The research leading to these results has received funding from the European Community's 7th Framework Programme under grant agreement nº 604187

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NOVEL BIOBASED PRODUCTS FROM SIDE STREAMS OF PAPER AND BOARD PRODUCTION

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SUMMARY

The paper and board production process, especially when carried out with paper for recycling as the raw material, leads to the generation of large amounts of side streams, mainly sludges, rejects and process water. The main two outlets for the European paper and board industry's (PBI) solid side streams have historically been landfilling and incineration. Both of them entail significant costs for the sector, while landfilling has been recently facing also regulatory limitations in several countries. Reducing these costs, and even turning them into profits, depends on the ability of the sector to utilise the valuable components in the side streams by reusing them internally or converting them to intermediates or products for other parties.

This report identifies and describes a number of side stream valorisation opportunities, either already on the market or in various stages of development, and aims to inform stakeholders in the sector of ways to utilise the full potential of their raw materials. The valorisation routes presented are organised in four categories, namely application of the side stream in its current form without further processing, application by conversion into a material product, application by conversion into energy, and application by conversion into an energy carrier and include the following options:

- Land management
- Absorbent materials production
- Building materials production
- Wood-plastic composites production
- Fractionation
- Hydrolysis to fermentation feedstock
- Nanocellulose production
- PHAs production
- Alginates production
- Incineration
- Gasification
- Pyrolysis
- Anaerobic digestion
- Secondary fuels production

The report demonstrates the significant potential for the valorisation of the large amounts of side streams of the paper and board industry, with several of the options described having the additional benefit of being able to produce high-value materials that could be reused within the sector's own production processes.

1. Introduction

The Confederation of European Paper Industries (CEPI), in cooperation with Kenniscentrum Papier en Karton (KCPK), published in 2011 the report "*Maximum value from paper for recycling – Towards a multi-product paper mill*". The basis for that document was the idea that obtaining maximum value per unit of paper for recycling (PfR) –a key raw material for a large part of the European paper and board industry (PBI)- is an important aspect of papermaking. Given that increased demand for biomass has been expected within traditionally non-biobased sectors, such as energy generation and chemicals production, as they are trying to move towards the realisation of Biobased Economy visions, it was suggested that extracting the maximum economic value out of PfR would sooner or later become a decisive factor with regard to the profitability of a paper or board producer. Taking into account that a significant amount of the PfR that is fed into the papermaking process does not leave it in the form of an end product but rather in that of side streams, efforts to find useful and profitable applications for it have been of great interest to the PBI as a means of improving its economic performance. The 2011 report attempted to bring into perspective a representative selection of side stream valorisation opportunities, which were either being implemented or under development at the time of publication, so as to inform stakeholders in the sector of ways to utilise the full potential of their raw materials.

The REFFIBRE FP7 project, running between 2013 and 2016, aims to help the PBI decrease waste generation, improve resource efficiency and strengthen its competitiveness through the production of novel products with a lower environmental impact and a high added value out of side streams. Methodologies, tools and models needed in order to determine the technical and economic feasibility of Multiple Output mill concepts, as well as to assess their environmental impacts, are developed within the project. Operational data is required so as to test and validate these models. The implementation of innovative technologies for the production of novel products on a demonstration scale is necessary in order to generate and collect real data from the chosen REFFIBRE cases. Based on the need for a pilot scale demonstration of novel valorisation technologies we have carried out within the project a new review of the opportunities either already available to and implemented by the PBI or currently in various stages of development. This review is now being made available as an update of the 2011 CEPI/KCPK report, enabling decision makers within the sector to remain up to speed with regard to the developments that have taken place in the past five years.

2. Paper and board industry side streams

The side streams generated by paper and board mills that are considered for the purposes of this report are defined as follows:

- Rejects (ragger, heavy, coarse, fine); produced during the utilisation of PfR, they can contain fibre lumps, plastics, metals, sand and glass. The most important types of rejects in terms of their valorisation potential are:
    - coarse rejects, produced during early filtration steps in which large non-fibre objects such as plastics are removed, and
    - fine rejects, produced during filtration steps with screens with very small slots so as to remove possible sticky content that may disturb the production process and diminish the quality of the end product; fine rejects contain a considerable amount of fibres
- Deinking sludge; produced during the flotation deinking of PfR, it contains mostly short fibres/fines, inorganic fillers, as well as ink particles
- Primary wastewater treatment sludge; produced during process water clarification by mechanical means, it contains mostly short fibres/fines and fillers
- Secondary wastewater treatment sludge; produced during process water clarification by biological means
- Process water (often referred to as wastewater when treated before its discharge); a key component of papermaking, it is usually treated on-site for the removal of contaminants

Reliable statistics regarding side stream generation by the PBI are difficult to come by; in 2005 around 11 million tonnes of solid waste were generated in Europe (including from pulp production) and roughly 70% (7.7 million tonnes) thereof originated from using PfR as a raw material[1]. According to the same source, the utilisation of PfR results in 50-100 kg of dry solid waste per tonne of packaging paper production, 170-190 kg per tonne of newsprint production, 450-550 kg per tonne of graphic paper production and 500-600 kg per tonne of tissue production. Different paper mills, however, produce different amounts of side streams of varying compositions. Information about process water is even more scarce; as an indication, more than 70,000 dry tonnes of COD were contained in the process water of the Dutch PBI in 2008, when the sector's production volume was around 3 million tonnes, 80% of which was based on the use of PfR as a raw material.

The main two outlets for PBI solid side streams have historically been landfilling and incineration, although the significance of the former has greatly decreased owing to bans imposed in several European countries. In any case, both options have entailed significant costs for the sector, with recent information from Germany and the Netherlands indicating that disposing of rejects and sludges could cost up to 100 € per tonne. Reducing these costs, and even turning them into profits, depends on the ability of the sector to utilise the valuable components in the side streams by reusing them internally or converting them to intermediates or products for other parties.

[1] Monte MC, Fuente E, Blanco A, Negro C. Waste management from pulp and paper production in the European Union, Waste Management, 29, pp. 293-308, 2009

3. Inventory of side stream valorisation opportunities

The opportunities identified for the purposes of this report are summarised in the table below. They are organised in four categories, namely application of the side stream in its current form without further processing, application by conversion into a material product, application by conversion into energy, and application by conversion into an energy carrier.

Table 1. PBI side stream valorisation opportunities discussed in this report.

Use as such	**On-site or external processing**	**Applied in the PBI**	**Applicable for**					
			Deinking sludge	Primary sludge	Secondary sludge	Coarse rejects	Fine rejects	Process water
Land management (land spreading, land remediation, landfill cover)	n/a	Yes, in some forms	✓	✓				
Absorbent materials production (animal bedding)	n/a	Yes	✓	✓				
Conversion to product								
Land management (composting)	n/a	No	✓	✓				
Absorbent materials production	Both possible	Yes, limited	✓	✓				
Building materials production	External	Yes, in some forms	✓	✓			✓	
Wood-plastic composites production	External	Yes, limited	✓	✓		✓	✓	
Fractionation	On-site	Yes, limited	✓	✓				
Hydrolysis to fermentation feedstock	Both possible	No	✓	✓				
Nanocellulose production	Both possible	No	✓	✓				
PHAs production	Both possible	No			✓			✓
Alginates production	On-site	No						✓
Conversion to energy								
Incineration	Both possible	Yes	✓	✓	✓	✓	✓	
Conversion to energy carriers								
Gasification	On-site	Yes, limited	✓	✓	✓	✓	✓	
Pyrolysis	On-site	Yes, limited	✓	✓		✓		
Anaerobic digestion	On-site	Yes			✓			✓
Secondary fuels production	On-site	Yes				✓		

A brief description of each valorisation possibility included in this report will be provided in this chapter. More extensive factsheets are provided in Annex I.

Land management

PBI deinking and primary wastewater treatment sludges can be used for a number of land management applications. Two practices are widely applied: land spreading, where sludges are spread on agricultural land for nourishing and conditioning purposes, and application as landfill cover, where sludges are used as a barrier cover in landfills, using their favourable permeability characteristics. Other land management options that have been suggested -but do not appear to have been applied yet in practice- are the use of sludge for land remediation, where the side stream is contributing to the revegetation of degraded soils (e.g. old surface mines), and the composting of sludge, which can offer a better product for use in agriculture and horticulture compared to the spreading of untreated sludge. Drawbacks common to some or all of these options include regulatory limitations, often negative public perceptions, limited potential for absorbing large side stream volumes and the necessity to pay gate fees for disposing of the side stream.

Production of absorbent materials

PBI deinking and primary wastewater treatment sludges can be used in the production of absorbent materials. This may take two forms, namely the production of animal bedding and the production of absorbent materials for liquids with applications in, for example, the cleaning of chemical and fuel spills. The production of animal bedding may require minimal to no processing of the side stream, while industrial absorbents can be produced by means of simple mechanical processing. Although this route offers some valorisation of the side streams, animal bedding production is not a high-value application, while the market prospects of large amounts of industrial absorbents from PBI side streams are uncertain. For both of these options, known examples of application in practice within the PBI already exist.

Production of building materials

The production of various materials used by the construction sector out of PBI side streams has been implemented for some time in some cases or is in various stages of development in others. The possibilities include application of PBI side streams in the production of cement, concrete, bricks, and various types of board materials (e.g. gypsum fibreboard, MDF, hardboard, etc.). PBI sludges have been applied for some time in brick and cement production, where they act as a fuel for generating part of the heat required by the process and as a partial replacement for virgin raw materials. Use of various types of PBI side streams, both sludges and rejects, has been suggested, but not widely applied yet, including in the production of panel materials for the construction sector, where their use is intended to partially substitute other fibre sources (e.g. PfR and wood). Current experiences with valorisation via the production of building materials (e.g. use in cement kilns) indicate that at least some of these possibilities involve a gate fee charged to the paper mill for disposal of their side streams.

Production of wood-plastic composites

Various types of PBI side streams, both sludges and rejects, could be used in the production of wood-plastic composites (WPCs). These are, as the name denotes, composite materials made of wood fibre, usually in the form of wood flour, and thermoplastic materials, such as PE, PP, PVC, etc. Depending on the characteristics of a given side stream, it could be applied either as a low-cost substitute for more expensive raw materials without leading to a deterioration of the end product quality, or as an additive that could improve the characteristics of the end product, for example by reinforcing it. WPCs have a growing market and various existing and potential applications. Each one of these applications sets its own requirements with regard to the characteristics and quality of the end product, which may pose higher, lower or no obstacles for the use of PBI side streams in the production process.

Fractionation

Although fractionation is included here among the identified side stream valorisation opportunities, it is in practice an intermediate step that, when undertaken, makes the pursuit of other valorisation routes possible or, at least, simpler and more efficient. The term “fractionation” denotes in this report the separation of one or more fractions from a side stream, although it can also be applied in the pulp stream, based on the specific characteristics of each fraction’s components. When applied on side streams of the PBI, fractionation can produce fractions that are either suitable for reuse within the same sector or attractive for applications outside the paper industry; the characteristics of the new fractions make them better suited for the proposed application than the untreated side stream would be, which improves the chances of profitable side stream valorisation instead of simply less costly disposal. The extent of side stream fractionation can be determined by the paper mill, depending on its wishes. Fractionation could be as simple as separating the organic (fibres, fines) from the inorganic (fillers) material in a sludge stream or as complex as producing various organic fractions of fibres and fines with different characteristics. Currently applied or proposed examples of side stream fractionation involve technologies that are already widely used within the sector, with their optimal combination appearing to be the key factor for success.

Hydrolysis to fermentation feedstock

Hydrolysis of PBI sludges for the production of sugars could become a major step towards the further integration of the sector within the emerging Biobased Economy. Cellulose in the side streams can be enzymatically broken down into glucose molecules, with the sugars being metabolically converted to chemicals (e.g. lactic acid) or energy carriers (e.g. ethanol). The fact that PBI sludges are cheap and geographically concentrated sources of cellulose, with the fibres having been extensively treated and thus more amenable to enzymatic treatment, makes them an interesting possibility for the production of sugars. Fractionation for the removal of ash could help improve the efficiency and economics of this route. No industrial references exist at this point in time but literature suggests that research in this topic has gained considerable momentum.

Production of nanocellulose

Nanocellulose is seen as a high-performance material that will start playing an increasingly important role in the future, with applications across many different sectors, including the paper industry. The production of one type of nanocellulose (nanocrystalline cellulose) from PBI sludges is being developed by an Israeli company on the basis of the acid hydrolysis of the sludge. The same company is also working on an array of this product’s applications, among which ideas of interest to the PBI, such as use in paper sizing and as gas barrier coating. The first demonstration plant for this production technology, initially with bleached pulp as raw material, will become operational by the end of 2016.

