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Sankey-Based Material Flow Analysis of Residual Biomass for Combustion: A Case Study of Latvia

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***Abstract* – Europe has increasingly utilised biomass as a renewable alternative to fossil fuels for combustion and heat production to meet climate targets. This shift has made the energy sector heavily dependent on primary wood biomass. However, recently implemented regulations have introduced restrictions on using primary wood in the energy industry. While low-quality biomass holds significant potential for combustion, there is limited information regarding the availability and quantities of non-wood biomass resources in Latvia. The authors used the Sankey diagram approach to evaluate the share of non-wood biomass resources that can cover roundwood consumption. None of the studied biomass resources in this article can individually cover the required energy demand. However, combining all the studied resources could potentially cover the required energy demand. Specially grown energy crops exhibit the highest potential, but other analysed biomass types are available locally and could be utilised in locally adapted boiler houses.**

***Keywords* – Brewer's spent grain; leaves; material flow analysis; perennial grass; reeds; short rotation woody crop; straw; sustainable consumption and production; wood.**

1. INTRODUCTION

Biomass has been used for combustion and generation of heat in all of Europe as a transition fuel, from fossil fuels, reaching a share of 60 % of the European Union's (EU's) bioenergy [1]. However, the EU Parliament has proposed to limit the use of primary wood biomass in the energy sector. This has been implemented into the Renewable Energy Directives' latest version [2]. The Directive also states that energy produced from saw logs, veneer logs, industrial grade roundwood, stumps and roots should not be financially supported by Member States. This has been done to meet the EU's renewable energy needs and biodiversity goals. A study was conducted that showed that both objectives could be achieved simultaneously [3]. Moreover, studies have shown wood prices will increase in the future; therefore, there is an economic incentive to decrease high-quality wood use for energy production [4]. The EU Renewable Energy Directive also suggests using biomass with low market competition should be used for bioenergy production [2].

According to Latvia's National Inventory Report on greenhouse gas emissions, the share of biomass in energy production has increased from 8.6 % (1990) to 40.5 % (2021). One of

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the reasons this has led to the continuous decrease in carbon stock change [5]. Moreover, in 2022, the Latvian Ministry of Economics announced that there would be support for district heating boiler change from natural gas to renewable energy sources, which in most cases would be using wood chips [6]. However, using wood chips contributes to increased logging, decreased carbon sinks, and biodiversity loss. For instance, there was a recent legal action against the Cabinet of Ministers regarding a norm set in 2022 that allows cutting trees with smaller diameters. This was taken to the Constitutional Court, which recently cancelled this norm because it was inconsistent with the Constitution, which protects everyone's right to live in a favourable environment. This has set a precedent for environmental organisations to be able to impact the norms set by the government on the issues of sustainability [7].

In light of the decisions of institutions at the EU and national levels, countries should look at alternative fuel sources. One of the options is shifting away from fuels; however, as noted before, ongoing support is being made for boiler houses to transition to biomass combustion boilers. This means that some form of biomass will be needed shortly. There are many alternative biomasses summarised in a "Phyllis 2" database, which is the largest database of biomass properties, including more than 3000 datasets [8]. However, many of those are not locally available. Martin *et al*. [9] have conducted a study that included 31 types of alternative biomass combinations of which alternatives to wood include rape, wheat, rye straw, spelt, flax, sorrel, and hay. However, it is unclear what quantities of these sources are available for fuel production.

In alignment with the circular economy, it is beneficial to find fuel from existing waste streams. The Sankey diagram approach can be used to identify fuels that have a potential waste stream. Sankey diagrams can have different levels of detail depending on the complexity of the process that is being analysed and the quality of the available data. The benefit of using Sankey diagrams is that, firstly, it requires gathering data to obtain a balance between input and output flows. This allows us to identify shortcomings in available data and necessitates the need for assumptions. Secondly, it provides a visual evaluation of the material or energy flows which cannot be achieved by the data provided in the table. Thirdly, the material flow consists of multiple steps, which add value to the diagram by also showing the scheme of the processes. Sankey diagrams are often used to illustrate material flows of the whole value chain [10].

The biomass material flows are interlinked with multiple sectors that can have a synergy, such as forestry and manufacturing or energy production, but are also competitive since some of the agricultural products used in energy production can also be used in food or other industries. One of the ways to understand existing sectors that are involved in the life cycle of a certain biomass is to look at the material flows. Material flow analysis (MFA) approaches have been used widely over the past decade to characterise the life cycles of materials and substances [11]–[14]. Understanding the entire system of material flows can help quantify potential primary and secondary source strengths, manage use more wisely, and protect the environment.

Although there are studies on the use of alternative biomass in energy production, there is a lack of quantitative accounting of its energy flow in the Latvian context. This paper aims to analyse the alternative biomass available in Latvia with the use of Sankey diagrams to evaluate what share of the primary roundwood used could be covered by alternative sources.

2. Methodology

MFA is a systematic assessment of the state and change of flows and stocks of materials within a system defined in space and time. MFA creates pathways between sources, stocks and sinks of materials. The two main principles of MFA are the definition of boundaries and balancing inputs and outputs so that the conservation of mass is ensured. Boundaries are used to limit the system which is being studied by identifying what the inputs are, how they are used and transformed, and what the outputs are. Within the study, an algorithm represented in Fig. 1 is used to develop Sankey diagrams.

