both road and aviation fuels in two efficient steps. The first step uses an efficient, recyclable, salt- and metal-free solvent-based system to solubilize birch bark under benign reaction conditions was a key outcome. The obtained gum was composed of lignin and suberin oligomers and could be directly processed in a conventional hydro processing unit set-up to afford hydrocarbons in the road and aviation fuel ranges (Kumaniaev et al. 2020).

BioTecNorte (Norte2020)	Eucalyptus bark	In this work, *Eucalyptus nitens* bark (ENB) was processed by alternative delignification process for ethanol production (Romaní et al. 2019).
InPaCTus (Portugal 2020)	Eucalyptus bark	This work aimed to evaluate the ethanol production from *Eucalyptus globulus* bark previously submitted to kraft pulping through separate hydrolysis and fermentation (SHF) configuration (Amândio et al. 2021).

2.2.2.5. Technological challenges of bark for biofuel production

High water content

Bark has typically a 50-55% moisture content which is not adequate for most of the current biofuel production technologies such as pyrolysis. For optimal performance, bark needs to be dried, reducing its water content to around 10%. Drying can be achieved by mechanically compressing the bark; however, mechanical pressing usually reduces the bark's water matter content to 40% only. For a more effective drying, heat is usually used to evaporate the water molecules within the bark. This process, although quick and simple, consumes a considerable amount of energy.

High ash content

Bark also has an elevated ash content compared to wood timber. This amount depends mainly on the type of bark, but it is usually between 5% and 10%. Being inorganic, ash is an unfavoured compound that usually causes complications for the different applications adopted to make use of bark. During combustion, bark can generate clinker in the furnace and thereby tends to create more demand for maintenance of heat sources. Increased ash content also generates more solid particulate emissions (Nosek, Holubcik, and Jandacka 2016).

Low heating value and low yield

Apart from its high water and ash contents, compared to black liquor, bark has a lower heating value. Bark's lower concentration in lignin and hemicellulose means that a lower yield of biocrude will be generated when the feedstock is fed to the BL2F process (Hornung 2022).

Technical feasibility: modifications needed to the BL2F process to adapt to bark

The use of bark as a feedstock for the BL2F process is feasible from a technical point of view since bark is a lignocellulosic biomass and hence has similar components of black liquor. However, some modifications are nonetheless required to adapt the process. Bark requires **grinding** and mild **chemical treatment**.

Grinding is the first stage to be executed in order to reduce the bark to macroscopic particles (typically a size of less than 1mm).

Having different physical properties compared to black liquor, grinded bark may constitute a challenge in regard to pumping. Pumps should be adapted to be able to feed grinded bark into the process. Larger pumping installations with larger diameters are probably needed (Hornung 2022).

Bark may also require mild chemical treatment with sodium hydroxide. As a lignocellulosic product, bark contains long cellulose fibres that need to be broken into smaller pieces to produce a wood slurry. This is usually done by using small amount of sodium hydroxide to break the body structure.

The **elevated ash content** of bark is not major challenge for the BL2F process since ash is mostly water soluble and can be removed during hydrothermal liquefaction The IHTL approach most probably helps with bark feedstocks to deal with this ash related issues.

Since bark is a by-product from wood-processing industry, it can be usually found at the proximity of sawmills and pulp mills. For example, at pulp mills, for every tonne of dry pulp produced, 100 to 300kg of bark are produced. As it is already located on site, this avoids the need to collect it, in opposition to forest residues which derive from wood harvesting and are usually left dispersed in the forest. Consequently, collection and transportation costs are negligible for bark.

2.2.2.6. Summary: Potential for bark-based biofuels

Table 7 evaluates the potential of bark-based biofuels based on the results from the study.

