Swedish chemical pulp mills produce over 8 million tonnes of cellulose pulp fibre annually for paper, packaging and tissue. These pulp mills have the potential to become major players as bioefineries in the future bioeconomy producing a wide range of new products in addition to paper, packaging and tissue. This roadmap provides an overview of the potential future products from Swedish pulp mills and how the RISE institutes can contribute to make this transformation happen by 2025.

Swedish pulp mills have a great potential to become part of the core in the future bioeconomy by 2025. This would entail, in addition to today’s production of cellulose pulp fibre and electricity, the manufacturing of a portfolio of biorefinery products: new environmentally sound products for use in advanced materials, chemicals and transportation fuels.

- From **cellulose**, the main component in wood, new products such as textiles fibres, non-woven and nanocellulose, can be manufactured.
- **Lignin**, the other main component in wood, can be used as a raw material for carbon fibre, resins, gasoline, diesel, specialty chemicals and in chemical building blocks for plastics.
- From **cellulose and hemicellulose**, chemical intermediates can be manufactured for use by the chemical industry.
- From **forestry residues**, syngas and bio-oil can be produced and further refined into transportation fuels and value-added chemicals.
- From pulp mill **waste streams**, biogas, algae-based chemicals and foodstuffs can be produced.

Some prerequisites to move in this direction are that the necessary resources are allocated into R&D and testing on pilot- and demonstration scale, and that economically and environmentally sound value chains are established (Fig. 1). These efforts need to be carried out in cooperation between industry and the RISE institutes. Some of the benefits for society on the whole are the creation of new
employment opportunities, the increased competitiveness of Swedish pulp mills, and a decrease in the use of fossil-fuel based resources.

Figure 1. A kraft pulp mill producing cellulose pulp fibre for paper, packaging and tissue can be developed to a biorefinery producing several intermediates for different value chains. This is described below and in detail in separate roadmaps. A roadmap has also been made for sensors for improved resource efficiency which would be relevant for all value chains in the figure.

Background

Swedish research on how to improve the resource efficiency of pulp mills began as early as the 1970’s and focussed on how to reduce emissions to water and air [1]. In the late 1990’s, the Ecocyclic pulp mill concept was developed by Innventia, with the goal of maximizing energy efficiency and minimizing waste and emissions [2]. During the past decade, Swedish research has focused on developing new pulp mill products [3]. One driving force is the declining market for printing and writing paper; another is the competition from newly established market kraft pulp mills in Asia and South America.

The kraft pulp mill provides an excellent platform for the production of cellulose fibres and – in the future – large amounts of wood polymers (lignin, cellulose and polymeric sugars) that can be upgraded as polymers or converted into chemical building blocks. A pulp mill biorefinery also has the potential of co-processing forestry residues; either into lignin and polymeric sugars or thermally into bio-oil, bio-coal and syngas. Waste streams from the mill could be used as the basis for the production of biogas, bio-coal, nutrients, micro-algae and foodstuffs.

Some examples that highlight the current strong research focus on new wood-based products are:

- Research on wood-based biorefineries and new products from cellulose, lignin, hemicellulose and waste streams within EU research programs (EU Horizon 2020/ BBI). Most topics involve creating knowledge about the entire value chain, including sustainability and market potential.
The pulp mill biorefinery

- A large number of Swedish national calls for projects and current ongoing research in this area; e.g., BioInnovation, ForTex, Skogskemi, BioBuF, Polynol, Swedish lignin-based carbon fibre, Innventia Research Programme.
- The significant involvement of the pulp, paper, and chemical industries in developing new product pathways from wood and other lignocellulosic biomass.

The Swedish forest industry of today

Sweden is the third largest pulp and paper exporting country in the world. About 80% of the pulp and paper production is exported, making the pulp and paper industry an important player in the Swedish trade balance. The forest industry gives rise directly and indirectly to about 175,000 jobs, or about 3.5% of the employment opportunities in Sweden [4].

The annual extraction of wood in Sweden is about 33 million tonnes, corresponding to about 170 TWh, 80% of which is used for pulp, paper and solid wood products and about 20% is forestry residues (bark, branches, tops) used for energy. Of the wood going to pulp mills, 50% is used to manufacture pulp and the rest is used for energy production (Fig. 2).