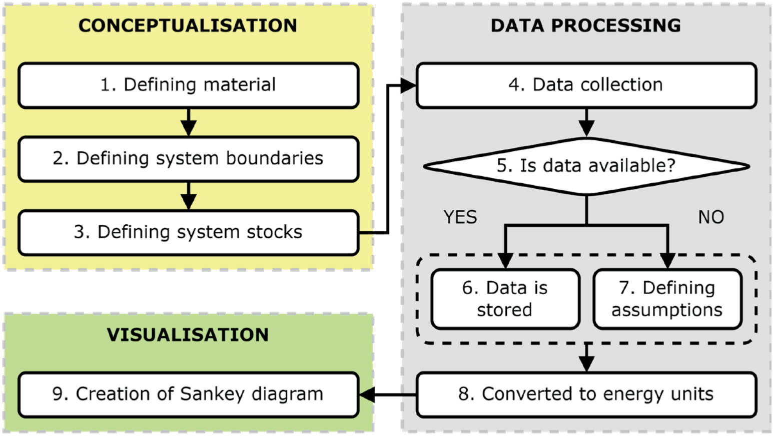

Fig. 1. Material flow analysis algorithm for the study.

2.1. Description of the Steps

2.1.1. Defining material

During 1st step, it is necessary to define the material that is going to be used as an alternative fuel. In some cases, there are differences within a material class, such as wood biomass, where different parameters and values are obtained if different species of wood are used. In other cases, the potential area of the crop is limited for subspecies, which affects the yield and final values. Therefore, within this step, a more specific definition should be made to increase the credibility of the data. Within this study, the materials analysed are wood, straw, tree leaves, brewer's spent grain, reeds, perennial grasses, and short-rotation woody crops.

2.1.2. Defining system boundaries

During the 2nd step, the boundaries of the material are defined. One of the output flows in all cases will be part of the fuel that can be used for energy production. The input is generally the total yield of the material.

2.1.3. Defining system stocks

During the 3rd step, the stocks of the material are defined. This step depends on the possible processes and utilisation options.

2.1.4. Data processing

The 4th step in data processing is data collection. Firstly, an assessment of available data in statistical databases is done (5th step). If data is easily available, then that data is used and stored for further processing (6th step). If the data is incomplete or there is no information available in statistical databases, then the next step is to define assumptions (7th step). The data that is being collected can include growing area, yield, higher heating value and other data required for calculations. If the obtained data is in mass units or other units, then the last step of data processing is the conversion of values into energetic values (8th step). Higher heating values (HHV) of the materials are used since the initial moisture content largely varies depending on the processing methods.

2.1.5. Creation of a Sankey diagram

For the 9th step, the freely available tool SankeyMATIC is used. The Sankey diagram is used to visualise the whole value chain of woody materials. In the diagram, the arrows represent the direction of a flow between the nodes. The width of the arrow is proportional to the magnitude of the represented flow, i.e., the amount of transferred biomass.

Respectively, the first MFA for wood is done to define the amount of roundwood that is used for energy production. To obtain this value, it is necessary to assess the possible amount of roundwood that is of lower quality and not suitable for higher added value product manufacture.

3. RESULTS

The following chapter reports on the MFA for the wood, straw, tree leaves, brewer's spent grain, reeds, perennial grasses, and short rotation woody crops using Sankey diagrams for visualisation.

3.1. Wood

The wood sector is an important part of Latvia's economy; therefore, the data availability is much higher compared to other types of biomass. Nevertheless, a Sankey type of data analysis requires multiple pieces of the value chain of the wood, which are still not fully covered by existing statistical data [15]. The Publications Office of the EU (POEU) have reported the woody biomass flows at the EU level and in each country for the year 2017 [10], [16]. The woody Sankey diagram in this study is based on these reports. The source for the data is a combination of National statistics databases, the Joint Forest Sector Questionnaire (JFSQ), Eurostat, Joint Wood Energy Enquiries (JWEE) and National Renewable Energy Action Plans (NREAP). In the mentioned report, the units are a million cubic meters of solid wood equivalent (Mm^3 SWE). The conversion factor of $9000\cdot10^{-9}$ PJ/m^3 SWE is used to obtain energetic values.

For wood, the material definition includes all species of wood. The system boundary starts with the inputs of the roundwood from forests (see Fig. 2). In this case, due to the combination of several data sources, there is a discrepancy with the stocks within the MFA; therefore, it is necessary to introduce inputs called "Unreported primary" and "Unreported secondary". The outputs are flows for energy production, other products, and exports.

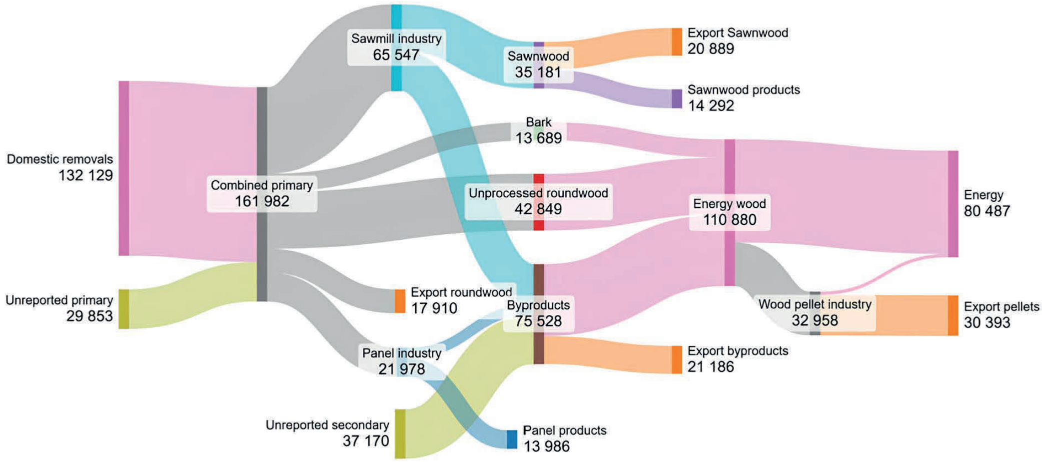

Fig. 2. Sankey diagram for the material flow of wood in Latvia, Units: TJ (based on [16]).