Table 7 Evaluation of the potential of bark-based biofuels in Finland and Sweden

Factor determinant to the success of bark-based biofuels	Evaluation	Rational
Availability of the feedstock	**Easy**	Finland and Sweden are countries with high availability of bark in comparison with other European countries.
Logistics	**Easy**	As bark is already available at sawmills and pulp mills, little or no collection and transportation are needed, thus eliminating the associated costs.
Competition between sectors	**Easy**	Bark is usually considered as a low value feedstock. Consequently, the competition in bark demand is usually low. Through better valorisation, bark could be an opportunity for the biofuel industry.
Cost competitivity of bark-based biofuels	**Complex**	With relatively lower yield, producing bark-based biofuels is considered to be a high-cost process, with the cost believed to be

		significantly higher than other bark usages, especially combustion. The process must be improved to be more economical. However, high moisture and ash contents reduce the fuel value of bark considerably, making it a cheap feedstock. This represents an opportunity for bark-based biofuels.
Regulations around bark-based biofuels	**Easy**	In terms of regulation, the use of bark for biofuel production is allowed by the RED II directive.
Technical feasibility of integrating bark in the BL2F process	**Medium**	The integration of bark in the BL2F process is technically feasible with minor modifications required to the process.
Societal perception of bark-based biofuels	**Medium**	Often thought to be contributing to unsustainable forest management and deforestation.
Environmental impact of bark-based biofuels	**Easy**	For the decarbonisation of the aviation and maritime sectors, biofuels are needed. In the short term, electrification is not an option for these sectors, meaning that this is an advantage for biofuels (Stenzel 2022).

In summary, the major opportunities and threats of bark-based biofuels for the BL2F process are the following:

Major opportunities are:

- High availability of bark in Finland and Sweden
- Convenient location of bark in pulp mills and sawmills
- Low competition for bark demand in other sectors
- Favourable regulations for the use of bark for biofuel production
- Positive environmental impact of bark-based biofuels

Major threats are:

- Low cost competitivity of bark-based biofuels
- Workable solutions exist for example FBC gasification and combustion in lime-kiln

2.2.3. Sawdust

Sawdust is a major side-product of the commercial mechanical wood processing (mostly in timber sawmills) and can be defined as the fragments and small pieces of wood remaining after the sawing process. Sawdust is also a side product of plywood process, but the amount is much smaller compared to sawmill flows.

2.2.3.1. Regulations around bark

The European Renewable Energy Directive RED II supports the use of residual forest biomass. The directive includes in its Annex IX a list of all feedstocks from which a produced biofuel is considered advanced (available in Appendix). As sawdust figures in this list, it is considered as suitable feedstock for advanced biofuels production.

2.2.3.2. Current usages of sawdust

In the EU, similarly to bark, sawdust is usually used in fuel boilers in forestry plants and district heating stations for electricity and steam production. The most common sawdust usages in Europe are illustrated in Figure 14:

- **Combustion:** Sawdust has traditionally been used as an untreated fuel in boilers and lime kilns to make heat and electricity.
- **Gasification:** Another application that take advantage of the available sawdust as a feedstock to produce combustible gas (Helanti 2022).
- **Sawdust pelletisation:** Turned into compressed fuels to produce wood pellets, it is used for heating through pellet combustion.
- **Liquid biofuel production:** Sawdust is also sometimes used for conversion to motor fuel components like ethanol in 2nd generation bioethanol plants. First commercial plants have started up (Valmet 2023a, 2023b). Other possibility might be pyrolysis, but this application remains very limited (Haile et al. 2021).
- **Pulp production:** Sawdust can be used as feedstock of pulp mill for special purposes like demanding packaging products, but the sawing reduces the original fibre length to level less than 2mm which can reduce the pulp strength when softwood is used.
- **Other uses** can be found in the field of construction and furniture, but they are still in development and only take place in niche applications such as fillers for the manufacturing of bricks and as a cement material.

