Resources, Conservation & Recycling 125 (2017) 218–232

Contents lists available at ScienceDirect

Resources, Conservation & Recycling

journal homepage: www.elsevier.com/locate/resconrec

Review

Towards a Multiple Input-Multiple Output paper mill: Opportunities for alternative raw materials and sidestream valorisation in the paper and board industry

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ARTICLE INFO

Keywords:
Paper
Pulp
Non-wood fibers
Waste management

ABSTRACT

The paper and board industry (PBI) faces a series of challenges, ranging from shifts in the availability and quality of raw materials to the generation of large amounts of sidestreams whose disposal entails significant costs. The concept of the "Multiple Input-Multiple Output (MIMO) Paper Mill" is proposed here as an option for addressing these issues by introducing, on the one hand, flexibility regarding the types of fibre sources that can be used as raw materials and, on the other, a full utilisation of all fractions of the raw materials, including those that were so far considered to be sidestreams of papermaking. With regard to raw material flexibility, researchers have implemented various pretreatment and pulping methods on potential alternative, non-wood, fibre sources for the PBI, which can be found primarily in agro-industrial residues and plants specially cultivated for this purpose. Research on the conversion of various types of papermaking sidestreams into energy and material products has also been extensive, with the new products aimed at (re)use within both the PBI itself and other sectors. Given that technical aspects have gained the most attention so far, more focus should now be placed also on the economic and organisational sides of the concept. It is also crucial to start evaluating integrated MIMO cases, taking into account the interconnected effects that new raw materials have on the papermaking process and its sidestreams, instead of looking into isolated MI and MO examples.

1. Introduction

The paper and board industry (PBI) is becoming increasingly aware of the need for changes in its long-established modus operandi due to the increasing competition for natural resources and the pressure on all sectors of the economy to reduce their environmental impact. The implementation of the biorefinery concept has been proposed as such a change, aiming at the more efficient and complete use of biobased raw materials and sidestreams. A traditional definition of biorefinery refers to the "sustainable processing of biomass into a spectrum of marketable products and energy" (Cherubini, 2010), or "a facility integrating biomass extraction and conversion processes and equipment to produce fuels, power, heat and value-added chemicals" (Rafione et al., 2014). A PBI biorefinery can, however, encompass additional characteristics in the form of raw material reclamation from papermaking sidestreams for (re)use by the same facility or the cascading of unusable fractions from one facility's processes as feedstock for another of the same or a different sector. This vision comes thus also close to the Chertow definition of industrial symbiosis (Chertow, 2007): a physical exchange of materials, energy and by-products among traditionally separate industries for realising a competitive advantage.

In order to illustrate this possible future of the PBI we can introduce a new concept, the "Multiple Input-Multiple Output (MIMO) Paper Mill". This is a facility that can convert a variety of raw materials, including −but not limited to- wood cellulose and paper for recycling (PfR), into a wide range of end products and intermediates, including −but not limited to- paper and board products. The conversion of existing paper and board mills into MIMO mills could be seen as a necessary step for the PBI in order to overcome several of the challenges that it faces today. It entails, on the one hand, a measure of flexibility regarding the raw materials from which its products can be made and, on the other, the full utilisation of all fractions of the incoming raw materials, including those that have so far been considered as sidestreams of the papermaking process. This conversion into MIMO mills requires increased cooperation with other sectors in the economy (e.g. agriculture, chemical industry).

Several factors motivate the partial substitution of traditional PBI fibre sources −virgin wood fibres and PfR- by alternative raw materials

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http://dx.doi.org/10.1016/j.resconrec.2017.06.020
Received 3 February 2017; Received in revised form 15 June 2017; Accepted 20 June 2017

in the MI side of the MIMO concept. These may be related to raw material supply, including the costs thereof, or the quality of the end product. Starting with supply-related factors, the foremost concern is an increasing competition for biomass. Studying the impact of waste-to-energy on the demand/supply of recycled fibre indicates that a direct competition between the uses of PfR as fibre source and fuel could arise in the near future under most scenarios evaluated, leading to higher prices (Ristola, 2012). Competition for wood could also increase; the renewable energy targets of the European Union can create a worrisome mismatch between fibre demand and supply, with significantly increased prices for both wood and PfR as a result (McKinsey and Company Inc, 2007). Another important factor is the limits of paper recycling and what happens when these are approached. Some European countries are approaching the theoretical maximum paper collection rates (ca. 90%), which means that easy to reach and high-quality sources (industrial, commercial) have already been tapped, leaving growth potential only in more disperse, lower-quality sources (households) (Blanco et al., 2013). The influence of this on PfR quality is clear. In Spain, where collection rates increased by 10% between 2005 and 2008 with a strong contribution from households, an increase of unusable material content in PfR by 57% and of moisture by 25% was recorded during the same period. This practically meant that a typical newsprint mill would face additional annual costs for raw material and waste disposal exceeding 1.3 M€ (Miranda et al., 2011). Commingled collection systems for recyclable materials, where applied, can also create serious PfR quality issues (Blanco et al., 2013; Miranda et al., 2013). Potential solutions to such challenges could come in the form of improved PfR sorting (Blanco et al., 2013; Bobu et al., 2010), e.g. via increased automation, but this would require large investments. PfR quality has also been showing signs of deterioration in terms of higher ash contents and worse dewatering behaviour, with subsequent impact on the papermaking process and end product characteristics. Finally, recovered paper trade poses extra challenges; demand in Asia has by far surpassed local paper recovery, leading to massive imports from North America and Europe. A study of trade patterns (Arminen et al., 2015) has indicated that high-income countries could have very little control over demand for their own PfR, since the trade is driven by import demand, and that low transportation costs favour the export of PfR to Asia.