Production of polyhydroxyalkanoates (PHAs)

PHAs are a family of polyesters that serve as carbon and energy storage units within certain microorganisms and have significant potential as biodegradable bioplastic materials. Their competitiveness against conventional plastics is currently limited due to their high production costs, but efforts made for their production out of side streams are promising to address this issue. PBI wastewater could be one of these side streams, utilised within a process that acts as a wastewater treatment process, resulting in the production of a valuable biobased product. Applying such a concept in practice could also help paper mills close their water loops without the usual accompanying problems. Production of PHAs out of industrial wastewaters, including those of the PBI, has reached pilot scale and the development of functioning PHAs value chains and markets should be the next step towards realising the concept in practice.

Production of alginates

A new aerobic wastewater treatment technology developed in the Netherlands is promising great process-related benefits, such as energy savings and reduced space requirements, when applied for the treatment of municipal and industrial wastewaters, either in new treatment plants or in retrofitted older installations. As well as being a treatment technology, this could be a valorisation possibility for the organic content of wastewater, as it can deliver a by-product in the form of alginate-like exopolysaccharides. These resemble alginates produced from seaweed and research is currently underway regarding possible applications of this by-product. One of the most interesting ideas is its potential use in paper sizing, a function that seaweed-based alginates also perform. The water treatment technology is already operational, primarily within municipal treatment plants, and the first installation focusing on the extraction of the alginate by-product is planned for 2017.

Incineration

One of the most widely applied options for dealing with PBI side streams, incineration has greatly benefited from the utilisation of fluidised bed technology which is more apt for feedstocks that are high in ash and moisture content. The production of steam and electricity can help a paper mill reduce its dependence on fossil fuels, lower its energy costs and add a new source of income, especially in countries where generous state incentives are available for the generation of green energy.

Gasification

Another technology available for the thermal treatment of PBI side streams, gasification leads to the production of synthesis gas, a mixture of CO, CO_2, CH_4, H_2O and N_2. Synthesis gas can either be used directly as fuel (e.g. co-combustion in a steam boiler) or converted to other fuels or chemicals. The high investment costs for the application of this technology may, in certain countries, be partially covered by state subsidies for the generation of green energy, as was the case with the first commercial reject gasifier that will become operational in 2016 in the Netherlands.

Pyrolysis

Another form of thermal treatment, in the total absence of oxygen, pyrolysis produces a mixture of solid, gaseous and liquid products, depending on the composition of the feedstock and process conditions. Pyrolysis oil and gas can be directly used as fuels, providing the pyrolysis process itself with the energy necessary, and the oil could potentially also be converted into other fuels or chemicals. When PBI sludges are pyrolysed the mineral fraction returns as a clean secondary product, which could be applicable again as a filler for papermaking if its quality is sufficiently high, while when mixed rejects are pyrolysed the metal fraction returns as a clean secondary product. Reject pyrolysis has already been commercially applied, while sludge pyrolysis is in the phase of pilot scale development.

Anaerobic digestion

The breaking down of organic matter by microorganisms in the absence of oxygen has already been widely applied within the PBI as a wastewater treatment technology but could be equally interesting for the treatment of secondary sludge from aerobic wastewater treatment. The latter requires, however, some form of pre-treatment in order to improve the digestibility of complex organic matter; several options have been suggested or are already on the market. The biogas produced by anaerobic digestion of water and sludge can be internally utilised by a paper mill so as to cover part of its energy needs, while sludge digestion can reduce the volumes that need to be disposed of and offer an array of other process benefits within the wastewater treatment plant.

Production of secondary fuels

Rejects from the stock preparation in paper mills utilising PfR as their raw material can be converted into various forms of secondary fuels (e.g. fluff or pellets) to be co-fired at energy generation plants or by other industrial users. This option has already been in practice for several years.

4. Discussion

The list of valorisation opportunities found above is far from exhaustive, with more options being developed worldwide by industrial parties or researchers; information about all of them is difficult to gather, due among other things to the secrecy that often surrounds new technologies. It provides, however, a good indication about the technologies that are already applied within the sector, as well as those whose development has gained significant recent momentum.

Conversion to energy and energy carriers has a strong presence in this report, with all five options described for sludges, rejects and process water having been applied in practice in at least one known case within the PBI. Although they make good use of the energy content of side streams, a development that is already a step forward compared to the era of landfilling, they are still not optimal solutions for a future in which the principles of the Biobased Economy and the Circular Economy will increasingly guide business decisions. In order to adapt to such a new reality more needs to be done with regard to extracting value out of side streams in another way, by utilising their potential as raw materials and not as energy sources. On the other hand, the current economic reality in certain counties, with subsidies and other incentives available for the generation of green energy, makes these valorisation options much more attractive and diminishes the risks of undertaking the significant investments needed for e.g. a new incineration or gasification facility. In our experience, removing this direct and/or indirect state support from the equation would quite possibly lead decision makers to reconsider their commitment to such energy generation-focused projects.

An important step towards optimally valorising the content of PBI side streams should be managing to reclaim as much high-quality material from them as possible for the sector's own operations. It can be said with some certainty that the maximum value of a tonne of reclaimed fibres will be obtained when they are applied in papermaking compared to any other valorisation possibility. Developments in the field of side stream fractionation could prove to be very important in this context, allowing the sector to keep the materials that can best serve its own production process, while seeking the optimal valorisation route for the fractions that have less to offer to the PBI. Some papermakers are already trying to implement side stream valorisation by means of recirculating the materials back to their production process without fractionation; this option has shortcomings however. Reintroducing all components of a side stream to papermaking can have a negative influence in terms of process parametres such as dewatering, drying, machine speed etc., or product characteristics such as strength; these adverse effects of side stream reuse can be avoided by means of fractionation.

Besides reclaiming fibres, this report showcases in a number of examples the potential of extracting other valuable materials for the PBI from the sector's side streams. The examples of PHAs, alginates and nanocellulose are characteristic of these possibilities. The PBI needs to pay more attention to producing its own additives in the years to come in order to improve process efficiency or product performance.

A factor that is often not adequately discussed, despite its importance, is the need to create partnerships in the field of side stream valorisation. Such partnerships must sometimes involve parties from within the PBI sector, e.g. when more paper mills pool together their side streams in order to gather sufficient quantities for attracting the interest of a third party that may have a use for them, or when one paper mill separates fractions from their side streams that could be best utilised by the producer of another paper or board grade. In other cases the potential partnerships may involve parties that belong to different sectors; a paper mill and a chemical producer, for example, could be brought together by their geographical proximity and the availability of mutually useful materials. Such local partnerships between a small number of parties could actually be easier to realise in the short term than national networks bringing together many stakeholders with often diverse priorities and needs.

5. Conclusions

Significant potential exists for the valorisation of the large amounts of side streams that are generated during the paper and board production process, especially when PfR is utilised as the raw material. A far from exhaustive list of such technologies and techniques has been compiled for the purposes of this report. These can be organised in four categories, namely application of the side stream in its current form without further processing, application by conversion into a material product, application by conversion into energy, and application by conversion into an energy carrier. Several of the proposed concepts have the added benefit that they could potentially lead to the reclamation of high-quality materials from PBI side streams to be reused within the sector's operations. It should be mentioned that local conditions, e.g. the composition of a mill's side streams, regional/national subsidy schemes, distance from necessary partners, etc., can play a major role in determining the attractiveness of any of the aforementioned options for any individual paper or board mill.

Appendices

Appendix 1. Factsheets of side stream valorisation options

Title: Application in land management
Raw material type: PBI sludges.
Short description: A number of land management options are available as an outlet for sludge generated by the PBI. The following options can make use of favourable sludge characteristics: • Land spreading • Land remediation • Landfill cover • Composting
Intermediate and end products: All land management options entail the direct application of sludge in the area selected.
Process: There are no complicated processes involved in the application of PBI side streams for land management. In the case of land spreading, for example, the practice consists of simply spreading the sludge on agricultural land or ploughing it into soil. Dewatering of the sludge (e.g. by screw pressing) can take place in advance so as to facilitate its storage and transportation. In the case of land remediation, the sludge can be applied in contaminated sites, such as old surface mines, in order to restore their ecosystem function by addressing nutrient deficiencies and toxicities that impede the re-establishment of self-sustaining plant cover. In landfills PBI sludges can be used for substituting other materials (e.g. clay, bentonite) in the hydraulic barrier layer or they can be used in the landfill's liner and its daily cover layers. Finally, composting of PBI sludge involves the solid phase decomposition of the organic matter by microorganisms under controlled conditions, leading to the production of a marketable product (compost) for application in agriculture and horticulture.
Benefits and Drawbacks: The land spreading of sludge can nourish and condition soil and assist in breaking down pesticides, and can be beneficial for water retention in fast-draining soils. On the other hand, large areas are required for this application, given that there are limitations regarding the maximum amounts applied, and the practice is restricted to certain periods throughout the year, which means that storage capacity for sludge is required. Some odour problems may also exist, especially during the first days after application. The heavy metals content of certain sludges could also be a point of concern, as well as the possibility of groundwater contamination via the leaching of salts, nitrates or heavy metals. The

greatest drawback of this route, however, is that land spreading is not allowed in several countries.

When applied to land remediation PBI sludges can be a valuable tool for the revegetation of degraded soils that face limitations with regard to water retention, acidity, nutrient availability and bulk density. The application of sludge can also chemically stabilise metals in polluted soils and convert them to forms that are not available for uptake by plants. A question with regard to this route is whether remediation activities could generate sufficient demand and absorb significant sludge quantities.

In landfill cover application PBI sludges demonstrate good permeability characteristics, no odour problems and can support vegetative growth. When incineration ash is added to them, geomechanical, chemical and stability characteristics can be further improved. In a world, however, in which landfilling is set to assume an increasingly peripheral role as a waste management option this outlet has no long-term potential.

Composting reduces sludge volumes and transportation costs, improves storage and handling, removes odours, degrades phytotoxic compounds and provides a better overall soil amendment than untreated sludge. Co-composting of sludge with nitrogen-rich organic waste (e.g. kitchen and catering waste) can be beneficial for both materials. The need for a large space is, however, one disadvantage of traditional composting processes.

Land management options, where legally allowed, do not appear to have a very attractive economic potential, limited either by the need to pay gate fees for the disposal of the sludge and/or by an insufficiently large demand.

Technology Readiness Level: Land spreading and use of sludge in landfill covers have been applied for many years. Composting of organic materials is also well developed, although no references were found in the case of PBI side streams, while the use of sludge in land remediation has been described in several studies but has not been, to the best of our knowledge, applied in practice.

Experiences in the Paper and Board industry: Land spreading of PBI sludge has been a popular outlet in some countries (e.g. United Kingdom), while reports of sludge use as landfill cover, especially in the United States of America (USA), also exist.

Literature/websites:

http://www.paper.org.uk/information/guidance/landspreadingcode_Nov2015.pdf

http://www.flagstaff.az.gov/DocumentCenter/Home/View/11013

www.uws.ac.uk/workarea/downloadasset.aspx?id=2147493392

Title: Absorbent materials production

Raw material type: Suitable for deinking and primary wastewater treatment sludges.

Short description: There are two main options with regard to the production of absorbent materials from PBI side streams: animal bedding and absorbents for oil and other hydrophobic and hydrophilic liquids from water or hard surfaces.

Intermediate and end products: The end product of this valorisation route is the absorbent material, which can have various forms (e.g. loose or pelletised) depending on the application.

Process: Depending on the intended product, the production process for an absorbent material may include steps such as drying, some form of mechanical treatment and mixing with other materials. As an example, the production from deinking sludge of the CAPSorb absorbent material for hydrophobic liquids is described in the following steps:

- Drying the deinking sludge to the point where releasing the cellulose fibres from the inorganic matrix can be efficiently performed by means of mechanical processing. This requires the sludge to be dried by up to 70-80% and waste heat from a paper mill can be used
- Mechanical processing (fluffing) of the dried sludge, which increases its surface area and absorbency and also makes it possible for the material to float, e.g. for cleaning oil spills on water surfaces
- Further chemical treatment (e.g. esterification) can be an optional step, when even better absorbency or buoyancy are required

Production of animal bedding for cow sheds in the USA by Syracuse Fiber Recycling, on the other hand, is described as involving simply mixing PBI sludge with cement dust so as to increase its dry matter content.

Benefits and Drawbacks: The benefit for paper mills when offering their side streams for the production of absorbent materials is to avoid sludge disposal costs. This valorisation route involves simple processes that require low investments, relative to other possibilities, and which can utilise already available unused resources, such as waste heat for sludge drying. It should be mentioned that experiences with PBI sludge as animal bedding indicate that its use can result in healthier and more productive animals compared to other alternatives.