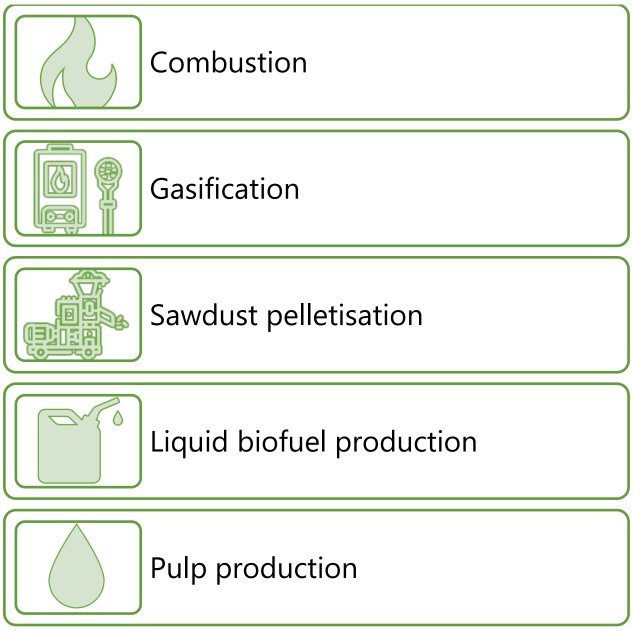

Figure 14 Most common sawdust usages in Europe

The advantages and drawbacks of each of the most common bark uses are then studied in order to compare and determine the opportunities and levers for the use of bark in advanced biofuel production.

Combustion

<table>
<tr><td colspan="2">Combustion of sawdust in boilers to produce heat and electricity.</td></tr>
<tr><th>Advantages</th><th>Drawbacks</th></tr>
<tr><td>• Bark combustion provides a low-cost solution to meet the needs of pulp and paper mills and sawmills in heat and electricity.
• Excess heat produced can be used for district heating.</td><td>• Sawdust combustion has a low economic return
• Air pollution from smoke and fly ash.</td></tr>
</table>

Gasification

<table>
<tr><td colspan="2">Gasification converts the organic biomass into gas.</td></tr>
<tr><th>Advantages</th><th>Drawbacks</th></tr>
<tr><td>• High energy conversion (thermal efficiency above 90%).</td><td>• The process requires low moisture content for feedstock. Sawdust must be dried by means of heat accounting for 10% of the total energy produced.</td></tr>
</table>

Sawdust pelletisation

Pelletisation transforms sawdust into pellets that can be later used for heating purposes.	
Advantages	**Drawbacks**
• Easy to handle, use and transport. • High energy content. • Environmentally friendly energy form. • Sawdust-derived pellets typically have low ash content, hence burn cleaner. • No drying is required if dry sawdust is used.	• High expertise required for pellet production. • Must be dried if wet sawdust is used. • Must be stored in a dry space to prevent them from coming into contact with water or moisture.

Liquid biofuel production

Liquid biofuel can be obtained from sawdust through several routes. One route consists of producing bioethanol through lignin separation, release and fermentation of cellulose sugars, and distilling the result to 90-percent ethanol. Another route involves heating wood in the absence of oxygen – in a process called pyrolysis – to produce a complex liquid called bio-oil which would then need further synthesis and upgrading.	
Advantages	**Drawbacks**
• High value creation from a low value feedstock. • Environmentally friendly energy form.	• High logistics costs, usually requires transporting sawdust to refining units that are not necessarily close.

Pulp production

Sawdust can be used as a feedstock for the production of low strength pulp to in turn produce packaging products.	
Advantages	**Drawbacks**
• Excellent raw material for specific products such as packaging products.	• Low pulp strength. • Limited applications.

A focus is made on the current uses of sawdust in Finland and Sweden.

Finland

In 2020, wood fuels represented the most important energy source in Finland, covering 28 per cent of the total energy consumption. Bioenergy production is largely integrated into forestry and forest industry and has a key role in the production of renewable energy in the country. These wood fuels are mainly derived from the by-products of the forest industry, essentially black liquor, but sawdust also represent a small fraction (Ministry of agriculture and forestry of Finland 2022).

The majority of sawdust is currently used in energy production, but due to its composition and possibilities of use, there would be more alternative uses. Most sawdust ends up being burnt either as such or in the form of pellets for energy production. About one third of the sawdust is used as raw material in the paper and wood processing industry, but the need for sawdust in mills is increasing (Metsä.fi Magazine 2020; Vanhala 2019)

Sweden

In Sweden, sawdust is mostly used for heating and electricity generation. Some other limited applications include pulp production and pellet production. Sawdust is considered a relatively pure and uniform product that can be suitable for different technologies and different applications. This creates a competition on sawdust demand. For example, apart from its usual use for heating purposes, sawdust is increasingly gaining interest for pyrolysis oil production, with some pyrolysis plants already opening up in Sweden (Normark 2022).