Figure 2. Total forest extraction in Sweden in TWh/year. An equivalent of about 90 TWh per year of wood is used in the pulp and paper industry. If bark and forestry residues are included, the total extraction of wood from the forest accounts for about 33 million tonnes of dry biomass per year, which corresponds to 170 TWh.

The kraft pulp mill of today

Figure 3 shows the principal flows of a typical kraft pulp mill. The main revenue comes from bleached cellulose pulp fibre, electricity surplus and some tall oil. A large pulp mill uses about 1.4 million tonnes of wood (7 TWh) to produce 600 000 dry tonnes of bleached cellulose pulp fibre per year.

Energy is generated from the combustion of the by-product black liquor which contains lignin and hemicellulose which has been extracted from the wood. Bark and other forestry residues are mainly used in the mill for steam and power generation. Most pulp mills can produce more energy than they need. A large market kraft pulp typically produces an annual surplus of power of about 0.4 TWh that can be sold to the power grid. This corresponds to the household electricity demand for about 16 000 homes. Revenue from electricity is however significantly lower than that from pulp. Developing higher-value products than energy from by-products (black liquor and forestry residues) is considered a priority. There is also a large surplus of low-value heat that could be used more efficiently.
Wherever possible, surplus heat is used by adjacent industries or for district heating but this is not very common due to the long distances between mills and other infrastructure.

This roadmap shows the routes for how both the main product (cellulose pulp fibre) and the by-products (black liquor, forest residues, low value heat etc.) of a modern pulp mill can be upgraded into renewable bio-based products such as textiles, foodstuffs, fuels, chemicals composites, carbon fibre and other advanced materials, well suited for the future bioeconomy.

The Swedish forest industry of tomorrow: the biorefinery

Sweden’s annual forest growth exceeds the annual extraction of 170 TWh of wood raw material by 230 TWh or 50 million tonnes of dry biomass [4] (Fig. 2). It is not possible to utilize this net annual growth in its entirety in an economic and sustainable way. Depending on economic and ecologic considerations it has in several studies been estimated that the annual potential of fuel grade wood above the extraction today is from about 20 up to 100TWh/y [5] [6][10]. Even if there is a potential to significantly increase the utilization of forestry residues the cost for processing into transportation fuels and chemicals often is underestimated due to lacking knowledge about the required conversion technologies. There is anyhow a potential to extract in a responsible way a significantly higher amount than today’s level. The Swedish Forest Agency states in its recent report that the potential additional extraction of forestry residues for the period 2020-2029 is between 20-30 TWh/y[10]. This would not only mean a significant increase in the utilization of forest biomass for replacement of fossil transportation fuels and chemicals but would also create many new job opportunities.
The multi-product pulp mill biorefinery
There are several ways to transform a pulp mill into a biorefinery for the production of higher value products than today’s paper grade pulp, tall oil and electricity. Four principal routes, which can be combined in different ways, are discussed here.

Route A. Upgrading cellulose pulp fibre to cellulose for higher value products
Figure 5 shows a number of potential future pulp mill products that could partially or completely replace production of cellulose pulp fibre. This is made possible by separation of hemicelluloses before further processing. Hemicelluloses could be used as bio-based raw material for different kinds of polymers, including oxygen barriers which can replace fossil-fuel based barriers in food and liquid packaging. Another application area, of interest for medical and hygiene applications, is hydrogels which can absorb large amounts of water and replace fossil-fuel based hydrogels in diapers and other products. The pulp mills in Sweden could, together, potentially extract over 1 million tonnes of hemicellulose annually and replace corresponding amounts of fossil-fuel based materials.

Separating hemicellulose also opens up the possibility to obtain pure cellulose. This cellulose can be used for production of textile fibres which could provide a more environmentally sound alternative to cotton. Together, all of the kraft mills in Sweden have a theoretical potential capacity to produce as much as 6 million tonnes of textile fibres and nonwoven annually. This is discussed in the Roadmap for Textile materials from cellulose.

Figure 4. Route A, upgrading of cellulose pulp fibre to cellulose (there are different types) for textile materials, advanced materials, and specialty cellulose.