The main drawback of this route is, in the case of animal bedding, the absence of a high-value end product or, in the case of absorbents for liquids, the uncertainty regarding the existence of a sufficiently large market, as all kinds of absorbents are competing not only among themselves but also against other options such as solidifiers and detergents.

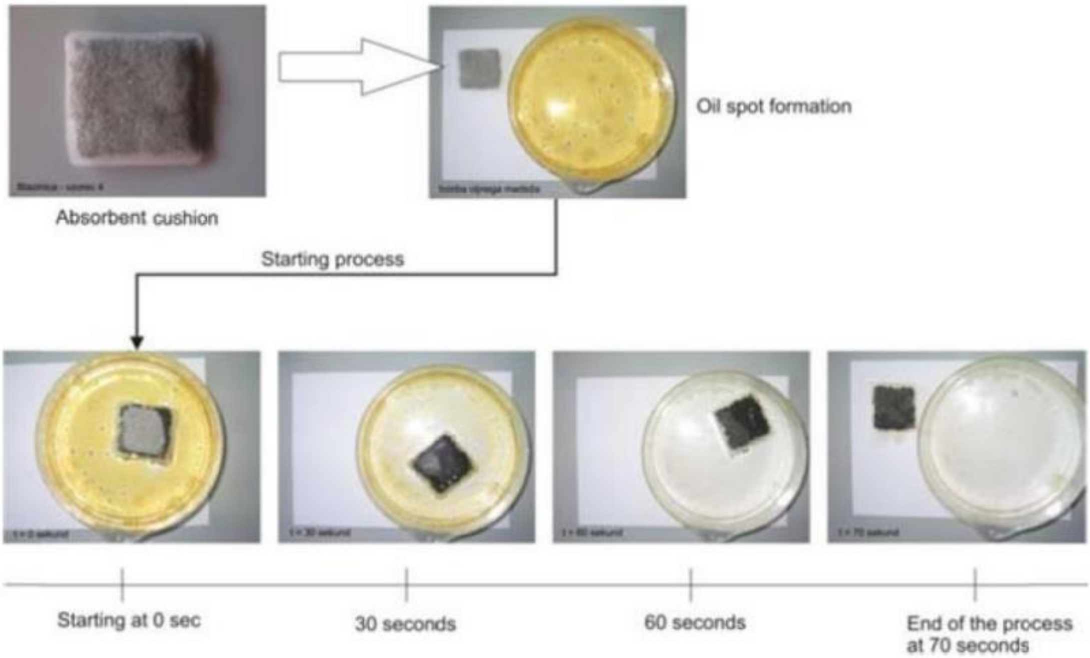

Figure 1. Demonstration of the CAPSorb absorbing material's capacity to remove oil from the surface of water (Source: TEC)

Technology Readiness Level: Both types of absorbent products mentioned here are already available on the market.

Experiences in the Paper and Board industry: Examples of animal bedding production from PBI sludges include Sappi Maastricht (the Netherlands) and Syracuse Fiber Recycling (USA), which collects sludge from various paper mills in the state of New York (e.g. SCA Tissue South Glenn Falls). Kadant GranTek (USA), on the other hand, is using PBI sludge for the production of its Gran-sorb absorbent for oil and other liquids.

Literature/websites:

http://www.gran-sorb.net/

http://www.toc.si/caps/

http://www.saratogian.com/article/ST/20131014/NEWS/131019773

http://www.sappi.com/group/Sustainability/2013%20Sappi%20Fine%20Paper%20Europe%20Sustainability%20Report.pdf

Title: Building materials production

Raw material type: Depending on the specific application, it can be a route suitable for the valorisation of PBI sludges, but also of fine rejects or even fly ash from sludge incineration installations.

Short description: Side streams of the PBI can be used for the production of materials with applications within the construction sector. Specific materials that have been explored, or where PBI side streams are already applied, include cement, concrete, bricks, as well as various types of panels.

Intermediate and end products: The end product varies depending on the specific application within the building materials' route, while no intermediate products are generated.

Process: For the production of bricks PBI sludge can simply be mixed with the clay that serves as the main raw material. Sludge addition of about 15% has been found to be acceptable for industrial production. It has been suggested that sludge could serve as a pore-forming agent in the production of insulating firebricks. These pores drastically reduce a brick's thermal conductivity, making it useful for both industrial applications and the realisation of energy savings in buildings.

In cement production PBI sludge is utilised for both its caloric value and as a raw material. The sludge can be dried with the use of waste heat available in the cement mill and subsequently added to the cement kiln; fibres are incinerated, acting as an additional fuel in the process, while the inorganic ash is a compound of the cement clinker produced. Some more potential applications have been proposed besides this already applied option. PBI sludge could be converted by means of calcination, a form of thermal treatment, into highly reactive metakaolin to be used as an additive in cement. Another possibility could be the production of sludge-cement composites for lightweight board applications (e.g. roofs, ceilings, etc.).

An interesting potential application of paper sludge ash that has been recently described in literature focuses on the side stream's conversion to a super-hydrophobic powder by means of simple, low-cost, surface functionalisation. A partial substitution of cement in concrete by this new material could improve overall concrete durability by increasing its resistance to water-induced deterioration processes.

An example of the possible applications of PBI side streams in the production of various types of panels for the construction sector is the case of gypsum fibreboard. Cellulose fibres from PfR (unused newsprint) are mixed with gypsum and water for the formation of a "mat". After dewatering by means of vacuum and pressing the board is cut to size and the moisture content is further reduced using dryers. PBI side streams (sludge and fine rejects) could serve here as sources of fibre to substitute PfR. Recent research has also focused on the use of PBI side streams for the partial (up to 20%) replacement of wood fibre in the production of MDF and hardboard.

Benefits and Drawbacks: The valorisation of PBI side streams via the production of materials for the construction sector entails a useful application of these streams, as well as the potential to induce virgin raw material and/or energy savings, depending on the application, in the production of the aforementioned products. Current experiences with such valorisation routes, however, indicate that the economic potential for the PBI is limited, as the side stream owner still needs to pay a gate fee to, for example, the cement mill for accepting material.

Technology Readiness Level: Depending on the specific application within the broader construction materials theme, technology readiness levels can vary. Some options, such as the production of cement and bricks, have been commercial for a long time, others, such as various types of panels, have been successfully demonstrated on pilot scale trials, while possibilities such as the super-hydrophobic powder from incineration ash are still at a research phase.

Experiences in the Paper and Board industry: The production of cement and bricks using PBI side streams has been widely applied for several years. In the field of panel production, the German company Fermacell has recently been evaluating samples of PBI side streams to identify the right materials to substitute PfR in gypsum fibreboard production.

Literature/websites:

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Wong HS, Barakat R, Alhilali A, Saleh M, Cheeseman CR. Hydrophobic concrete using waste paper sludge ash, Cement and Concrete Research, 70, pp. 9-20, 2015

Title: Wood-plastic composites production

Raw material type: Potentially suitable for most types of PBI side streams (deinking and primary wastewater treatment sludges, fine rejects, fly ash from sludge incineration facilities). The characteristics of the side stream used, however, will have a strong influence on the composite's quality and, therefore, its potential applications.

Short description: Side streams of the PBI can be used in the production of Wood-Plastic Composites (WPCs). As the name denotes, WPCs are composites made of wood fibres, usually in the form of wood flour, and thermoplastic materials such as PE, PP, PVC, etc. Depending on the nature of the side stream to be valorised via this route, it can either constitute a cheap filler that partially substitutes more expensive raw materials or it can improve the composite's properties, e.g. by having a reinforcing effect.

Intermediate and end products: The intermediate product of side stream valorisation via WPCs production is granules of the composite material, which can be subsequently used for the production of the selected end products by means of injection moulding, profile extrusion etc. A wide array of end products is possible, depending on the characteristics of the composite.

Process: The first step in the production of WPCs from PBI side streams is the drying of the side streams, as the dry matter content of the input material needs to be high (around 90%). Given the need to remove most of the moisture, evaporation drying is likely to be necessary. The dried side stream is subsequently compounded at a given ratio with the selected thermoplastic material, and possibly also some chemical additives, such as colourants and coupling agents, for the production of the WPC granules.

Benefits and Drawbacks: The WPCs market has been showing strong growth lately, with the European market having been forecast to grow from 220,000 tonnes in 2010 to 350,000 tonnes at the end of 2015. Many applications of these materials are found within the building sector, ranging from door and window frames to decking and tiles, and from wall siding to fences. Other applications can be found, as an indication, in furniture and the automotive sector. It should be mentioned that each of these products may need to adhere to a certain set of regulations, which will need to be scrutinised in order to determine the compliance of the proposed side stream-incorporating new product.

Given that many of the applications of WPCs are found in items that need to be also aesthetically pleasing, a potential drawback of side stream use may be the possibility of altering the appearance of the end product. This needs to be investigated for each proposed combination of a side stream with an intended end product. A path with lower barriers may be found in the form of products in which only practical characteristics are of concern. An example thereof is transportation pallets, which, if made with the use of side stream-incorporating WPCs, could help paper producers apply within their own supply chains items produced via the valorisation of their own side streams.

The need to dry the side streams in order to be usable in WPCs production is a drawback but, depending on the local situation, some paper mills may be able to apply waste heat already available on their sites.

Technology Readiness Level: WPCs production is already commercial and utilises long-established processes. The incorporation of PBI side streams will not require the development of new technologies but rather extensive testing in order to determine whether a specific side stream is applicable for the production of a specific product.

Experiences in the Paper and Board industry: The only existing application of the WPCs route for the valorisation of PBI side streams so far has been the use of waste from adhesive label production by UPM for the production of the UPM ProFi WPCs.

Figure 2. Outdoor decking constructed with UPM ProFi WPC material (Source: UPM)

Literature/websites:

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Huang HB, Du HH, Wang WH, Shi JY. Characteristics of paper mill sludge-wood fiber-High-Density Polyethylene composites, Polymer Composites, 33, pp. 1628-1634, 2012

Soucy J, Koubaa A, Migneault S, Riedl B. The potential of paper mill sludge for wood–plastic composites, Industrial Crops and Products, 54, pp. 248-256, 2014

Title: Fractionation
Raw material type: Suitable for deinking and primary wastewater treatment sludges; application to the main pulp stream during the paper and board production process can also be considered.
Short description: The concept of fractionation can be defined for the purposes of this report as the separation of one or more fractions from a specific stream, either of "waste" material or pulp, based on the specific characteristics of each fraction's components. When fractionation is applied at side stream level it could provide fractions that are reusable within the paper and board production process, as well as fractions that are more attractive than the original material for external applications. Pulp fractionation, on the other hand, can produce pulp streams that will be subjected to different forms or varying degrees of processing (e.g. selective refining) based on their fibre characteristics, as well as fractions that are unusable by the paper mill (e.g. ash).
Intermediate and end products: The products of a fractionation process may depend on the wishes of the party implementing it. In the case of side stream fractionation one could opt for an organic (fibres, fines) and an inorganic (mineral fillers) fraction, or could move beyond this level by also producing separate fibre and fines fractions.
Process: The specifics of a fractionation process can vary depending on what the intended outcome is. A filler reclamation system (ECO plant) from effluent treatment sludge operating at Stora Enso Oulu can be used here as an example. A wire washer is used for separating the recoverable inorganic material from fibres and other rejects; this material is subsequently subjected to centrifugal cleaning for the removal of impurities (e.g. dirt). The reclaimed fillers are chemically treated for a slight brightness increase and dosed to the paper machines, while the rejects of the process are thickened and, after being mixed with bark, combusted in a solid fuel boiler. Another example is the concept proposed by Kadant for sludge fractionation into fibres, bonding fines, non-bonding fines and ash. Here a fibre fraction is generated first from a sludge stream by means of screening. In the next step flotation is applied for separating ash from fines. The fines are then split into a bonding fines and a non-bonding fines fraction by means of hydrocyclones.