2.2.3.3. Availability of sawdust in Europe

One major limitation in the use of bark and sawdust is its availability. Although considered to be available in significant quantities, sawdust on its own, is not capable of replacing a significant quantity of fossil fuels consumed in the transportation industry in Europe (Gaspar 2022).

Finland

In 2016, Finnish forest industry generated a total 27.7 million tonnes of side streams, consisting of 49.2% black liquor, 28.5% solid wood-based waste (including sawdust), 14.1% sludge, 4.4% ashes, and 3.8% others. Sawdust is a major side-product of the commercial mechanical wood processing, with sawmilling producing between 20% and 30% sawdust of final timber production (Kamrul et al. 2018).

According to the preliminary data of the Natural Resources Institute Finland (Luke), sawdust is the second main industrial by-product of the Finnish forest industry, accounting for nearly a third of the total amount of side stream. Every year in Finland, sawdust is produced as a by-product of around **2 million tonnes or 4 million solid cubic metres**. Solutions that allow sawdust to be used more fully than at present would allow the creation of new value chains around the existing side stream, providing new business opening options for sawdust producers (Kallioinen 2020).

However, in recent years, some Finnish sawmills have been struggling to find a buyer for their sawdust. Reasons for the abundant supply of sawdust in Finland include increased sawing volumes and subsidies for the use of woodchips in electricity production, which has caused power plants to prefer them over sawdust (Timberbiz 2019).

Sweden

With more than 100 sawmills producing sawn wood products, the Swedish sawing industry produces around 3 million tonnes of sawdust each year. This represents a large raw material base to draw on, for which there is otherwise not much demand. According to Björn Alriksson, Group Manager in Biotechnology at RISE Processum, it is also such a large quantity that there is capacity to supply all domestic and international flights departing from Sweden with fuel (Hasbar 2019).

2.2.3.4. State of the art: Benchmark of biofuels based on sawdust

Sawdust can be used to produce bioenergy, including biofuel. In fact, several companies in Europe have been experimenting with the use of sawdust for biofuel production. Four organisations were identified on this market segment across Europe. They are described in Table 8Table 8.

Table 8 Organisations involved in the production of sawdust-based biofuels

Organisation	Feedstock	Description
Pyrocell (Sweden)	Sawdust	TechnipFMC and the Dutch company BTG-BTL based in Twente will design and build a production facility in Sweden where wood residues will be converted into bio-oil. The process used to convert the residual waste materials into oil is called fast pyrolysis, and it produces a 'green' sustainable product that can be used to replace fossil oil. The Swedish joint venture Pyrocell, consisting of the wood industry company Setra and the oil company Preem, will be utilising this new technology. Pyrocell's plant is located at Setra Kastet sawmill in Gävle on Sweden's Baltic coast. It converts sawdust, a residual product in Setra's industrial process, into non-fossil pyrolysis oil. The pyrolysis oil is then processed further to make renewable diesel and petrol at Preem's refinery in Lysekil (Agro & Chemistry 2019).
Sekab (Sweden)	Sawdust	The technology is called CelluAPP and was developed in the lab in Domsjö. It takes residual products from the forest, such as sawdust, and processes them into green raw materials such as wood sugar, ethanol and lignin. In turn, they can become products that contribute to climate change adaptation: from biofuels to asphalt and medicines (Sekab 2020).
ST1 Nordic Oy (Finland)	Sawdust	"The Cellunolix® plant project in Kajaani, north-eastern Finland: bioethanol plant based on sawdust (Businesswire

		2014). The production capacity of Kajaani mill is ten million litres of ethanol per year. The production process starts by separation of lignin from cellulose, after which cellulose sugars are released and fermented with yeast, ending as sugar. Finally, the result is distilled to 90% ethanol (forest.fi 2016).
Fortum (Finland)	Sawdust and forest residues	Fortum's plant located in Joensuu, eastern Finland is the world´s first integrated CHP and bio-oil production facility, supplied by Valmet. It produces bio-oil through pyrolysis using mainly sawdust and forest residues and have a 50000 tonnes capacity per year. Fortum uses the produced bio-oil in its own heat plants. Additionally, the remaining bio-oil is supplied to a district heat production station in Iisalmi, as a substitute to heavy and light fuel oil (IRENA 2018).