The global textile fibre demand is expected to increase by the year 2050 by a factor of 2 to 3 from today’s 96 million annual tonnes as a result of the growing world population and generally increasing prosperity [7]. At the same time the annual world production of cotton is considered to have reached its limit (25-30 million tonnes) due to competition for cultivated land from the food, animal feed and
biofuel sectors. Cotton production is associated with environmental concerns, such as water scarcity, soil degradation, the use of fertilizers, and hazardous pesticides. New sources of bio-based textile fibres are therefore sought after. Cellulose-based textiles from sustainable forestry show great potential to fulfil future demands. The production of nonwovens is steadily increasing and new applications are being explored. The global consumption of nonwoven is estimated at 9 million tonnes in 2015 and valued at $37.4 billion. The annual market growth for nonwoven for the period 2015-2020 is projected to be 6.2% [8]. Today, nonwoven is almost solely made from fossil-fuel based sources but there is a strong market trend towards decreasing the carbon footprint and adapting nonwoven products to the bio-based economy [9].

Another promising potential for cellulose from pulp mills is the production of specialty cellulose such as nanocellulose which has a wide range of possible value-added applications. By 2020 it is expected that it will be used as a reinforcing agent in paper and thermoplastic products, as an oxygen barrier in packaging and as a consistency modifier in concrete. Several other nanocellulose applications are being developed. For more information see Roadmap for Materials from nanocellulose.

Kraft cellulose pulp fibre has also interesting applications in different kinds of bio-based composites for use in numerous applications such as furniture, packaging, sporting goods and medical devices. One recent industrial product in this area is the composite DuraPulp developed by Södra. For more information see Roadmap for Bio-based composites.

**Route B. Upgrading lignin into value-added products**

In a kraft pulp mill almost all lignin in the incoming wood ends up in the black liquor which is then combusted for the recovery of process chemicals and the production of steam and power. An alternative way forward is that a portion of the lignin is separated and used for the sustainable production of more valuable products such as carbon fibre, activated carbon and resins such as wood glue. The lignin polymer could also be depolymerized and upgraded into bio-based aviation fuel, gasoline, diesel and chemicals (Fig. 5).

![Figure 5. Route B, upgrading of the by-product lignin into carbon fibre, diesel, gasoline and chemicals.](image-url)
Lignin constitutes about one third of the incoming wood into a pulp mill. During pulp production it is almost completely dissolved in the black liquor. As much as half of this can be separated from the black liquor prior to combustion using the LignoBoost™ process. The total capacity for lignin extraction from pulp mills in Sweden is about 2.8 million tonnes per year; enough to produce over 1 million tonnes of carbon fibre that could substitute steel in motor vehicles. This would allow a production of about 25 million new cars with 10% lower weight and thereby an almost 10% lower fuel consumption. For comparison, about 12 million new cars are produced each year in Europe. For more information see Roadmap for Lignin-based carbon fibre.

Route C. Chemical intermediates and transportation fuels from forestry residues

Kraft pulp mills could become integration sites for the upgrading of forestry residues and other biomass (Fig. 6). The cellulose and hemicellulose content of forestry residues could be converted to second generation (“non-food”) sugar from which chemicals such as ethanol and lactic acid could be produced. The lignin in the forestry residues could either be used for internal energy production or separated in the pulp mill and used for the production of more valuable products, as discussed above in the Route B scenario.

In addition to ethanol, high value chemicals could be also produced from wood sugars, for example lactic acid and butanol. Butanol can be used for a variety of industrial chemicals. Lactic acid can be polymerized to polylactic acid and could, by using forestry residues as a raw material, theoretically replace as much several million tonnes of fossil-fuel based plastic materials per year.

Figure 6. Route C, upgrading of forestry residues integrated in a kraft pulp mill for production of motor fuels and chemical intermediates such as ethanol, butanol and lactic acid.
Another approach is to upgrade forestry residues thermally into motor fuels (demethyl ether (DME), methanol or synthetic diesel) and chemicals. However it should be stressed that the processes for making these conversions are not yet ready for industrial implementation and much R&D is needed to find economically viable technologies.

Upgraded forestry residues may also be used in the steel industry as a substitution for coal in the reduction part of the process. Ultimately this would lower CO₂-emissions from the Swedish steel industry with several million tonnes of per year. This is discussed further in Roadmap for Biofuels for low-carbon steel industry.

Raw materials for use in different kinds of specialty chemicals can be extracted from bark prior to energy production. The value of such products can be relatively high if they are produced with a high grade of purity and used, for example, in for health or skin care products.

Route D. Symbiotic processes for pulp mills and the food industry: production of fish and vegetables from waste streams using by-products

Heat, nutrients, organic material and CO₂ in pulp mill waste streams can be utilized for production of products like biogas, algae, fish and vegetables.