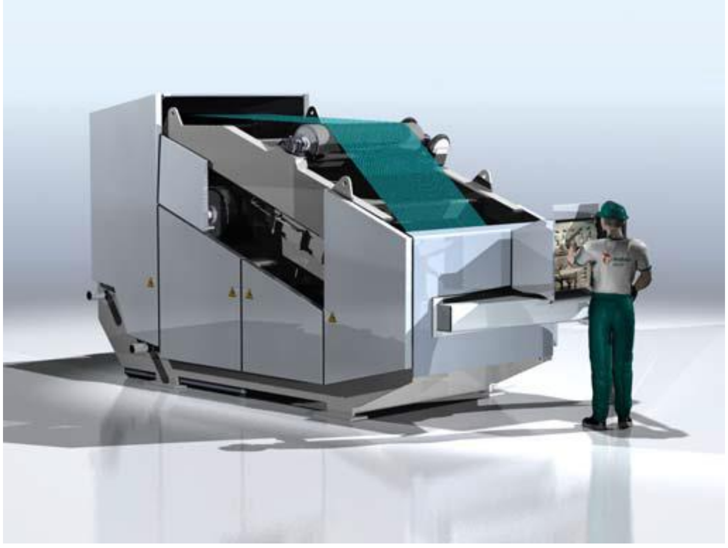

Figure 3. Wire washer used for filler reclamation at the ECO plant (source: Jortama, 2003)

Benefits and Drawbacks: Applying fractionation concepts in practice can entail several benefits for the PBI. First of all, a fuller utilisation of the purchased raw material can be achieved by reclaiming perfectly good fibres that were lost during their first pass through the production process. An indicative example of the potential in this area is offered by the application on a laboratory scale of the Kadant fractionation concept on deinking sludge from tissue production; it was found that about 20% of the feed consisted of recoverable long fibres. A further 10-15% of the feed consisted of recoverable fines with good bonding potential that are considered able to improve strength properties of the paper product when returned to the production process. Such reclaimed fractions can either be utilised by the same paper mill that produced the original side stream or offered to neighbouring paper producers. Besides this possible internal utilisation of reclaimed fractions fractionation could also be a step towards the realisation of more extended circular economy cases with the participation of parties from other sectors. Being able to separate the organic and inorganic fractions of a side stream could make both of them much more attractive for actors interested in having one fraction without the other (e.g. for green chemicals production from cellulosic side streams or for the neutralisation of acid side streams by means of affordable calcium carbonate). It is therefore possible that fractionation could play an important role in moving from a situation where a paper mill is paying high gate fees so as to have its sludge incinerated by a third party to a situation where fractions of this sludge can find their own best possible applications (within and outside the PBI), while reducing the operating costs of the mill or even constituting new sources of income.

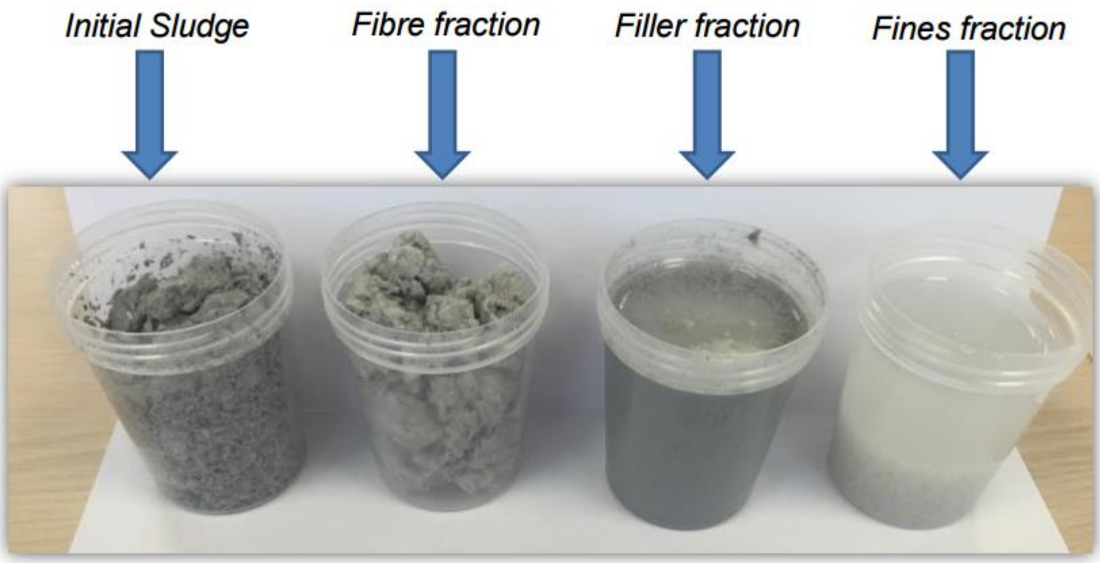

Figure 4. Fractions (produced on laboratory scale) of deinking sludge from a tissue producer (source: Kadant)

If fractionation is applied as part of the stock preparation for treating all or part of the pulp stream, instead of as an end-of-pipe solution, it could, as well as having the aforementioned benefits, make the targeted treatment of specific fractions possible (e.g. refining of only one raw material fraction), thus improving both overall pulp quality and the energy and/or resource efficiency of the production process. Given that this report is focused on side stream valorisation opportunities, these possibilities will not be further analysed here.

Technology Readiness Level: Known fractionation concepts, such as the aforementioned Kadant system or the ECO plant, make use of equipment whose utilisation is widespread within the PBI (e.g. wire washers, hydrocyclones, flotation cells, etc.). The critical step here is not, therefore, developing new equipment but combining existing tools in the right way for the task at hand.

Experiences in the Paper and Board industry: It has already been mentioned that Stora Enso Oulu has applied in practice the ECO plant for filler reclamation and reuse. Another filler recovery system (Trenntechnik) has also been operated at a former Stora Enso mill (Uetersen, now Feldmuehle Uetersen).

Literature/websites:

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Title: Hydrolysis to fermentation feedstock

Raw material type: Deinking sludge, primary wastewater treatment sludge.

Short description: Cellulose-containing side streams of the PBI have been receiving attention as a potential feedstock for enzymatic hydrolysis in order to produce fermentation sugars, to be subsequently converted into green fuels or energy.

Intermediate and end products: Depending on the type of process applied (see Process below), cellulose can be converted into sugars as an intermediate product, or directly converted into the end product. The potential end products from the conversion of PBI side streams that have received the most attention are ethanol and lactic acid, but a much wider range of chemicals can be produced via fermentation processes, including propionic acid, 1,3-propanediol, 3-hydroxypropionic acid, succinic acid, 2,3-butanediol, butyric acid, butanol, etc.

Process: The enzymatic hydrolysis of cellulose refers to the breaking down of cellulose chains into glucose molecules by cellulase enzymes, while fermentation is a metabolic process that converts sugars into acids, alcohols or gases. Two options are available with regard to carrying these out, namely Separate Hydrolysis and Fermentation (SHF), where the two processes occur sequentially in separate reactors, and Simultaneous Saccharification and Fermentation (SSF), where the two processes take place simultaneously within one reactor. In general, SSF is considered to be beneficial in terms of process integration, as only one tank is required, and of shorter residence times, while SHF offers the optimal process conditions for each step.

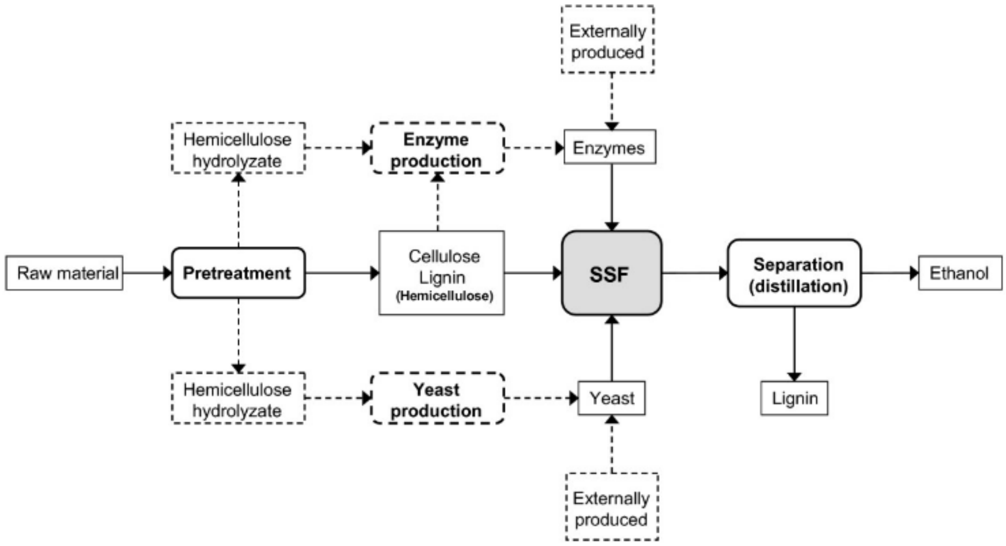

Figure 5. Schematic representation of an SSF process

Sludge fractionation could offer certain advantages when implemented as a pre-treatment method before an enzymatic hydrolysis process. Calcium carbonate in PBI sludges adsorbs enzymes with a higher affinity than cellulosic fibres, thus limiting saccharification efficiency, while the removal of inorganics can also help reduce the reactor sizes required, thus lowering the investment costs. Besides fractionation, other proposed additional steps are aimed at reducing enzyme dosages, and thus overall process costs, and include the addition of cationic polyelectrolytes in order to promote enzyme binding to cellulose, as well as pre-treatment of the sludge with hydrogen peroxide in order to increase enzymatic digestibility by dissolving lignin and exposing (hemi)cellulose to enzyme attack.

Benefits and Drawbacks: The conversion of PBI side streams to fermentation feedstock by means of enzymatic hydrolysis has the potential of being a major step towards the closer integration of the sector into the emerging Biobased Economy. Many of these fermentation products already have well established markets or are expected to become increasingly important in the future, especially when the currently used petrochemical-based raw materials can be replaced by biomass.

PBI side streams are considered to have several upsides as sources of cellulose for hydrolysis. They are concentrated in significant volumes and at low cost in permanent sites, which already have utilities and infrastructure that could be used for the proposed processes. Cellulose fibres in PBI side streams have already been extensively treated (mechanically, chemically) and thus are much more accessible to enzymes than “raw” lignocellulose sources; this has the potential to reduce enzyme use during hydrolysis, with the cost of enzymes being a very significant factor in overall hydrolysis economics. SSF can also be focused on the most easily accessible polysaccharides, with the residue of the process being anaerobically digested into biogas, thus allowing the production of both chemicals and energy with reduced residence times for the hydrolysis process.

Technology Readiness Level: Known research on the production of fermentation feedstock from PBI side streams is still on a laboratory scale. To the best of our knowledge no further upscaling has taken place so far.

Experiences in the Paper and Board industry: None yet.

Literature/websites:

Marques S, Santos JAL, GÍrio FM, Roseiro JC. Lactic acid production from recycled paper sludge by simultaneous saccharification and fermentation, Biochemical Engineering Journal, 41, pp. 210-216, 2008

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Chen H, Han Q, Daniel K, Venditti R, Jameel H. Conversion of industrial paper sludge to ethanol: Fractionation of sludge and its impact, Applied Biochemistry and Biotechnology, 174, pp. 2096-2113, 2014

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Title: Nanocellulose production

Raw material type: Suitable for deinking and primary wastewater treatment sludges; a low lignin content is required.

Short description: The Israeli company Melodea has been working on the production of nanocrystalline cellulose (NCC), with PBI side streams serving as the feedstock for an acid hydrolysis process. Besides the potential of this route as a side stream valorisation option, NCC could become an additive in paper production to improve certain product properties.

Intermediate and end products: NCC is the end product of the acid hydrolysis production process, without any intermediate products.

Process: Nanocrystalline cellulose, also known as cellulose nanocrystals or nanowhiskers, is produced by means of acid hydrolysis of cellulose fibres, usually with sulfuric acid. The amorphous regions of cellulose are preferentially hydrolysed, while the crystalline regions are more resistant to acid attack. Washing and centrifugation steps are part of the production process, separating cellulose sediment from the liquid phase, while mechanical treatment (e.g. sonication) is applied in order to disperse the obtained nanocrystals as a uniform stable suspension. Melodea has also developed technology that allows it to recover most of the acid used for the hydrolysis in order to repeatedly reuse it.