Several stakeholders are producing advanced biofuels based on sawdust, demonstrating that there is potential for the use of sawdust for fuel production. These initiatives are adopting technologies such as pyrolysis and gasification that are different from the HTL process developed by the BL2F project. Hence, they will not be considered as competitors since several options are required for the decarbonisation of the transport sector and are therefore complementary rather than competing.

2.2.3.5. Technological challenges of sawdust for advanced biofuels

Sawdust is usually wet and airy with a typical moisture content of 50-55%, a net calorific value (dry basis) of 18.9-19.2 MJ/kg and a particle size distribution of 0.2-2mm. The high moisture content does not constitute a challenge for the BL2F process, in opposition to other alternatives uses.

Logistically, since sawdust is a by-product from wood-processing industry, it is usually found at proximity of sawmills and pulp mills. For example, at pulp mills, for every tonne of dry pulp produced, 10 to 30 kg of sawdust are produced. At sawmills, these figures are even higher.

As sawdust is already located on site, this avoids the need to collect it, in opposition to forest residues which derive from wood harvesting and are usually left dispersed in the forest. Consequently, no collection and transportation costs are associated with sawdust.

2.2.3.6. Summary: Potential for sawdust-based biofuels

Table 9 evaluates the potential of sawdust-based biofuels based on the results from the study.

Table 9 Evaluation of the potential of sawdust-based biofuels

Factor determinant to the success of sawdust-based biofuels	Evaluation	Rational
Availability of the feedstock	**Complex**	Finland and Sweden are countries with high availability of sawdust in comparison with other European countries. However, this feedstock is already used for heating purposes or more recently, for gas or oil production. This can limit the availability of sawdust for new usages such as advanced biofuel production.
Logistics	**Easy**	As sawdust is already available at sawmills and pulp mills, little or no collection and transportation are needed, thus eliminating the associated costs.
Competition between sectors	**Medium**	Sawdust is a high quality and uniform feedstock, generally suitable for different usages. This can create a strong competition for the demand in sawdust. Thanks to a higher valorisation, producing advanced biofuels from sawdust can still be an opportunity for the biofuel industry.
Cost competitivity of sawdust-based biofuels	**Complex**	Due to its properties, sawdust is usually a more expensive side-stream compared to bark. The production of advanced biofuels from sawdust is considered to be a high-cost process, with the cost believed to be significantly higher than other sawdust usages. The process must be improved to be more economical.
Regulations around sawdust-based biofuels	**Easy**	In terms of regulation, the use of sawdust for biofuel production is allowed by the RED II directive.
Technical feasibility of integrating sawdust in the BL2F process	**Medium**	The integration of sawdust in the BL2F process is technically feasible without significant modifications to the process.
Societal perception of sawdust-based biofuels	**Medium**	Often thought to be contributing to unsustainable forest management and deforestation.

Environmental impact of sawdust-based biofuels	**Easy**	Biofuels are needed for the decarbonisation of the aviation and maritime sectors. In the short term, electrification is not an option for these sectors, meaning that this is an advantage for biofuels (Stenzel 2022).

In summary, the major opportunities and threats of sawdust-based biofuels for the BL2F process are the following:

Major opportunities are:

- Convenient location of sawdust in pulp mills and sawmills
- Low competition for sawdust demand in other sectors
- Favourable regulations for the use of sawdust for biofuel production
- Positive environmental impact of sawdust-based biofuels

Major threats are:

- Limited availability of sawdust in Finland and Sweden in comparison with other European countries
- Low cost competitivity of sawdust-based biofuels

3. Conclusion

The report has demonstrated that the three feedstocks studied have potential for advanced biofuel production in the BL2F process.

Through the Renewable Energy Directive (RED II), EU and national regulations allow the use of sewage sludge, bark and sawdust for advanced biofuel production which could contribute to the decarbonisation of the aviation and shipping sectors. On the other hand, the cost competitivity of the advanced biofuels from these three feedstocks remains a challenge compared to fossil fuels.