Biogas can be produced by the anaerobic digestion of organic material in waste streams from the pulp mill. The average amount of organic waste in form of sludge produced from external treatment is about 10 kg per tonne of pulp, which for all of pulp mills in Sweden would result in production of about 11,000 tonnes (0.17 TWh) of methane gas, which would meet about 0.5% of the gasoline demand in Sweden.

Algae can be cultivated on waste streams from pulp mills including CO₂-rich flue gas and waste streams containing nutrients and carbon. Algae contain lipids, carbohydrates and proteins that can be used as raw material for a number of different chemicals and fuels. Pulp mill flue gases contain about 2.5 tonnes of biogenic CO₂ per ton of pulp. All of the pulp mills in Sweden together produce about 19 million tonnes of biogenic CO₂ per year which, theoretically, could be used for the production of large amounts of algae.

Fish and vegetables can be produced in large amounts using heat and nutrients in waste streams from pulp mills. This is described in more detail in the Roadmap for Food industry and pulp mills in symbiosis.

The RISE institutes: unique areas of competence

Innventia has unique competence in all the processes of the kraft pulp mill, from wood handling to the final product, chemical and energy recovery systems as well as separation and upgrading of wood polymers into various products such as carbon fibres, nanocellulose and textile cellulose. Two cornerstone competence in Innventia’s approach are the processing of nanocellulose and the production of lignin from pulp mill black liquor. Another key competence is technical and economic analysis of entire pulp mill systems analysis including biorefinery options (separation thermal and chemical biorefinery processes), and techno-economic assessment of pulp mill biorefineries. SP has unique competence in thermochemical processing of bio-oil and syngas, catalytic processing of biomass for chemicals and biofuels, biochemical processes for ethanol and other chemicals and the bioprocessing of waste into biogas, algae, fish and vegetables.
Swerea has unique competence in cellulose fibre and cellulose processing into textile cellulose, cellulose fibre composites and lignin carbon fibre composites.

R&D and resource requirements

The development of Swedish pulp mills into biorefineries has made substantial progress in the past few years. Pulp mills have huge potential to become a core in the future bioeconomy via a portfolio of new cutting edge biorefinery products – in addition to the current production of pulp and electricity – that includes environmentally sound advanced materials, chemicals and transportation fuels.

The current products and the future product opportunities are shown in Figure 1. A prerequisite for this development is that significant resources are allocated to R&D and testing on pilot- and demonstration scale, allowing economically and environmentally attractive value chains to be established.

These efforts need to be carried out in cooperation between universities, the industry and the RISE institutes. Some of the benefits for society on the whole are the creation of new employment opportunities, increased competitiveness of Swedish pulp mills and a decrease in the use of fossil-based resources contributing to a reduction of CO₂-emissions.

The most important areas in need of further development are the value chains for:

- Cellulose in to specialty fibres such as textiles, nonwoven and nanocellulose.
- Lignin in to carbon fibres, resins, gasoline, diesel, and chemical building blocks.
- Forestry residues to chemical intermediates for the chemical industry.
- Forestry residues in to syngas, bio-coal, bio-oil for transportation fuels and chemicals.
- Products from pulp mill waste streams such as biogas (methane), nutrients like phosphorous, fish, vegetables and algae-based fuels, as well as other chemicals and foodstuffs.

In summary, the RISE institutes, in close collaboration with universities and industry, are well positioned to meet the challenges of creating the forest industry’s contribution in the future bioeconomy.

Sources

1. Swedish Forest Industries Federation


5. Swedish Forest Agency, Skogsstatistisk Årsbok


7. www.thefiberyear.com


The RISE Research Institutes of Sweden – Innventia, SP, Swerea and Swedish ICT – are a major R&D player in the bioeconomy sector, with a combined annual turnover in the field of SEK 800 million (€85 million). During 2014-2015 the activities in the RISE project RISE Bioeconomy were reviewed. Areas with the greatest growth potential were identified and strategies for how to move forward were published in the following eight roadmaps for the period 2015-2025:

- The pulp mill biorefinery
- Textile materials from cellulose
- Materials from nanocellulose
- Bio-based composites
- Lignin-based carbon fibres
- Biofuels for low-carbon steel industry
- Food industry and pulp mills in symbiosis
- Sensors for increased resource efficiency