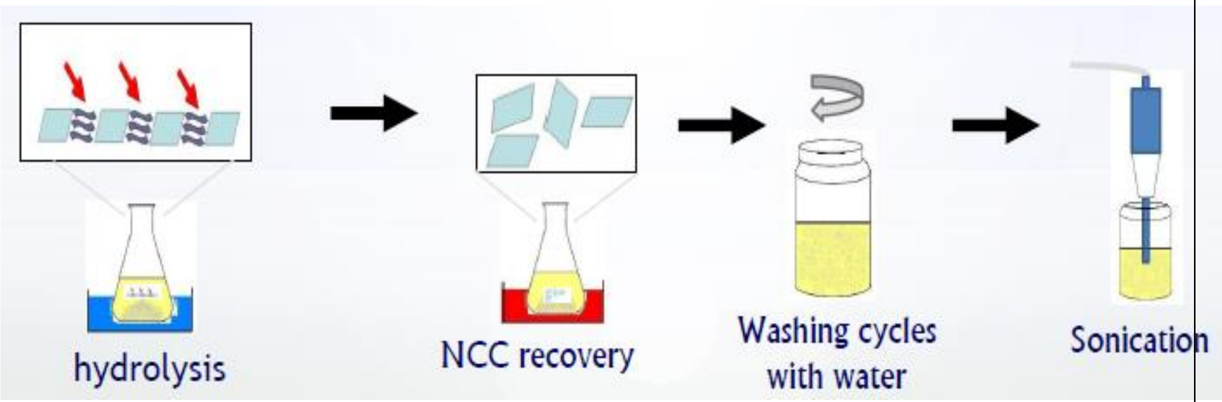

Figure 6. Main steps of the NCC production process (source: Melodea)

Benefits and Drawbacks: This route offers the possibility to valorise current side streams by converting them into high-value products. The produced NCC is a material with a multitude of potential applications within various sectors and could therefore become a significant source of income for the side stream-generating paper mill. Some of the examined NCC applications include the following:

- Transparent gas barrier coating for packaging materials, e.g. substituting aluminium in food packaging
- Anti-friction coating
- Foams for sandwich composites
- Foams for insulation materials
- Additive in various materials and products (e.g. cement, acrylic glues, paints, thermoplastics, etc.) to improve properties such as adhesiveness, scratch resistance, tensile strength, erosion resistance, bonding, etc.

Figure 7. NCC foam panels (source: Melodea)

Of additional interest to the paper sector is the potential of NCC's use as an additive in paper and board production. Paper sizing with the use of starch/NCC mixtures is an example of such an application currently under evaluation so as to determine whether this could result in reduced starch use and/or the production of paper products with improved performance. Although still some way from realisation in practice, it is conceivable that in the future it may be possible for the paper industry to convert its side streams into additives of value for its own production processes and products.

One drawback of this valorisation route is its requirements with regard to the properties of the side streams that can be considered promising feedstocks for the economically viable production of NCC. These requirements may cover parametres such as the fibre and lignin contents of the input material. The absence of a sufficiently developed nanocellulose market is also an issue for now, but nanocellulose is seen as a material with a huge potential for the coming years.

Technology Readiness Level: The first demonstration plant making use of Melodea's process for the production of NCC from bleached pulp will become operational within 2016. The plant is located in Sweden and has a capacity of 100 kg NCC per day.

Experiences in the Paper and Board industry: So far there are no cases of commercial production of NCC from PBI side streams or of commercial use of NCC in paper production. It should, however, be mentioned that Holmen is an investor in Melodea.

Literature/websites:

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Brinchi L, Cotana F, Fortunati E, Kenny JM. Production of nanocrystalline cellulose from lignocellulosic biomass: Technology and applications, Carbohydrate Polymers, 94, pp. 154-169, 2013

Title: Polyhydroxyalkanoates production

Raw material type: Process water and secondary wastewater treatment sludge.

Short description: An alternative to traditional wastewater treatment technology is offered in the form of utilising the organic content of the water as food for polyhydroxyalkanoates (PHAs)-accumulating microorganisms. The term PHAs refers to a family of polyesters that serve as carbon and energy storage units within certain microorganisms and which also have considerable potential as a bioplastic material.

Intermediate and end products: The intermediate product of a wastewater treatment plant that aims at producing PHAs will be PHAs-enriched biomass; the PHAs must be extracted from the biomass at a subsequent step and constitute the end product in the case of this route. The discarded biomass after the extraction of the PHAs can be seen as a secondary product, e.g. as a source of nutrients.

Process: A wastewater treatment plant geared towards the production of PHAs will need to perform two functions:

- Cultivation, which refers to selecting PHAs-producing microorganisms from the bacterial flora present, and
- Accumulation, where the previously selected microorganisms are fed until maximising the PHAs content in their cells

Both of these functions, which can be performed in two separate steps or combined into one, simultaneously serve to treat the wastewater treatment plant's influent. If the process is carried out in separate phases, then in the first phase selective pressure is applied on the microbial culture in the form of alternating periods of short presence of a carbon substrate (feast) and long absence of the carbon substrate (famine) under fully aerobic conditions; PHAs-storing bacteria generally outcompete other bacteria in such a feast-famine regime. The cultures that are enriched with PHAs-accumulating microorganisms in the first step are used in the second step in order to produce PHAs. For this purpose they are supplied with an excess of substrate while simultaneously withholding other nutrients so as to inhibit growth and direct as much carbon as possible towards PHAs storage. It must be noted that these two steps may in some cases be preceded by a pre-treatment of the raw material by means of acidogenic fermentation. As Volatile Fatty Acids (VFAs) are readily utilised by many species of bacteria as a substrate for the synthesis of PHAs, the fermentation degree of an influent is an important parametre to be evaluated in order to determine whether this pre-treatment step is necessary in any given case. When carried out, this fermentation pre-treatment can have an additional function by influencing the ratios between the different VFAs types that will form the substrate; this "engineering" of the substrate can in turn offer some degree of control over the composition of the produced PHAs co-polymers and thus some control over the material properties of the end product itself.

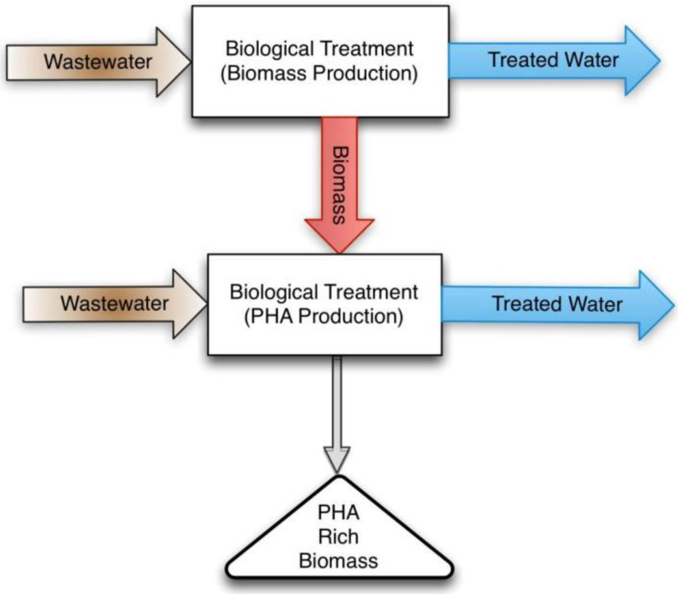

Figure 8. Two-step PHAs production from wastewater (Source: AnoxKaldnes)

The same principles can also be applied when the secondary sludge of a wastewater treatment plant is valorised via the production of PHAs. In this case the sludge is hydrolysed for the production of VFAs, which are subsequently fed as substrate to the selected PHAs-accumulating microorganisms.

The polymer stored within the microorganisms still needs to be extracted before it can be further processed. Various extraction methods aimed at breaking down the cell walls exist, including mechanical processes (e.g. centrifugation), chemical processes (e.g. organic solvents, acids, bases) and biological processes (e.g. enzymes).

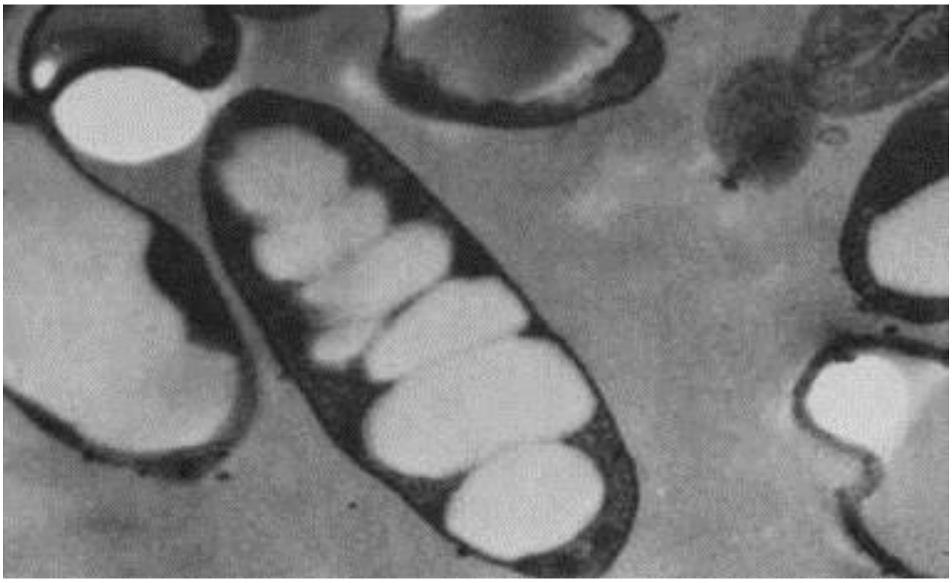

Figure 9. PHAs stored inside bacteria

Benefits and Drawbacks: The benefits of applying the PHAs production technology for the treatment of a paper mill's process water depend on the choices made with regard to the business model implemented. Three main possibilities can be distinguished here:

- "*Buy and Operate*" model; a paper mill invests in and operates a PHAs-producing wastewater treatment installation. A completely new business is added to the mill's activities, entailing the production of PHAs-enriched biomass, as the extraction of the biopolymer is a process that, in order to be economically feasible, needs to be carried out at a scale larger than the amount of material available even within a large paper mill. The enriched biomass can therefore be supplied to centralised extraction facilities that collect material from several neighbouring producers

- "*Outsource*" model; a third party invests in a PHAs-producing wastewater treatment installation on the site of the paper mill and is also responsible for the subsequent steps (extraction, sales)

- "*COD supplier*" model; the paper mill offers its process water to a third party as a feedstock for PHAs production and thus acts as a COD supplier

Based on the scenario selected, the paper mill can benefit in the following ways:

- Creating a new source of income, either in the form of enriched biomass ("Buy and Operate" model) or in the form of COD in its process water ("COD supplier" model); COD in process water is thus converted from a cost factor to a source of additional profits

- Creating the conditions for closing the internal water loop, a possibility present in all three scenarios. Up to now, paper mills that wish to reuse their process water are faced with problems of smell, slime formation, etc. due to the increased biological activity in water with high COD loads. This creates problems in the process and the working environment and entails significant costs for biocides intended to control this biological activity. Adding a PHAs-producing "bio-kidney" to the mill's water loop can deliver clean water back to the production process, while eliminating all problems associated with a closed water loop, and offer a new product/source of income

The main drawback associated with this valorisation route is the currently low level of development of a PHAs market. The industrial production of PHAs is based exclusively on the utilisation of pure microbial cultures of genetically modified microorganisms or natural PHAs producers, which require a sterile environment, for the conversion of the selected raw materials in order to maintain good control over the process and the end product. Given the very specific requirements that must be met (sugar or glucose as feedstock, pure cultures, sterile environment, axenic reactors, etc.), the production costs are high, which has an adverse effect on the product price and on the competitiveness of these biopolymers. Moving towards production on the basis of mixed microbial cultures that utilise side streams as feedstock can immensely improve the competitiveness of PHAs but this is a gradual process that will require a number of years before leading to a fully developed PHAs market and value chain. One option in the meantime could be to apply the technology as a "bio-kidney" in order to reap the benefits of a closed water loop, while finding stop-gap applications for the enriched biomass (e.g. internal use in paper production).

A further potential benefit of the PHAs route could be their possible utilisation as a raw material for the PBI, thus potentially making circular patterns possible, with the sector producing PHAs from its side streams and then using them internally in its production process. Some work has been carried out with regard to the improvement of barrier properties (against oxygen, water and oil) by means of PHB coating with encouraging results. Research has been aimed towards the use of PHAs dispersions as binders for pigment coatings that improve smoothness, optical properties and printability, replacing non-biobased polymers. At a commercial level, Metabolix is working on PHAs latex coatings (e.g. for coffee cups, but also for wax-coated board boxes for transporting wet produce) that will replace non-biodegradable polymers, thus ensuring the repulpability of the paper product. Besides applications under research or development, Shenzhen Ecomann already offers commercially a PHAs compound for extrusion coating of paper products. This product serves as an example of an advantage of PHAs over PE in terms of processing parametres. Polyethylene resin, namely, requires a much higher temperature (around 300 °C) for extrusion coating of paper compared to PHAs resin (165-175 °C). When working with heat-sensitive additives, such as active compounds added to novel packaging systems, this can be an important issue. The main attraction of PHAs as a component for paper coatings is of course their biodegradability, which ensures full recyclability of the end product as well as opportunities for the marketing of paper products as being completely “green”. More research and development work is, however, still needed in this field.

Technology Readiness Level: Pilot scale installations for PHAs production out of wastewater or secondary sludge have been operational within various sectors, including municipal wastewater treatment, the food industry and the paper industry.