- Bark presents an important opportunity since this feedstock is available in Finland and in Sweden. Logistics is also optimal as bark is available at pulp mills, which doesn't lead to additional collection and transportation costs for the BL2F technology. Additionally, the competition in bark demand in other sectors is also low, providing advantages for advanced biofuel production.
- Similarly for sawdust, logistics is optimal as it is available in pulp mills, therefore easing the use of sawdust for biofuel production in the BL2F process. Sawdust availability is however a challenge and cannot replace a significant quantity of fossil fuels consumed in the transportation industry in Europe.
- Sewage sludge presents major opportunities for advanced biofuel production in Finland and Sweden due to the challenges and controversies of its usages in other sectors (mainly agriculture, incineration and landfill). However, the availability of sewage sludge is limited in Finland and Sweden, which is a key brake for the development of sewage sludge-based biofuels in these countries.

The combination of several feedstocks, i.e., sewage sludge, bark and sawdust and black liquor in the BL2F process is also feasible. Transportation would however be challenging in case of a co-processing of sewage sludge and wood residues (sawdust, bark and black liquor).

Deliverable 6.5, the exploitation plan, will continue preparing the groundwork to maximise the results of the BL2F project.

4. Recommendations for the BL2F project

Feedstocks potential for the BL2F technology

While the explored feedstocks have demonstrated market potential, bark appears the most promising for advanced biofuel production within the BL2F process. The availability of bark in pulp mills is an opportunity, as well as its moderate pre-treatment requirement, which is less challenging than sawdust. Sawdust comes in at the second place.

Bark and sawdust take priority over sewage sludge. As they are residues from the forest industry, they both have stronger benefits in terms of logistics, as the value chain of black liquor is already established as part of the BL2F process. Different types of forestry residues including black liquor, bark, and sawdust, are available in pulp mills or close to them.

Sewage sludge comes in third place as its availability and logistics represent key challenges in comparison to bark and sawdust. There is however more potential for sewage sludge-based biofuels in European countries where sludge is available in higher quantities (e.g., Germany, UK, France).

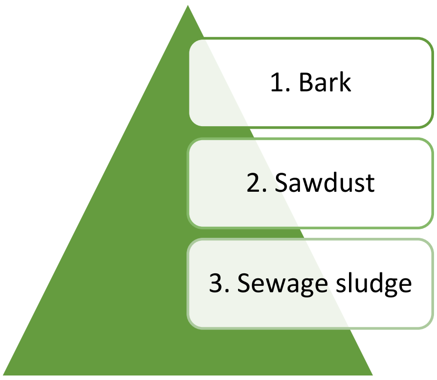

Figure 15 Ranking of feedstocks studied for biofuel production within the BL2F process

Deployment of the BL2F technology

A blend of several feedstocks (i.e., black Liquor, sawdust, bark, and sewage sludge) are possible to use within the BL2F process. This means that the technology could be used as:

- One solution for pulp mills to make advanced biofuels by favouring bark and sawdust
- Or as a solution to make advanced biofuels from black liquor, bark, sawdust, and sewage sludge: the location would not require to necessarily be at pulp mills and logistics would need to be studied.
- Other feedstocks, such as bio-sludges from pulp mills and agricultural waste would need to be further studied.

The location is expected to be in Sweden or Finland as highlighted in D6.3. Market potential, since they are the most suited and equipped countries to adopt IHTL technology at their pulp mills, and their advanced biofuels market is important in Europe.

A technological solution to valorise by-products for pulp mills

It is expected that pulp mills will find a great interest in valorising black liquor, bark and sawdust for advanced biofuel production in a growing market and with a more mature technology.

Structural and cultural contexts are evolving rapidly and are becoming more friendly to sustainable advanced biofuels solutions as favouring and ambitious policies are enacted across countries and are pushing industries to shift.

In order to optimise costs, one recommendation would be to build the value chain within the same country and at very close locations. As Finland and Sweden appear as promising markets, both countries could be suitable to scale-up and implement the technology.

This solution could be modular:

- A process could be integrated in pulp mills producing an important amount of black liquor, bark and sawdust
- A mobile IHTL process could pump black liquor at small pulp mills, enabling them to sell advanced biofuels in small quantities.

The IHTL process could also be separated in another location close to pulp mills, that would gather the quantities of black liquor, bark, sawdust, and paper sludges. This last option would however be unlikely as the transportation of considerable volumes of black liquor would be very challenging due to high costs and safety issues.