Moving to product quality-related factors, a development that could promote the use of alternative fibre sources is the lately problematic image of PfR as raw material for the production of food packaging. Mineral oils in particular have been in the spotlight with regard to their possible migration to foodstuff packaged in paperboard produced out of PfR (Biedermann and Grob, 2010; Lorenzini et al., 2010; Biedermann et al., 2011). Their origin is traced to printing inks and, depending on various conditions, they could migrate to the packed foodstuff in concentrations that far exceed the accepted limits by means of evaporation from the packaging and condensation on the content thereof. Given that the selection of only specific PfR types as raw material can be of limited value (Biedermann et al., 2011), the remaining solutions involve either introducing functional barriers in paper packaging or moving away from PfR for certain types of foodstuff packaging. Mineral oils are, in any case, one among several potential issues: a list of 157 hazardous chemical substances −49 of which were mineral oils- found in paper products and PfR has been compiled as a basis for a priority list of chemicals to be monitored (Pivnenko et al., 2015). 51 of these substances tend to remain in the solid matrix during paper recycling and can therefore end up in the new product, while 24 of these are classified as persistent and potentially bio-accumulating.

The management of sidestreams generated by the papermaking process −primarily during stock preparation and wastewater treatment- constitutes an important cost factor for the PBI, making technologies that could reduce sidestream management costs, or even make them profitable, very interesting. Reliable statistics about sidestream generation by the PBI are difficult to come by; in 2005 some 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 raw material (Monte et al., 2009). 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 sidestreams 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 the year 2008, when the sector's production volume was some 3 million tonnes, 80% of which was based on the utilisation of PfR.

The two main outlets of these sidestreams have historically been landfilling and incineration, although the significance of the former has been gradually decreasing owing to regulatory limitations in several European countries. In any case, both options entail significant costs for the sector, with recent information from Germany and the Netherlands indicating that disposing of solid sidestreams costs up to, or even more than, 100 €/t. Reducing these costs, or even turning them into profits, depends on the ability of the sector to utilise valuable components in the sidestreams by (re)using them internally or converting them to intermediates or products for other parties on the MO side of the MIMO concept.

This paper aims to review developments relevant for the transformation of the paper mill into a MIMO mill and to identify promising alternative inputs and outputs. The current level of knowledge regarding their technical and economic potential is to be examined, so as to provide a basis for further research. In the first part (MI) we are, therefore, looking into alternative sources of cellulose fibres for papermaking, while in the second part (MO) our attention turns to potential new products or intermediates, the production of which could utilise current papermaking sidestreams. MO possibilities only for paper and board mills will be examined, while opportunities for pulp mills, where the situation is completely different (e.g. availability and valorisation of lignin), fall beyond the scope of this work.

2. Multiple inputs opportunities

The potential alternative (i.e. non-wood) fibre sources for the PBI can be divided for the purposes of this article into two categories:

- Residues of the agro-industrial sector, including the food industry
- Plants cultivated as fibre sources

Exceptions beyond these categories are also possible, with an example being the production in the Netherlands of moulded fibre packaging (egg cartons) with grass from nature conservation areas partially substituting PfR (Anon, 2017a). In any case, regardless of this categorisation, alternative fibre sources have some common characteristics. Compared to softwood and hardwood, their contents of ash (silicate) appear to be higher, those of lignin lower, while cellulose contents are comparable (Judt, 1993). Lower levels of lignin indicate that their pulping may be easier and cheaper, while pulp mechanical strength is directly proportional to cellulose content (Ververis et al., 2004). Another factor in favour of such sources is the multitude of possible applications (green biorefinery, utilisation of agricultural residues after food production). This could lead to attractive business cases for the PBI, with low and stable prices for alternative fibres supported by the valorisation of all plant components. A common disadvantage, on the other hand, is the seasonal availability of such −mostly annual- plants, which means that ways of ensuring a steady, year-round fibre supply are necessary. Transportation issues may, further, arise due to the high volume and low density of non-wood fibre sources compared to wood or PfR (Ashori, 2006).

Fig. 1 summarises the multiple input opportunities for a MIMO mill.