Experiences in the Paper and Board industry: The Dutch paper industry has been a front-runner in evaluating the potential of PHAs production as a process water valorisation route. DS Smith Paper De Hoop, Eska and Smurfit Kappa Roermond Papier have cooperated with AnoxKaldnes (subsidiary of Veolia Water Technologies) in evaluating on laboratory scale the potential of their process waters as PHAs sources, while Eska has served as the site for a pilot-scale installation developed by the Technical University of Delft and Paques.

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Manandhar S, Dagnon K, D’Souza N. A Study of mechanical properties of polyhydroxyalkanoates (PHAs) coated on kraft paper, paper presented at the 37th Annual Conference of the North American Thermal Analysis Society (NATAS), Lubbock, 2009

Title: Alginates production

Raw material type: Process water.

Short description: A new aerobic wastewater treatment technology, Nereda, has been developed in the Netherlands, substituting conventional activated sludge with aerobic granular sludge. The new process offers several improvements as a water treatment technology for municipal and industrial facilities, while producing alginate-like exopolysaccharides (ALE) as a by-product that could have applications, among others, within the PBI.

Intermediate and end products: ALE is the by-product of the Nereda wastewater treatment process; the granular sludge containing the ALE could be viewed as an intermediate product if applications for it without the extraction of the ALE can be found.

Process: The characteristic that separates the Nereda wastewater treatment process from conventional aerobic activated sludge treatment is the formation of sludge granules instead of flocs. Granular sludge has certain advantages compared to activated sludge flocs, such as improved settling and the formation of a structured matrix for biomass growth; this contains spheres with anaerobic, aerobic and anoxic conditions, which are populated by different microorganisms including phosphate accumulating organisms (PAO), nitrifiers, denitrifiers and glycogen accumulating organisms (GAO). This allows for a simultaneous execution of the processes required for nutrient removal and provides the foundation for a simple process with minimal space requirements.

Nereda uses an optimised sequencing batch reactor (SBR) cycle in which the four steps of a typical SBR cycle are reduced to three:

1. Simultaneous fill/draw; during this stage the wastewater is pumped into the reactor and at the same time the effluent is drawn
2. Aeration; biological conversion takes place during the aeration phase. The outer layer of the granules is aerobic and accumulates nitrifying bacteria. This forms nitrate that is then denitrified in the anoxic core of the granules. Phosphorous uptake occurs in the final step
3. Sedimentation; following the biological processes, a sedimentation phase separates the clear effluent from the sludge. The time for phase separation is short due to the settling properties of the granular sludge. The system is then ready for a new cycle

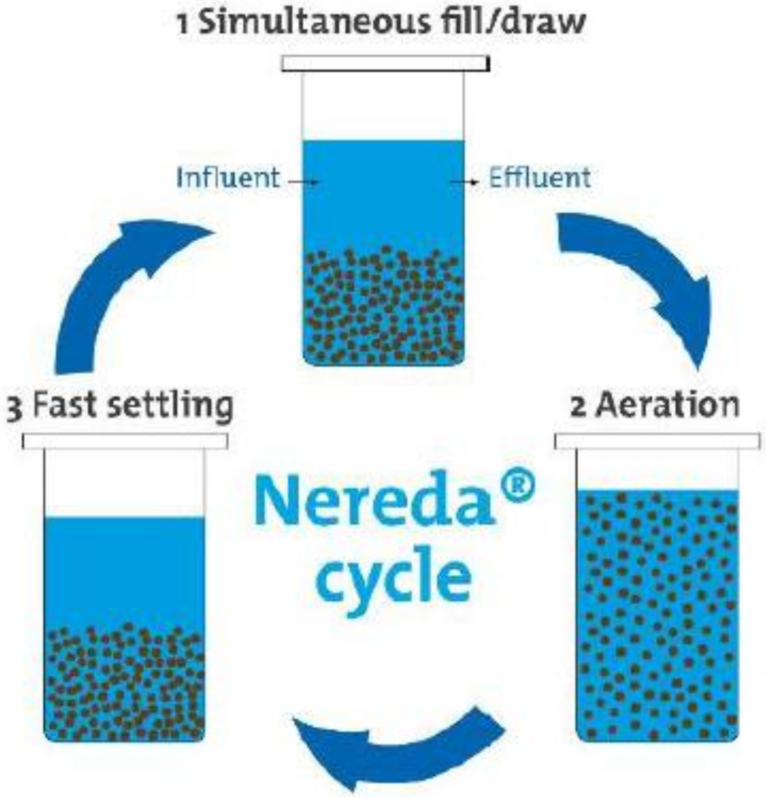

Figure 10. The 3-step Nereda wastewater treatment process (source: Royal HaskoningDHV)

The granular sludge of the Nereda process contains 15-25% ALE, which can be extracted by means of technologies currently utilised for alginate extraction from seaweed. Besides being a valuable by-product in itself, the extraction of the ALE reduces excess sludge volumes and improves the dewatering and digestibility of the remaining excess sludge. As a rule of thumb, 2.5 kg of ALE per person-equivalent per year can be produced at a Nereda wastewater treatment plant, which means that a 400,000 person-equivalent plant could produce 1,000 tonnes of ALE annually.

Benefits and Drawbacks: The benefits of implementing the Nereda technology can be divided into two categories; the benefits generated when the technology is judged purely on its wastewater treatment merits, and those stemming from the extraction and further valorisation of ALE in granular sludge.

As a wastewater treatment option, Nereda offers a range of benefits compared to conventional aerobic installations. These include the following:

- Lower operational costs; less mechanical equipment (e.g. pumping stations) is needed due to the simplicity of the process, thus reducing energy consumption by 25-35%. Costs for process chemicals are also much lower
- Lower initial investment; again due to the need for less mechanical equipment, but also due to reduced tank volumes as a result of the more concentrated biomass

- Lower space requirements; Nereda treatment plants can be up to 75% smaller than conventional installations due to operations being concentrated in a single tank and the redundancy of a large part of the conventional mechanical equipment

It should be mentioned that applying the Nereda technology is possible in both completely new treatment plants and when retrofitting existing facilities; in the latter case, the retrofit can lead to increased plant capacity and/or improved effluent quality. Furthermore, it is possible to use "hybrid" systems, where the Nereda process cooperates with conventional aerobic treatment. In this case part of the influent is treated by each technology and the surplus granular sludge can be used for the inoculation of the aerobic activated sludge in order to improve its performance and settling characteristics.

When the scope of Nereda is extended to being seen as a process water valorisation technology, the extraction of value from the content of the process water in the form of an ALE product becomes its added benefit. This content has so far been mostly removed, in order to comply with effluent regulations, but often without a useful application, the most notable exception being the production of biogas in anaerobic wastewater treatment installations. The Nereda process offers an alternative to this. ALE is considered as a product with possible applications in the textile sector, where alginates are already in use, in agriculture and land management, while new outlets are also being considered (e.g. bioplastics). Even more significant for the PBI, however, is the potential use of ALE within its own production processes, primarily as a biobased sizing agent. Work in this direction is ongoing and is based on the use of alginates from seaweed as an additive by the Asian paper industry. A circular pattern, where the PBI can produce a material necessary for its own processes from its own side streams, is therefore a conceivable possibility for the future, depending on the outcome of ongoing research into ALE application.

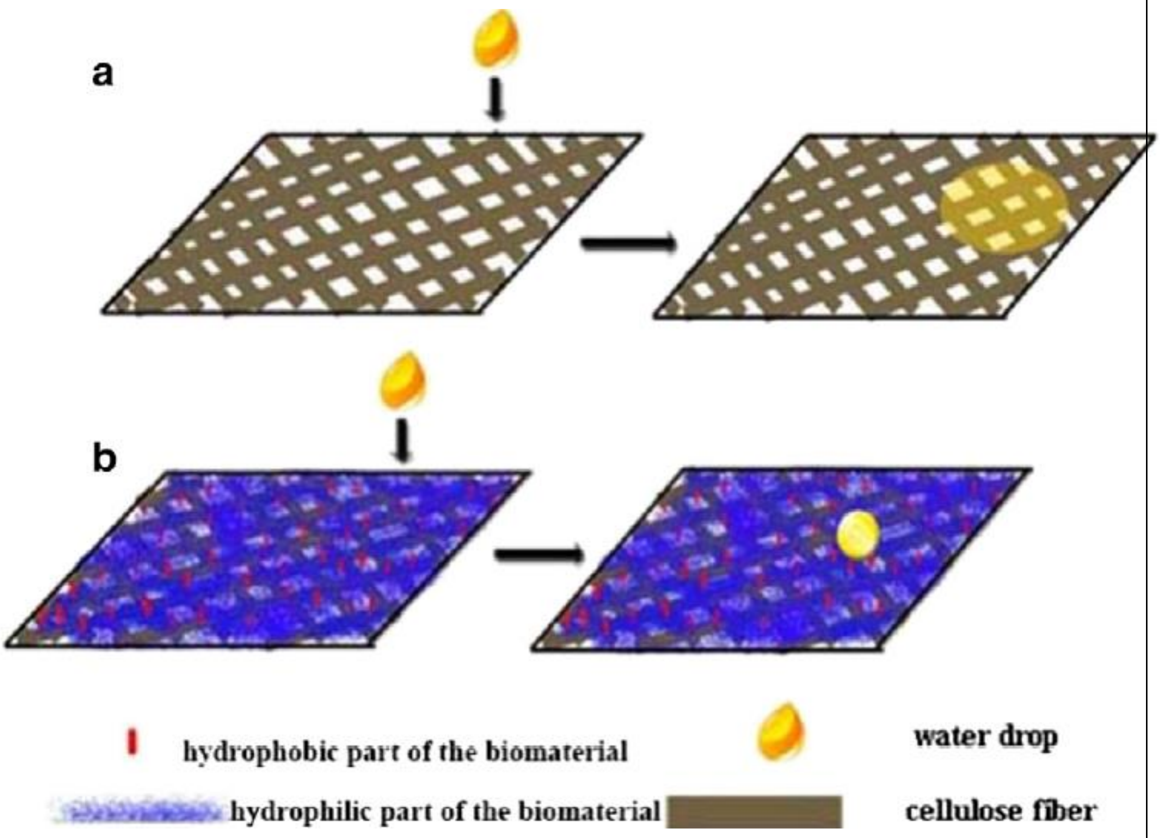

Figure 11. The water barrier effect of ALE on cellulosic fibres; a: Cellulosic fibre networks are porous and water easily penetrates them; b: ALE forms a film on the cellulosic fibre network, with hydrophobic groups repulsing water droplets (source: Lin et al., 2015)

Technology Readiness Level: Nereda is already operational in several installations worldwide, primarily in municipal wastewater treatment facilities. For industrial users its references are limited to the food sector, but the technology has been tested successfully on paper industry process water at pilot scale and no significant challenges are expected regarding its full-size application (see also retrofitting and “hybrid” scenarios above). The first ALE extraction installation, with an annual capacity of 150-200 tonnes, is planned for 2017, while research on ALE applications (including within the PBI) is ongoing.

Experiences in the Paper and Board industry: So far there are no cases of commercial Nereda installations within the PBI or of commercial application of ALE within the sector. Alginates from seaweed, however, are already used by the PBI; an example is the Scogin alginate product of the US chemicals producer FMC BioPolymer, which is applied in surface sizing and coating.