The flows defined in the report [16] did not fully satisfy the flow balance by excluding local products. Therefore, extra flow stocks, such as sawn wood and panel products, are introduced. Based on the collected and processed data, for this study, it is assumed that the total energetic inflow of roundwood in Latvia is 162 PJ. Unprocessed roundwood constitutes 42.8 PJ. If around 16 % of the roundwood is of lower quality than the total inflow, it will result in 25.9 PJ of low-quality roundwood within the 42.8 PJ, which is suitable only for energy production. That leaves 16.9 PJ of roundwood within the final energy consumption of 80.5 PJ in Latvia, which is currently covered by roundwood that could be used for other purposes. Respectively, 16.9 PJ is the amount of energy that must be covered by alternative biomass fuels. That is with the assumption that changes in biomass fuel demand in the case of an increase are covered by a reduction in the amount of wood pellets that are exported.

Main findings:

– Based on the data used in this study, Latvia needs 80.5 PJ of energy. 42.8 PJ are used by wood in the form of firewood. The rest (37.7 PJ) are residues, pellets and briquettes, which are produced mostly from residues. Using the average value of 16 % for low-quality roundwood, which equals 26 PJ available for firewood, and primary energy covered by wood at 80.5 PJ, the residues 37.7 PJ, and leaves 16.9 PJ to be covered by low-quality biomass.
– Data from POEU [16] and the Central Statistical Bureau of Latvia (CSB) [15] have discrepancies. Some data, such as pellet export, have a closer match.
– Wood byproducts currently cover around 47 % of the energy industry's needs in Latvia.
– In 2017, around 41 % of the energy produced by wood was produced by burning firewood, which comes from cutting low-quality primary wood. The share has decreased to 33 % in 2022.
– In the same period, there is an increase in pellet consumption by 40 %. Around 92 % of the pellets are being exported.
– Based on data from POEU and assuming the average low-quality roundwood share (16 % of all cut roundwood), the energy that must be covered by low-quality biomass is 16.9 PJ.

3.2. Straw

Around 75 % of agricultural residues are in the form of straws. Straw is the primary agricultural residue and accounts for approximately 20 % of the total biomass produced in the EU, making it the first option as an alternative to wood biomass. Approximately 42–63 Mt of straw is available in the EU every year (see Fig. 3). Around 17–28 Mt are used for livestock, which is later worked back into the soil. That is a promoted method in the EU as it reduces the need for fertilising. Alternatively, the use of cover crops can also improve soil fertility. One method that is not supported is the burning of straw left on the field as a measure for pest and disease control, and sometimes a method to get rid of the straw that is not worked into the soil [17].

One of the methods to estimate the potential availability of straw is based on deriving it from the amount of grain produced. It has been estimated that around 35–53 kg of straw is produced per 100 kg of grains, depending on the type of wheat [18]. The next limitation is the sustainable removal rate of the straw from the field to maintain the quality of the soil. It has been estimated that around 30–60 % of the straw can be removed, while some have chosen specifically 40 % [19]. The variability is due to the many factors that can impact soil fertility, such as crop yields, soil type and climate.

Statistics databases include straw that is being used as a commercial product; however, if the straw is used within a closed circle of agriculture, its use and thus the amount are not registered. Straw has several uses outside the soil incorporation, such as for frost prevention in horticulture, as an ingredient for mushroom cultivation, as a building material, and in the energy sector [17], [20]. These uses show up in statistics [21] gathered by surveying State and local government enterprises. The total consumption of straw in Latvia in 2022 was around 20 kt. Around 14 kt were used in industry, and 6 kt were used in other sectors.

Statistical data from CSB is available for the amount of grain that is produced. In 2022, the total production of wheat, rye, barley, and oats was 3174 kt of grains. Of those, wheat is around 78 % [22]. The assumption is that for every 100 kg of grains, there is 33 kg of straw or 30 %, which results in around 1000 kt of straw potentially being harvested. The sustainable removal rate is also 30 %. The HHV for straw is taken as $17 \cdot 10^{-9}$ PJ/kg.

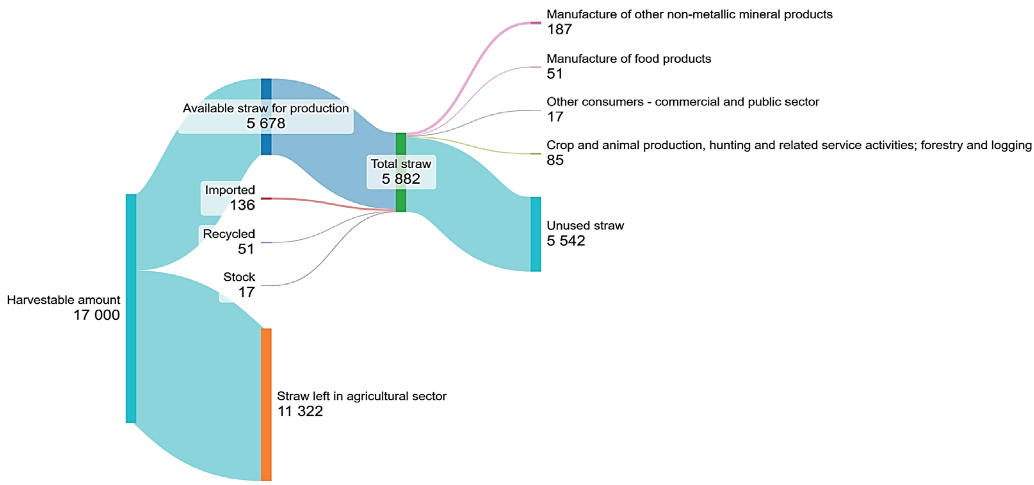

Fig. 3. Sankey diagram for the material flow of straw in Latvia, Units: TJ.