A solution to blend forest residues with sewage sludge

For sewage sludge, the HTL process could eventually be integrated in the wastewater treatment plants, or the HTL plant could be located close to the WWTP to avoid the challenging transportation of sewage sludge between the plants. These options should be studied to understand whether they would be technically feasible or not.

Environmental analysis and Life Cycle Cost

Techno-economic assessment would need to be performed by SINTEF to assess the influence of by-products sales, the cost of transportation, among other costs. Additionally, the environmental benefits of adding these by-products would need to be demonstrated with a Life Cycle Assessment while scaling up the technology.

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Appendix

Appendix 1 – Annex IX of the Renewable Energy Directive RED II

"Part A: Feedstocks for the production of biogas for transport and advanced biofuels, the contribution of which towards the minimum shares referred to in the first and fourth subparagraphs of Article 25(1) may be considered to be **twice their energy content**."

Table 10 Advanced Biofuel sources, Part A and Part B of Annex IX in RED II

Part A	Part B
• Algae if cultivated on land in ponds or photobioreactors • Biomass fraction of mixed municipal waste • Biowaste from private households subject to separate collection • Biomass fraction of industrial waste not fit for use in the food or feed chain • Straw • Animal manure and sewage sludge • Palm oil mill effluent and empty palm fruit bunches • Tall oil pitch • Crude glycerin • Bagasse • Grape marcs and wine lees • Nut shells • Husks • Cobs cleaned of kernels of corn • **Biomass fraction of wastes and residues from forestry and forest-based industries, namely bark, branches, precommercial thinnings, leaves, needles, treetops, saw dust, cutter shavings, black liquor, brown liquor, fibre sludge, lignin and tall oil** • Other non-food cellulosic material • Other ligno-cellulosic material except saw logs and veneer logs	• Used cooking oil • Animal fats classified as categories 1 and 2 in accordance with Regulation (EC) No 1069/2009

Appendix 2 – Study on other paper industry residues (paper and pulp mills sludges) and their potential for advanced biofuel production

Sludge is one of the solid wastes produced at pulp and paper mills in large quantities and represents a huge environmental problem. The sludge is collected from the wastewater treatment units and results from primary treatment (primary sludge), secondary treatment (bio sludge) or from deinking.

Generally, it consists of organic and inorganic substances in different quantities based on the origin of the cellulose fibres (raw materials), the final products produced at the mill and the methods of production. These substances are generally cellulose, hemicelluloses, lignin, wood resins, binders, paper additives, kaolinite (clay), calcium carbonate ($CaCO_3$), heavy metals and ash.

Chemical characterisation of paper mill sludge has shown that cellulosic materials represent more than 50% of the sludge content. This source of cellulose, sludge, can offer a sustainable and inexpensive source to produce valued materials (Amândio, Pereira, Rocha, Serafim 2022; Gibril, Lekha, Andrew, Sithole 2018).

Current usages:

Disposal of sludge from pulp and paper mills is mainly **directed to landfills**, while some sludge waste is **incinerated**. When incinerated, the residual ash is then used as a substrate for composting and applied for soil conditioning in some forest areas (Haile et al. 2021).

Overview of the usages:

- Energy:
  - Electricity generation (combustion)
  - Pyrolysis, direct liquefaction
  - Gasification or anaerobic digestion
  - Bioethanol production

- Agriculture:
  - Compost

- Construction:
  - Cement base

- Disposal:
  - Incineration
  - Landfilling

- Promising applications: Integration in materials
  - Bio-composites
  - Bioplastics

- Cement and asphalt

Regulations:

Government regulations banning the landfilling of wastes are imminent, making these disposal methods not viable options going into the future because of the associated environmental hazards

Availability:

The mill sludge accounts for the main waste from pulp and recycled paper production. Per unit of paper production 23.4% sludge is generated.

Finland

In Finland, the paper and pulp industry produces 578000 tonnes of sludges yearly. Most of the sludges are incinerated or landfilled, which is associated with adverse environmental and economic impacts (Alakangas, Hurskainen, Laatikainen-Luntama, Korhonen 2016).