Literature/websites:

http://www.royalhaskoningdhv.com/en-gb/nereda

Lin YM, Nierop KGJ, Girbal-Neuhauser E, Adriaanse M, van Loosdrecht MCM. Sustainable polysaccharide-based biomaterial recovered from waste aerobic granular sludge as a surface coating material, Sustainable Materials and Technologies, 4, pp. 24-29, 2015

Title: Incineration
Raw material type: Suitable for all types of sludges (primary and secondary wastewater treatment sludges, deinking sludge) and for fine rejects.
Short description: Incinerating PBI side streams for the generation of steam and electricity has become one of the most commonly applied side stream disposal methods in Europe despite the fact that the high moisture and ash contents of PBI sludges are unfavourable for this process. The utilisation of fluidised bed technology has been beneficial due to the ability of such combustors to better handle high ash and moisture streams.
Intermediate and end products: Steam as an intermediate product when the goal is electricity generation or as an end product when used internally by the paper mill, and electricity as an end product by utilising the generated steam.
Process: In a typical setup in a paper mill environment, the sludge after some pre-treatment (if necessary, e.g. pressing for dewatering/increasing the solids content, mixing of different sludge types or of sludge with other materials, etc.) is fed to a fluidised bed combustor. This usually consists of a cylindrical refractory-lined vessel, where the fluidising air is introduced and uniformly dispersed. The sludge burns on a fluidised bed of inert material (e.g. sand, limestone), while in the upper section of the vessel oxidation of any unburnt organic matter takes place. The conditions within the vessel provide for complete, controlled and uniform combustion and for a significant combustion efficiency improvement, especially for high-moisture fuels. Emissions from fluidised bed combustors are lower than those of other conventional technologies due to the absence of a flame front, the lower and uniformly distributed combustion temperatures and the low amount of excess air within the combustor. High combustion efficiency lowers CO in flue gases and desulphurisation/denitrification processes are available for further reducing the emission of pollutants. The high thermal inertia of the combustor limits temperature fluctuations due to variations of fuel feeding rates and/or heating value and ensures quick start-up after short stoppages. Maintenance requirements are generally reduced owing to the absence of moving parts. Combustor fumes can subsequently pass through a heat recovery steam generator; the generated steam can expand in a steam turbine for electricity generation.
Benefits and Drawbacks: The main benefits of incineration are considered to be energy recovery from PBI side streams and the reduction of waste volumes to be disposed of. Energy recovery can reduce the reliance of the paper mill on other fuels and generate additional income for the company (even in the range of millions of euros annually) by offering electricity to the grid, especially when generous state economic incentives are present. On the other hand, the realisation of an on-site incineration facility requires a high capital investment, still needs disposal or valorisation routes for the remaining ash and must comply to the local air emissions regulations. Furthermore, the very high moisture content of PBI

side streams means that at least dewatering will be necessary in order to facilitate a self-sustaining combustion.

Technology Readiness Level: Various types of incinerators, including fluidised bed ones, have been commercially available for years.

Experiences in the Paper and Board industry: Some examples of on-site side stream incineration include Parenco (the Netherlands), Papierfabrik Utzenstorf (Switzerland), Stora Enso Langerbrugge (Belgium), Metsä Tissue Katrinefors (Sweden) and Mayr-Melnhof Hirschwang (Austria).

Literature/websites:

http://www.siemens.com/press/en/pressrelease/?press=/en/pr_cc/2006/06_jun/02065046_1387997.htm

Caputo AC, Pelagagge PM. Waste-to-energy plant for paper industry sludges disposal: technical-economic study, Journal of Hazardous Materials, B81, pp. 265-283, 2001

Title: Gasification

Raw material type: Suitable for both sludges and rejects.

Short description: Gasification usually involves the partial oxidation of the input material by air, oxygen and/or steam for the production of synthesis gas, which is mainly composed of CO, CO_2, CH_4, H_2O and N_2. This is a more versatile energy carrier than heat and can also serve as a feedstock for the production of chemicals.

Intermediate and end products: Syngas can be seen as an end product, when it is used in internal combustion engines for electricity generation, or as an intermediate that can be converted into other types of fuel via the Fischer-Tropsch process or into chemicals (methane, methanol, dimethyl ether) via catalytic processes.

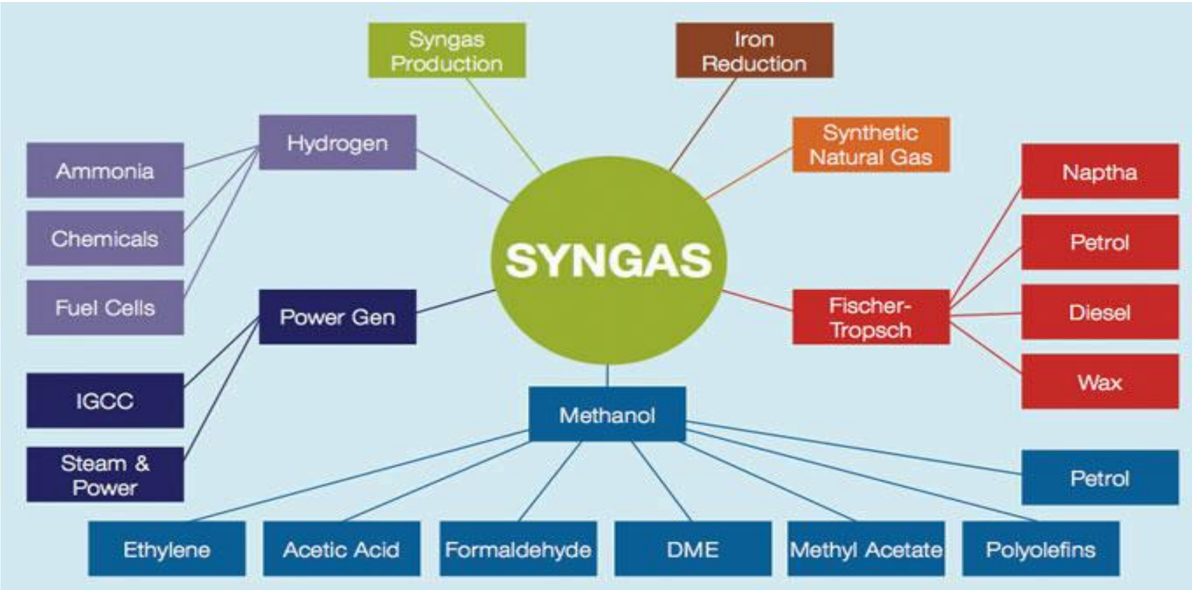

Figure 12. Possible applications of syngas (Source: Waste to Energy Systems)

Process: In a fluidised bed gasifier the feedstock is injected into either a bubbling or circulating bed of sand or a mixture of char and another inorganic heating or catalytic medium (e.g. dolomite). Rapid heating rates achieve gasification temperatures almost instantaneously. The oxidising agent (air, oxygen-enriched air, CO_2, steam or a combination of the above) provides the fluidising medium and participates in the gasification reactions.

In a proposed setup for the gasification of the rejects of a paper mill, the first step has been defined as the pre-treatment of the rejects. This is required in order that the input corresponds to the requirements of the selected gasification technology; in the case of fluidised bed gasifiers, for example, the rejects can be fed as fluff or pellets, but with a size of <30 mm, their moisture content should be <40%, and the presence of heavy inert components (e.g. glass, metal, etc.) should be avoided. The above means that the pre-treatment steps required may entail sieving, magnetic removal of metals, shredding, etc., while drying may or may not be required depending on the local situation. The pre-treated rejects are subsequently fed to the reactor, which has a temperature of about 800 ^{O}C and is also fed with air as an oxidising and fluidising medium. The produced syngas is cooled from about 800 ^{O}C to about 500 ^{O}C, with the reclaimed heat being utilised for hot air supply to the gasifier and for the combustion of the syngas. Ash and particulate matter are removed from the syngas in order to minimise the maintenance needs of the boiler that uses it as fuel, while other impurities (sulfur, chlorine, heavy metals) can be removed from the exhaust gas after the combustion instead of from the fuel itself.

It is doubtful whether the utilisation of syngas can easily take place in a gas turbine without extensive gas cleaning beforehand, which means that (co-)combustion in a steam boiler is an easier solution. Another limiting factor for use in a gas turbine is the lower caloric value of syngas compared to natural gas (5 MJ/m^3 compared to 31 MJ/m^3). The inhomogeneity of the rejects is expected to be problematic with regard to the conversion of syngas to other products (methanol, Fischer-Tropsch fuels).

Benefits and Drawbacks: The main benefits of gasification are considered to be energy recovery from PBI side streams and the reduction of waste volumes to be disposed of. Energy recovery can both reduce the reliance of the paper mill on other fuels, or even generate additional incomes for the company by offering electricity to the grid, especially in countries where generous state economic incentives are available.

On the other hand, an on-site gasification facility requires a high capital investment for its realisation and must comply to the local air emissions regulations. Furthermore, the very specific requirements set by various gasification technologies with regard to the characteristics of the input mean that various forms of pre-treatment will be necessary, depending on the local situation (sludges or rejects, moisture contents, etc.). Pelletisation of the fuel or mixing with other fuels (e.g. wood chips) may also be necessary or advantageous.

Technology Readiness Level: Gasification is a mature technology, with roughly 300 plants operating worldwide comprising around 700 gasifiers (primarily for coal, but with biomass and waste streams expected to grow in significance). About 25% of worldwide ammonia production and 30% of worldwide methanol production are based on gasification.

Experiences in the Paper and Board industry: The first known application of gasification in the PBI can be found in the Netherlands, where Eska will bring by the end of 2016 into operation a reject gasifier supplied by Leroux & Lotz. The facility will be processing 25,000 tonnes of rejects annually in a fluidised bed installation; the produced syngas will be used for steam generation for the paper mill, reducing its natural gas consumption by 18 Mm^3/year.

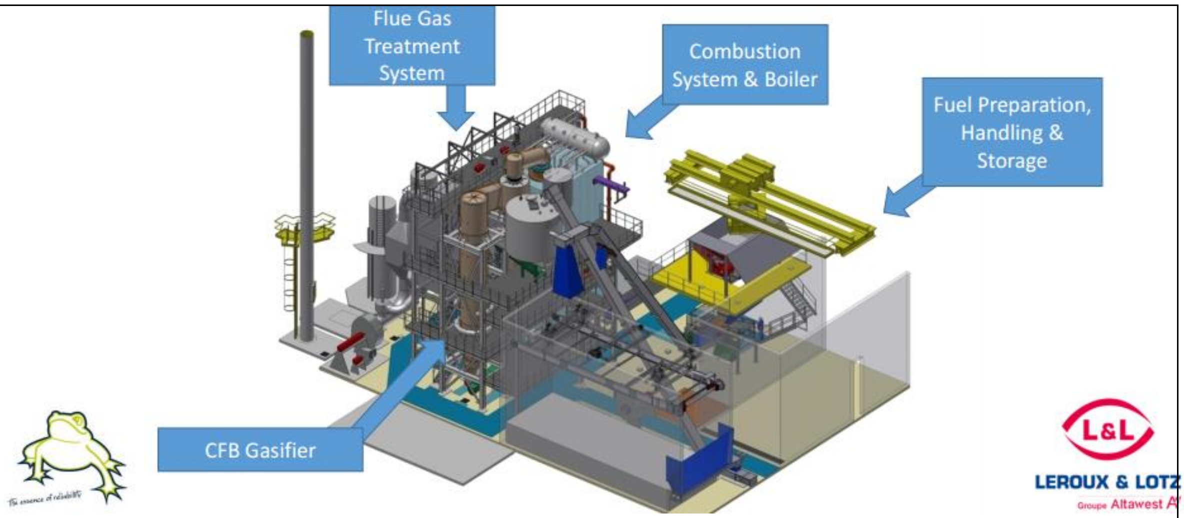

Figure 13. The reject gasification installation of Eska (Source: Leroux & Lotz)

Literature/websites:

http://www.gasification-syngas.org/resources/the-gasification-industry/

http://www.kcpk.nl/algemeen/bijeenkomsten/presentaties/20160203-vg-middag-sessie (sheets 25-40)

Ouadi M. Sustainable energy from paper industry wastes, Aston University, 2012 (available here: https://core.ac.uk/download/files/7/9636633.pdf)

Title: Pyrolysis

Raw material type: Suitable for both sludges and rejects.

Short description: Pyrolysis refers to the thermal decomposition of organic matter in the complete absence of oxygen. When applied to biomass or waste streams it can increase energy density, thus making energy transportation much more efficient. In the context of the paper industry, pyrolysis can serve as a conversion as well as a separation technique, as it can convert the organic content (fibres, plastics) of side streams into fuels (pyrolysis oil, pyrolysis gas) while reclaiming the inorganic content (metals, minerals) in a clean form.

Intermediate and end products: The main products of a pyrolysis process (pyrolysis oil and gas) can be seen as either end products that can be used as fuels for heat and power generation or as intermediates when the goal is the production of other types of fuels or chemicals. A pyrolysis oil refinery has been proposed, which will be able to produce a wide range of products through the fractionation of pyrolysis oil; possibilities include pyrolytic lignin for the replacement of fossil phenols and bitumen, pyrolytic sugars as feedstock for other chemicals, acetic acid, etc.

Process: The main process parametres that can influence the outcome of a pyrolysis process are the temperature reached (generally between 280 and 850 ^{O}C), the heating rate and the residence time; variations of these will have an influence on the ratios of the main pyrolysis products: liquid (oil), gaseous (gas) and solid (char).

In the context of the PBI, a distinction can be made between the pyrolysis of mixed rejects and that of sludge. In both cases it is the organic content of the feedstock, namely the plastics in the case of mixed rejects and the cellulosic matter in the case of sludges, that is converted into pyrolysis gas within the reactor. The inorganic matter, namely metals in the case of mixed rejects and mineral fillers in the case of sludges, is reclaimed as a clean secondary product of the process in both cases. The pyrolysis gas is subsequently partially condensed into pyrolysis oil. Part of the produced oil and/or gas, as well as any char produced in the process, can be used to supply the energy needed for the pyrolysis process itself, while the remaining oil and/or gas can either be used as fuel within the paper mill (e.g. in a dual-fuel diesel engine) or offered to third parties. Some pre-treatment may be required prior to feeding the side stream to the reactor, depending on the type of material (e.g. shredding and drying for rejects, drying for sludges).