Other minor flows come from Latvia's statistics database; however, the largest impact on the availability is the assumption about the harvestable amount of straw and the sustainable removal rate. The final potential energy that could be produced from straws is 5542 TJ. From the total amount of 16.9 PJ of energy that must be covered by alternatives, the straws could cover around 29 %.

Main findings:

- There are around a million tons of straw available in Latvia. It is assumed that around 70 % of the straw is used in the agricultural sector, which leaves around 300 kt for manufacturing if the sustainable removal rate for the straw is assumed to be 30 %.
- The sustainable removal rate is the main factor that affects the amount of available straw. Some agencies suggest that no straw should be taken out of the fields. Other studies from Europe suggest removal rates of around 40 %. However, those studies also suggest deeper analysis for rates depending on the fertility of the soil;
- Straw has high ash content in the range of 4–10 %, which complicates their use. Additionally, straw has very low ash melting temperatures around 600 °C, which makes the use of straw in wood boilers much more complicated. The HHV for straw is taken as $17 \cdot 10^{-9}$ PJ/kg;
- Straw could cover 29 % of roundwood consumption.

3.3. Tree leaves

Fallen tree leaves from deciduous trees that shed them in autumn transform into a natural humus, which is a nutrient source for the trees and other plants [23]. In urban areas, leaves do not fulfil this purpose since most of the leaves are either collected or fall on surfaces like asphalt, concrete, and other human structures. In those cases, leaves are problematic and usually require removal by mechanical means. Leaves in these areas are collected and can be used for composting. In Riga, most of the leaves are collected and, together with other biological waste, are deposited at the Getlini waste disposal site; therefore, there are no statistics on the amount of leaves that are being collected [24]. There, the leaves, along with other organic matter, are used to generate gas for cogeneration plants. However, there are several practical challenges, for example, when leaves are collected, they are put into plastic bags. For one, plastic bags need to be removed for gas production, but also people tend to throw other garbage in the bags that are waiting to be transported to landfills, thus rendering them unsuitable for composting. Additionally, some of the leaves are cut into smaller fractions and left on the ground to provide nutrients for the trees, reducing the availability of the leaves for other uses.

Estimates of the amount of leaves that can be collected outside of forests are based on a study which analysed the share of the trees in Europe that are outside of the forests [25]. In the case of Latvia, this number is not specifically provided but is given as a range around 0–5 % (see Fig. 4). For Estonia, the number 3 % is reported, which is used for Latvia as well. However, the tree biomass outside of the forests differs from area, because tree density outside of forests can be smaller and have less mass per area. In the case of Estonia, this mass is around 1 % of the total biomass. The forest covers around 50 % of Latvia, which is around 3.2 Mha, and 1 % of that area is around 32 300 ha. The average urban biomass density is around 10 t/ha, which comes out to 323 kt of biomass. The mass of leaves depends on the age and type of tree, but the assumption is that around 5 % of the total mass makes up the mass of leaves, which results in 16.1 kt of leaves in Latvia. It is assumed that most of the leaves are either cut into smaller fractions and left until next year or are collected and placed in organic waste containers, and thus not accessible for collection for energy production. Respectively, it is assumed that only 10 % of the leaves could be collected for energy production, which results in 1.61 kt of leaves.

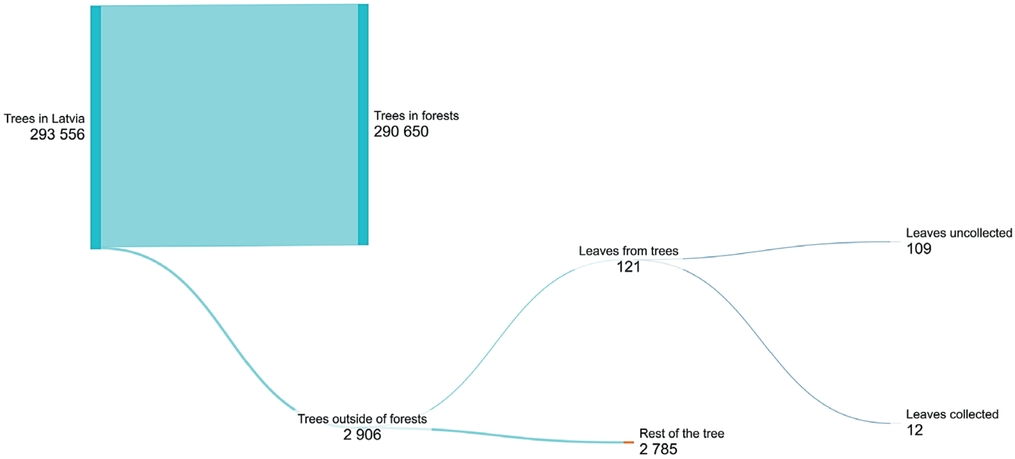

Fig. 4. Sankey diagram for the material flow of leaves from trees outside of forests in Latvia, Units: TJ.

With the HHV of leaves assumed as $7.5 \cdot 10^{-9}$ PJ/kg, the potential energy from collected leaves is around 12 TJ. With the current roundwood consumption of around 16.9 PJ, leaves would cover less than 0.1 %. If the share of the leaves that are collected is increased, the maximum amount of energy that could be obtained from leaves is 121 TJ, which is around 0.7 %.

Main findings:

– The high moisture content of the leaves (around 40 %) is favourable for the use of leaves for anaerobic fermentation for biogas production, but does not support using leaves for energy production in direct combustion [23];
– The nitrogen content in the combustible matter of dry leaves is 12 times higher than the nitrogen content in the combustible matter of firewood from deciduous trees. This observation has a negative impact when using the leaves as fuel, as nitrogen oxides are emitted into the air [23];
– The ash melting temperature is around 850 °C [23];
– According to EN 14961−1 (2010), if the production of ash from firewood is in the range of 0.3–0.7 %, then the production of ash from leaves of hard deciduous trees (except for the leaves of birch) is generally 20 times higher [23];
– The availability of the leaves suitable for collection is very limited. With the used assumptions of HHV of $7.5 \cdot 10^{-9}$ PJ/kg, even if all the leaves from trees outside of forests are collected, it would produce 12 TJ and cover less than 1 % of the current roundwood use.

3.4. Brewer's Spent Grain

During the beer production process, a by-product called brewer's spent grain (BSG) is produced, which is currently sold in Latvia and around the world as food for animals or thrown away as waste. BSG is rich in sugars, protein derivatives, phenolic compounds and other components that occurs during the boiling of wort and the fermentation process.

BSG is a readily available by-product that consists of the barley grain husks together with parts of the pericarp and seed coat layer, which is obtained as solid residue after the production of beer wort. The amount of BSG coming out of the process is dependent on the amount of beer produced (see Fig. 5). Reduction in the name of resource efficiency is difficult to achieve; therefore, the yield of around 20 kg of wet BSG (around 80 % water) per 100 L of brewed beer is constant [26]. Different grains are used in the production of beer, and as a result, there are different types of beer lagers, which differ from each other in terms of composition. However, the ratio to produce one litre of beer is about 0.2 kg of spent grain, as the leftover is kept [27].

The calorific value of raw BSG with high moisture content (~80 %) is around $7.7 \cdot 10^{-9}$ PJ/kg. When dried, the HHV is around $20.5 \cdot 10^{-9}$ PJ/kg [28]. Since beer production takes place from several types of malt, different types of by-products are produced after beer production, which differ from each other in terms of their properties. The table shows a comparison of different BSGs that have been subjected to physical and chemical analysis, as well as higher heat of combustion tests [26].

The data for Latvia [29] shows that around 80 kt of beer was produced in 2022. That results in around 20 kt of BSG before losses. Using the assumption that some 20 % is not obtainable, then it results in a final value of around 16 kt of BSG available in Latvia. However, the use of BSG for combustion is only one of the alternatives. The limited possibility of using it directly due to the high moisture content requires the moisture level to be reduced from 80 % to less than 18 %. Comparably, there are methods where BSG can be used directly, such as for animal feed [30]. Other uses include composting or the production of other products such as biogas. Using assumptions that around 70 % of the BSG is used for feed, around 10 % of biogas results in 20 % of the waste. From 16 kt of BSG, around 20 % is available for energy production, which results in 3.2 kt of BSG. The BSG has a calorific value of $18 \cdot 10^{-9}$ PJ/kg.

If there is no use of BSG for feed or biogas production, then the maximum availability for combustion is 288 TJ. If the assumptions of other uses are used, then around 58 TJ of BSG is available for combustion in Latvia, which is around 0.34 % of the current roundwood consumption.

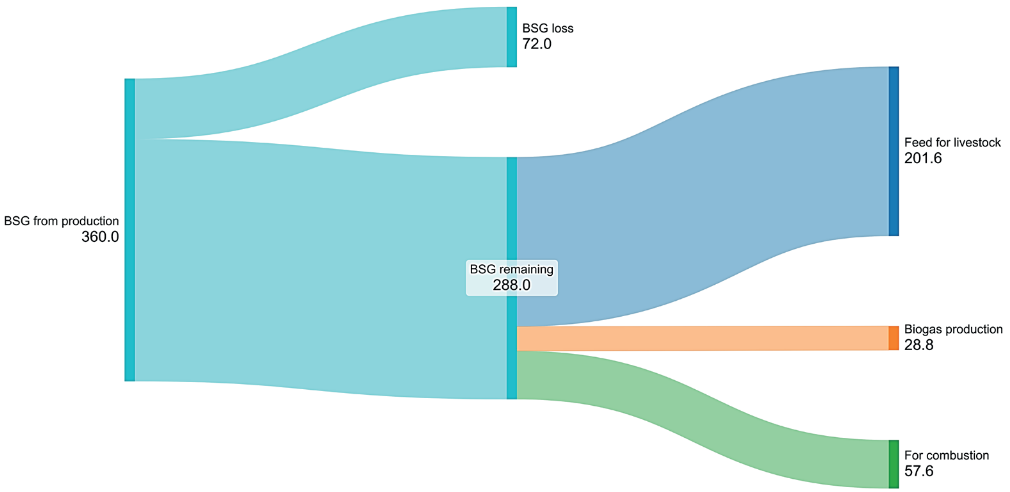

Fig. 5. Sankey diagram for the material flow of brewer's spent grain in Latvia, Units: TJ.

Main findings:

- BSG has a higher heating value comparable to wood (HHV 18–20·10^{-9} PJ/kg) [28];
- BSG has ash content similar to wood in the range from 0.5–2.5 % in most cases [26], [28];
- It is suggested that BSG be used in combustion, organised to have a temperature above 500 °C to have lower ash content.
- The main limitation of the BSG is high moisture content (~80 %) and very limited availability;
- BSG could cover around 0.1–0.5 % of the current wood consumption and 0.34–1.7 % of the current roundwood consumption.

3.5. Reeds

Reed (Phragmites) is a perennial plant of the grass family, which can reach up to 4.5 m high. The trunk is hollow and green with yellow nodal points in the green growing season. In the winter season, the colour of the trunk changes to yellowish brown, as the moisture content in the plant decreases. Leaves are bluish-green or yellow, reaching 50 cm in length and 3 to 4 cm in width. It blooms in late summer, and it also develops a fruit that contains grey seeds and hairs, spread by the aid of wind and water. Each plant produces more than 1000 seeds per year, but they can only reproduce the plant if spread in larger groups. The plant reproduces with a root system and creeping rhizomes, whose vegetative shoots can reach 10–15 m in length. Propagation with the root system makes reeds particularly durable and easy to propagate, giving them the ability to occupy new areas rapidly [31].

Currently, several species are considered invasive worldwide due to their ability to rapidly spread and form monodominant reed stands, exterminating native reed species [32]. However, in Latvia, it is not considered invasive. Some sources compare common reeds with the reed canary grass (RCG), which is a field-grown grass that yields around 6–8 t/ha in the spring harvest and stays productive for 10–12 years. In Finland, the cultivation area for RCG was around 17 000 ha in 2006 and was already then used in heating plants mixed with wood [31].

In studies where use for energy production is considered, instead of common reed, RCG is researched. Also, in Latvia, there was a study [33] to test the growth of RCG in different soils. The study was conducted in 2012 and mentions that at that time, there had been no breeding of RCG in Latvia. Field trials with 10 wild accessions of RCG were carried out to evaluate their suitability. A population "Brigena" had good characteristics, such as winter hardiness and high dry matter yield. That study says that the growth of reed for energy production is rapidly increasing and has exceeded 800 ha with a yield of around 6–9 t/ha (see Fig. 6).

Main findings:

- The moisture content of the reeds depends on the time of the year and fluctuates between 15–60 %. The lowest moisture content suitable for combustion is reached between January and March [31];
- The calorific value of the reed is around 19·10^{-9} PJ/kg, and RCG is around 18·10^{-9} PJ/kg;
- The ash content is around 2–4 % for reeds and 5 % for RCG;
- Problematic, as other straws are the melting point, which has a deformation point of around 1130 °C to 1250 °C for autumn and spring harvests, respectively [33];
- The dry matter yields vary around 8–9 t/ha [33].

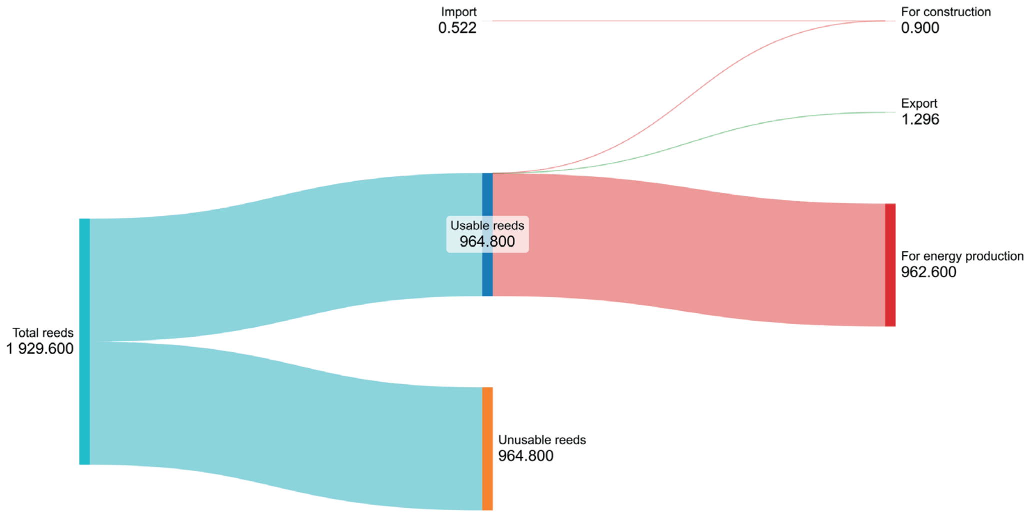

Fig. 6. Sankey diagram for the material flow of reeds in Latvia, Units: TJ.

3.6. Perennial grass

Previous studies of available land area for growing energy crops have stated that around 13–16 % of agricultural land in Latvia in 2013 met the characteristics of abandoned agricultural land, which equals 308–369 thousand ha [34]. A study on land availability for short-rotation woody crops suggests that the total available land in Latvia is 261 710 ha [35]. This unused land could be used for perennial grass production. Perennial grasses are herbaceous, lignocellulosic plants that grow for more than two years. They bloom in the spring and die in the autumn.

Research in Latvia has been done on perennial grasses: reed canary grass [33], [36], [37], *festulolium* [37], [38], while in other countries also *festuca*, *phalaris*, *dactylis*, *lolium* [38]. Reed canary grass was investigated separately, so *festolium* is considered.

Festulolium combines the stress resistance of fescue with the bulky yield of the ryegrass [39]. The dry matter yield of the *festulolium* ranges from around 2–7 t/ha [29], depending on the mowing regimes (one or two-cut regimes) and treatment (mineral fertilisers, wood ash or digestate). A study in Ireland reported a yield of 12.8 t/ha in wetlands [38] and a study from Italy reports 14–18 t/ha [39] – therefore the yield was assumed 6 t/ha.

Considering the total available land in Latvia, the yield of 6 t/ha and the higher heating value for perennial grass (*festulolium*) $16.5 \cdot 10^{-6}$ PJ/t – the total energy potential amounts to 25 909 TJ (see Fig. 7). However, recognising that not all land could be used, only land parcels larger than 10 ha were considered viable – this reduces land availability to 115 152 ha [35]. This study assumes that 5 % of the perennial grass yield would be used for biogas production. With all the assumptions, perennial grass could provide around 10.8 PJ of energy, which covers 64 % of the 16.9 PJ deficit that is covered by roundwood.

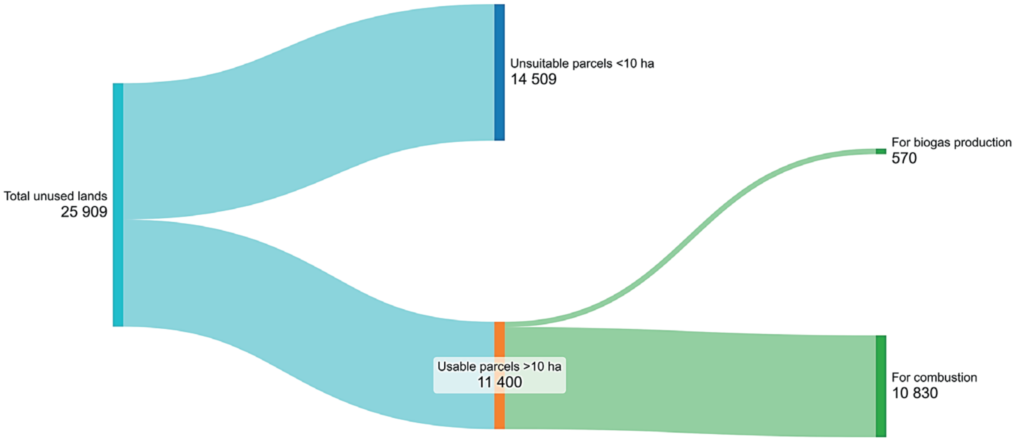

Fig. 7. Sankey diagram for perennial grass (*Festulolium*) in Latvia, TJ.

Main findings:

- The higher heating value of perennial grass (*Festulolium*) is around 15–16·10^{-9} PJ/kg.
- The ash content is around 6 %, and the melting temperature of around 700 °C could be a problematic aspect [40].
- There is a large area of land that is unmanaged and overgrown. Considering that parcel sizes larger than 10 ha would be better suited for industrial activities, the available land area is 11 515.2 ha.
- Dry matter yield is around 6 t/ha as reported in studies in Latvia, which is lower than reported in other countries, where yields up to 18 t/ha have been achieved, indicating that this crop could be used more efficiently in other climate conditions.
- Some studies suggest using grasses for biogas production; therefore, in this study, it is assumed that around 5 % of the available land would be used for biogas production.
- With all the assumptions, perennial grasses could provide around 10.8 PJ of energy, which covers around 64 % of the 16.9 PJ of necessary energy that is currently covered by roundwood.

3.7. Short-Rotation Woody Crop

Short rotation woody crops (SRWC) have been studied in Latvia for the afforestation of abandoned lands. In this study, it is assumed that the potential planting area for SRWCs is the same as the one available for the perennial grasses [35].

The dry matter yield of hybrids of aspen, birch, and alder ranges from around 5–15 t/ha [41]. This study assumed the yield of hybrid aspen to be 6 t/ha. Considering the total available land in Latvia, the yield of 6 t/ha and the higher heating value for hybrid aspen 19·10^{-6} PJ/t (data from Phyllis2 database) – the total energy potential amounts to 29 834 TJ (see Fig. 8). However, recognising that not all land could be used, only land parcels larger than 10 ha were considered viable - this reduces land availability to 115 152 ha [35]. With all the assumptions, hybrid aspen could provide around 13.1 PJ of energy, which covers 78 % of the 16.9 PJ deficit that is covered by roundwood.

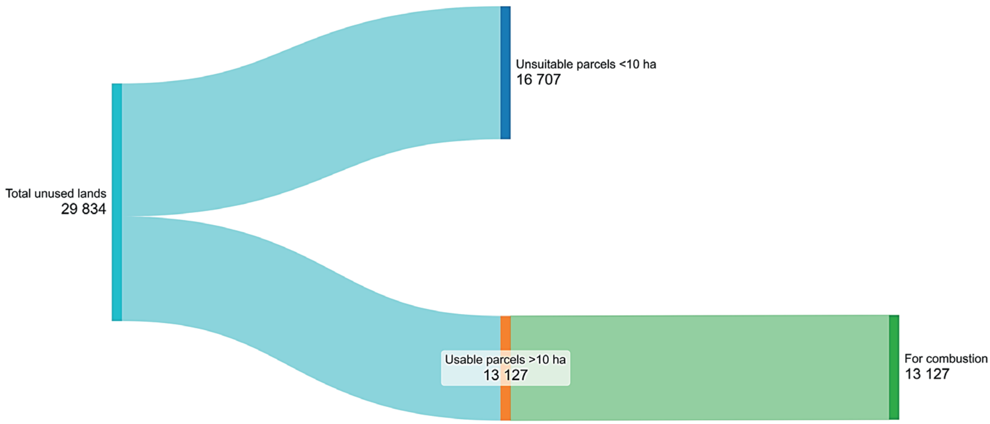

Fig. 8. Sankey diagram for material flow of short rotation woody crops in Latvia, Units: TJ.

Main findings:

- The higher heating value for SRWC is around $19 \cdot 10^{-9}$ PJ/kg;
- Abandoned lands with parcel sizes larger than 10 ha were considered as potential areas for growing SRWC. This area is equal to 115 152 ha. With an estimated yield of 6 t/ha, the total energy is 13 127 TJ.

3.8. Summary

In this article, alternative fuels for wood have been analysed to determine their potential to replace the use of roundwood in the energy sector. Roundwood comes in different qualities. In this article, an assumption is made that around 16 % of the roundwood is of a quality that is not suitable for other manufacturing sectors. That still leaves around 16.9 PJ of energy that is currently covered by roundwood that can be used for sectors other than energy. Respectively, this study analysed alternative solid biomass types to cover that energy.

Six alternative solid biomass fuel types have been analysed using Sankey diagrams – straws, tree leaves, brewer's spent grain, reeds, perennial grasses, and short rotation woody crops. From these, the last two exclude each other since they have the same potential growing area. The potential energy production by type is summarised in Fig. 9.

Individually, from the alternative fuels analysed, the perennial grass (10 830 TJ) or short rotation wood crop (13 127 TJ) provides the largest potential energy source. However, even using all the identified areas of unmanaged lands with parcels larger than 10 ha would not cover the 16.9 PJ of roundwood currently used in the energy sector. The straw (4890 TJ) and reeds (963 TJ) have a more limited growing area and have other uses. Straw is also limited in the amount that can be removed from the fields so as not to degrade the soil quality. Brewer's spent grain (58 TJ) and collectable leaves (27 TJ) are potentially providing such a small amount of energy that they would have minimal impact on the national scale.

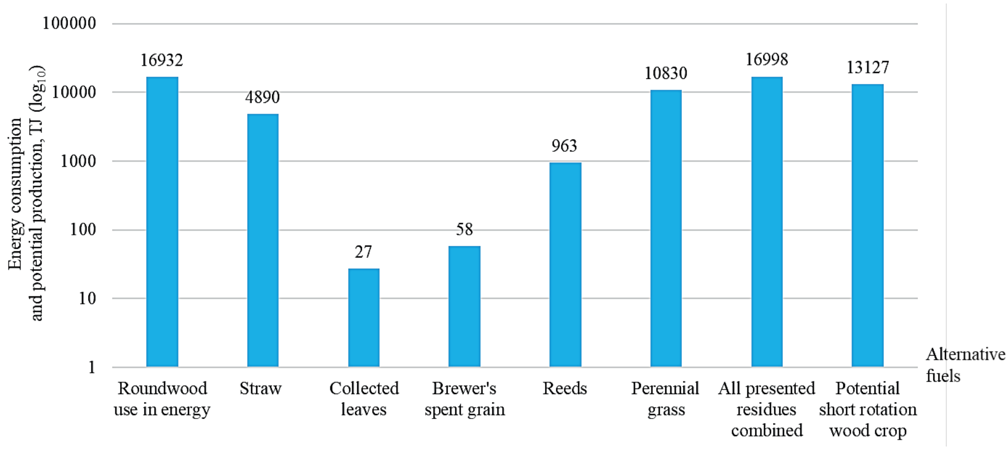

Fig. 9. Summary of potential energy that can be produced by alternative fuels, next to the energy that is currently covered by roundwoods, which could be used for other purposes.

4. Conclusion and Discussion

The use of high-quality roundwood in the energy sector is not supported within the EU's path to sustainability. This study analyses the potential alternative solid biomass types that could be used in the energy sector. With the assumption developed within this study and available data, around 16.9 PJ of roundwood is used in the energy sector, which is of high enough quality to be used in other sectors.

The material flow analysis approach uses Sankey diagrams to visualise the material flows and evaluate their potential and availability. The data sources, inputs, outputs, and conversion approaches have been presented for the six alternative fuel types: straws, tree leaves, brewer's spent grain, reeds, perennial grasses, and short rotation woody crops.

None of the studied alternatives can cover the required 16.9 PJ of energy; however, the combination of all the studied materials can cover it. The largest potential is for the specially grown energy crops – perennial grasses or short-rotation woody crops. The perennial grasses have shorter growing periods; however, they also have lower ash melting temperatures and higher ash content, which can be detrimental to use in existing biomass boilers. Short rotation of woody crops would take longer to grow, but their quality is closer to that of already used wood chips. However, neither can be considered as residues, but if they are grown in currently unmanaged lands, then it could benefit the sustainability of the energy sector.

Straw is obtained in the agricultural sector after the grains have been removed. There is a large variety of practices and possible removal rates for straws. The current soil type, condition, and growing principles determine what a sustainable straw removal rate is and what part of the straw should be worked into the soil. In this study, a removal rate of 30 % is used, which yields 4890 TJ of available energy from straws. However, straws would still be problematic when used as a replacement for wood since they have higher ash content and lower ash melting temperature.

Brewer's spent grain has calorific value and ash content more like wood. The main drawback is the availability, which depends on the beer production rates. Another problem is the high initial moisture content from the manufacturing process. This makes it more suitable for biogas production than direct combustion.

Tree leaves collected outside of forests are often either burned by individual households in the autumn or brought to landfills by municipalities. Therefore, their use in the energy sector would reduce the negative impact. However, the moisture and ash content are high, and the energy content, the ash melting temperature and availability are low, making it unsuitable as an alternative fuel for wood in the energy sector.

A combination of multiple alternative biomass sources could reduce the use of roundwood in the energy sector. Some of the biomass types have local availability and could be used in local boiler houses that would be specifically adapted for that fuel type. That would ensure that lower quality properties, such as higher ash content and lower melting temperature, do not disrupt the operating process.

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