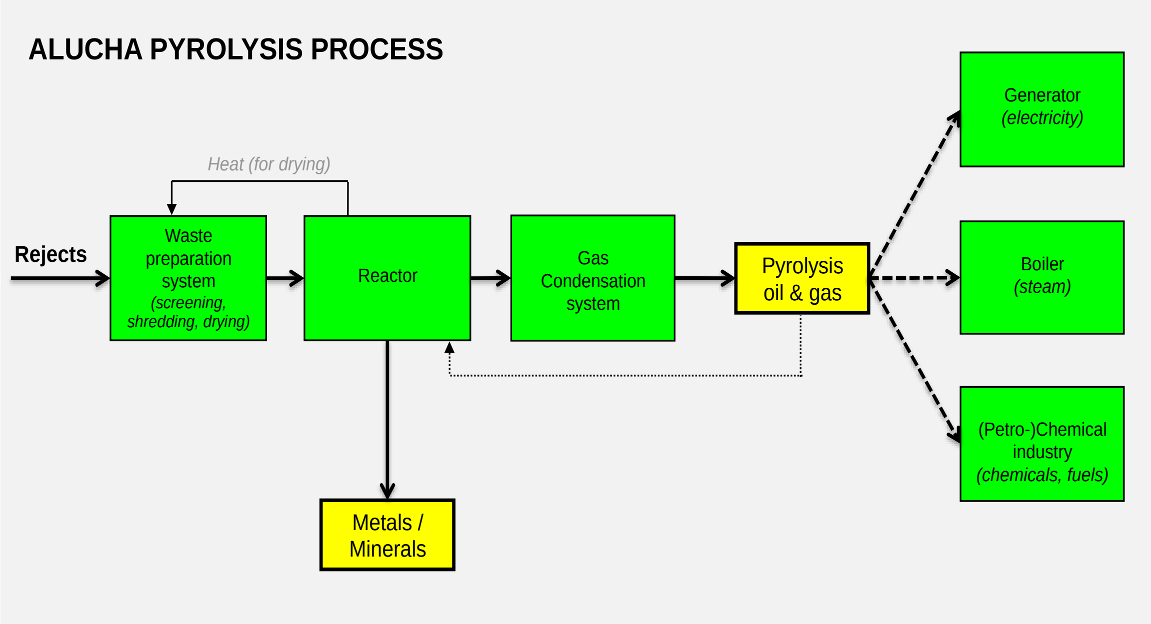

Figure 14. The reject pyrolysis concept of Alucha (Source: Alucha)

Benefits and Drawbacks: Pyrolysis can be advantageous for the PBI primarily with regard to reclaiming energy out of the side streams and reducing the volumes of waste that need to be disposed of. The pyrolysis oil and/or gas can help reduce the dependence of the paper mill to fossil fuels, thus lowering the energy bill of the paper producer, or generate additional income by offering to third parties either the fuels directly or the power generated on-site via their utilisation. The secondary products of side stream pyrolysis can also generate income for the paper mill: reclaimed metals from reject pyrolysis can be offered to metal recyclers, and reclaimed minerals from sludge pyrolysis can either be offered to sectors that use such raw materials or, if they are of sufficient quality, can be reused by the paper industry, substituting “fresh” inorganic fillers.

A drawback of the pyrolysis process is that it requires a feedstock with a very low moisture content (<10%), which means that evaporative drying of the side stream will be required. Depending on the local situation, however, this may be performed by means of locally available waste heat, or by utilising energy from the produced oil/gas/char. Another potential shortcoming is the quality of the produced oil. This may contain partially cracked compounds with a high molecular weight, resulting in a viscous oil that could be problematic in storage/handling thus requiring an upgrade before use as fuel. Pyrolysis oil from deinking sludge was found to be miscible with biodiesel and the blend of sufficient quality so as to allow a diesel engine to achieve its full power.

Technology Readiness Level: Pyrolysis is a mature technology with many installations operating worldwide, processing a wide array of feedstocks (e.g. plastics, old tires, wood, empty fruit bunch, etc.).

Experiences in the Paper and Board industry: The first full scale pyrolysis installation within the PBI, supplied by Alucha, has operated within the former Stora Enso Barcelona mill (currently Barcelona Cartonboard), where it has been used for the processing of mixed rejects (plastic and aluminium) from the recycling of beverage cartons as a fibre source.

Alucha is furthermore working in close cooperation with SCA for the development (currently on pilot scale) of PBI sludge pyrolysis.
Literature/websites: http://www.alucha.com/ http://www.storaenso.com/newsandmedia/from-juice-carton-to-car-parts Ouadi M. Sustainable energy from paper industry wastes, Aston University, 2012 (available here: https://core.ac.uk/download/files/7/9636633.pdf)

Title: Anaerobic digestion

Raw material type: Anaerobic digestion has already been widely applied for wastewater treatment but is also being considered as an option for PBI biosolids (waste activated sludge from aerobic wastewater treatment).

Short description: Anaerobic digestion refers to a series of processes during which microorganisms break down organic matter in the absence of oxygen.

Intermediate and end products: The primary end product of anaerobic digestion (of both wastewater and sludge) is biogas, which can either cover part of the internal energy demand of the paper mill or be offered to third parties. In the case of waste activated sludge, the digestate from anaerobic digestion contains compounds of high agronomic value and could be further processed into commercial fertilisers.

Process: The key stages of anaerobic digestion are the following:

- *Hydrolysis*; the breaking down of high-molecular-weight polymeric components of organic matter into their monomers (sugars, fatty acids, amino acids)
- *Acidogenesis*; the further breakdown of the monomers by acidogenic bacteria. Volatile fatty acids are formed, as well as NH_3, CO_2 and H_2S
- *Acetogenesis*; further digestion of molecules created in the previous stage with production mainly of acetic acid and also CO_2 and H_2
- *Methanogenesis*; intermediate products from the preceding stages are converted into CH_4, CO_2 and H_2O. The remaining material (digestate or sludge) consists of indigestible organic matter and the remains of dead microorganisms

Wastewater treatment plants of paper mills have been using anaerobic digestion for many years. The main bottleneck for the anaerobic digestion of waste activated sludge is the hydrolysis of complex organic matter; slow and incomplete hydrolysis results in a long period of sludge retention (20-30 days), and large reactors and high investment costs. This could be overcome by means of the thermal, mechanical, chemical or biological pre-treatment of the sludge, which would enhance its anaerobic digestibility. Examples of such sludge pre-treatment include the Thermal Hydrolysis Process of Cambi (CambiTHP), in which sludge is pre-treated with high-pressure steam, and the MicroSludge concept of Paradigm Environmental Technologies, where a high-pressure homogeniser is used for disrupting microbial cells in waste activated sludge.

Benefits and Drawbacks: In the case of anaerobic digestion as an option for PBI wastewater treatment, the main benefit of the process is the production of biogas. In PfR-utilising mills, anaerobic digestion can achieve a 58-90% COD removal, while generating 0.24-0.4 m^3 CH_4 per kg COD removed. This happens while 0.02 tonnes of sludge per tonne of removed COD are generated, compared to 0.4-1 tonne of sludge per tonne of removed COD in aerobic wastewater treatment. Anaerobic water treatment, however, usually needs to be combined with aerobic treatment in order to produce an effluent of sufficient quality for release into surface water. A benefit of combining aerobic and anaerobic wastewater treatment is the limited space requirements; these can be 25-50% of the space required for aerobic treatment alone.

The proposed anaerobic digestion of PBI biosolids can also reduce their volumes to be disposed of by 30-70%. Furthermore, it can improve their dewatering, thus leading to reduced polymer use, while the produced reject water is rich in nutrients and could be recirculated back to the activated sludge process so as to reduce the need for the addition of extra nutrients. In mills where primary and biological sludge are mixed for dewatering (e.g. prior to on-site incineration), diverting the biosludge to anaerobic digestion can be beneficial for the mechanical dewatering of primary sludge and the efficiency of sludge incineration.

Technology Readiness Level: Anaerobic digestion as a wastewater treatment method is well established; as a sludge treatment solution it has not yet been implemented within the PBI, although it is widely applied in the case of excess sludge from municipal wastewater treatment facilities (often in co-digestion with other materials). Various technological solutions for the pre-treatment of PBI biosolids aimed at improved digestibility thereof have been proposed and are currently in various levels of development or market introduction.

Experiences in the Paper and Board industry: Some indicative examples of anaerobic digestion facilities for wastewater treatment within the PBI include the following: Industriewater Eerbeek (the Netherlands, wastewater treatment plant serving three neighbouring paper mills), Smurfit Kappa Roermond Papier (the Netherlands), Smurfit Kappa SSK (United Kingdom), DS Smith Paper Lucca (Italy), Sappi Stockstadt (Germany), Sappi Lanaken (Belgium). The only operational example of anaerobic digestion of waste activated sludge in the broader pulp and paper sector can be found in Norway, where Borregaard has implemented it in its Sarpsborg speciality cellulose plant, combined with the CambiTHP pre-treatment technology.

Literature/websites:

Meyer T, Edwards EA. Anaerobic digestion of pulp and paper mill wastewater and sludge, Water Research, 65, pp. 321-349, 2014

Stephenson R, Mahmood T, Elliot A, O'Connor B, Eskicioglu C, Saha M, Ericksen B. How Microsludge® and anaerobic digestion or aerobic stabilization of Waste Activated Sludge can save on sludge management costs, Journal of Science and Technology for Forest Products and Processes, 2(1), pp. 26-31, 2012 (available here: http://www.paptac.ca/J-FOR/J-FOR_Vol2-issue1.pdf)

Title: Secondary fuels production

Raw material type: PBI rejects.

Short description: Rejects from the stock preparation in paper mills utilising PfR as their raw material can be converted into various forms of secondary fuels (e.g. fluff or pellets) to be co-fired at energy generation plants or by other industrial users.

Intermediate and end products: The secondary fuel is the end product of this valorisation route, without any intermediate products.

Process: The examples of fluff and fuel pellets from rejects as applied by two Dutch paper mills will be described for the purposes of this report.

For the production of fluff, rejects undergo an initial selection so as to remove glass, metal and other large objects. The next stages of the process include dewatering in a screw press, disc screening, metal extraction and crushing before returning to the screening cycle. The screening accept is subsequently subjected to ferrous metal removal and drying for the production of the fluff in its final form. The fluff has a final dry matter content of about 90% and a caloric value of 20-30 MJ/kg. The heat for its drying is mainly provided by the utilisation of paper machine condensate.

For the production of fuel pellets from rejects, on the other hand, the rejects are dewatered in screw compactors, the compressed mass having a dry matter content of over 60%. Sieving separates the larger particles (>30 mm), which are cut into smaller fragments in a shredder. The sieve also loosens the compacted mass, which allows magnetic removal of remaining iron particles. After re-mixing of the shredded particles, the organic mass dries in a rotating drum dryer, where the dry matter content is increased to 93%. While the heaviest particles remain behind in the dryer, the light fraction is transported by the drying air and reclaimed in a separator and two cyclones. About 66% of the drying air returns to the dryer. Finally, the product, still at a high temperature, passes through a pelletiser. The pellets are cooled in a counter-flow air cooler to 5 °C above outside air temperature. The drying air from the drum dryer and the counter-flow dryer is discharged through a gas scrubber, where dust and odours are removed. The fuel pellets have a caloric value of 23.7 MJ/kg and can be co-fired with coal, oil or natural gas in blast furnaces, cement kilns, etc.

Benefits and Drawbacks: A benefit of the secondary fuels route is that it attaches some value to rejects which, due to their heterogeneity, appear to have limited valorisation options available. The use of waste heat available in the paper mill for the drying required is another positive aspect of the process. This route requires however a significant investment for the production of a material that could be faced with price volatility; it is possible that the paper mill may need to pay a gate fee to the users of the reject-derived fuel, but it is also possible, depending on the market situation, that the paper mill receives a positive price for this product.

Technology Readiness Level: Secondary fuel production from rejects has been operational for several years.

Experiences in the Paper and Board industry: The examples mentioned above correspond to two Dutch paper mills, namely DS Smith Paper De Hoop (fluff) and Smurfit Kappa Roermond Papier (pellets with the commercial name Rofire).

Figure 15. Rofire fuel pellets produced by Smurfit Kappa Roermond Papier

Literature/websites: