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Efficiency and sustainability indicators for papermaking from virgin pulp—An emergy-based case study

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ABSTRACT

The pulp and paper sector is the fourth-largest industrial sector worldwide in terms of energy use, accounting for approximately 6% of the total industrial energy consumption and contributing to 2% of direct carbon dioxide (CO_2) emissions produced by industries. The definition of the environmental profile of this industrial sector is crucial, due to the high market demand of paper and the increasing concern for the environmental costs of the whole papermaking process. A sustainability perspective should rely on a wider and holistic viewpoint, properly including all direct and indirect interactions with the environment. To this purpose, the Emergy (spelled with "m") Accounting method (EMA) is very appropriate for the evaluation of the efficiency, effectiveness and sustainability of the papermaking process under different perspectives (resource quality, fossil energy and material consumption, environmental and human-driven support). Several studies concerning environmental impacts, eco-efficiency, and cleaner technologies in the pulp and paper sector have already been carried out, but none of them addressed resource quality and resource generation costs from a supply-side point of view. This study aims to fill this gap in the literature by highlighting the direct and indirect contribution in terms of natural capital and ecosystem services to the pulp and paper production process.

By means of EMA performance indices, this paper aims to assess the environmental sustainability associated to the production of pulp and paper, so as to identify those process steps that entail the highest environmental costs and require improvements. Three forest management scenarios − based on Spruce/Pine, Eucalyptus and Poplar production for raw material supply − were evaluated to assess the sustainability and the efficiency of each species. Moreover, the marginal costs of achieving higher energy and material efficiency are investigated, with a special focus placed on the identification of the effects of energy input flows on additional demand for environmental services.

The research results show that the largest supply-side environmental costs are generated by the industrial processing activities, due to high energy, water and chemicals consumption. Only a minor role is played by forestry activities that supply the raw feedstock, although forestry management practices certainly affect both the final productivity and the energy balance, through the amount and use efficiency of the farm inputs. Additionally, among the three forest systems under study, Spruce/Pine forest management displays the most sustainable option for paper production because, basing on the emergy indices, it presents the best sustainable contribution to both the economy and the environment of the investigated region. In conclusion, the application of EMA approach allowed a more comprehensive assessment of forestry and industrial operations, contributing to assist decision makers in implementing the best environmental management of papermaking process.

1. Introduction

The pulp and paper industry is one of the largest industries in the world, with very high capital investments (Bajpai, 2015). In 2014 the world's total paper production amounted to 406 million tons. Asia which accounts for 45% (179 million tons) of paper production, is by far the largest paper producer. Europe (107 million tons) and North America (85 million tons) are also significant producers (Bajpai, 2015). In particular, in Europe in 2015, the eight leading paper and board producing countries were Germany (24.9%), Finland (11.4%), Sweden (11.2%), Italy (9.7%), France (8.8%), Spain (6.8%), Austria (5.5%) and Poland (4.8%). As regards the grade, more than half of the paper and

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board product mix is packaging and wrapping paper and board (53%); about 31% is office paper, the remainder is newsprint, household and sanitary paper (CEPI, 2016).

Industrial production of pulp and paper is an intensive consumer of energy (fossil fuels, electricity), natural resources (water, wood) and chemicals (Avşar and Demirer, 2008). The pulp and paper sector consumes 6% of energy and releases 2% of direct carbon dioxide (CO_2) emissions in the industrial sector worldwide (IEA, 2016). This industry ranks fourth in terms of energy consumption among industries; nonetheless, it is one of the least CO_2-intensive industries because of the large utilization of biomass as substrate (EC, 2015). Since 1990, CO_2 emissions intensity of the European paper industry have decreased by approximately 25% (Worrell, 2011). However, given the projected continuing increase in pulp and paper production, future reductions (e.g., by 2030 or 2050) in energy use and CO_2 emissions will require further innovations beyond the technologies available for implementation today. Innovations will likely include development of better processes and materials for pulp and paper production or technologies that can economically capture and store the CO_2 emissions (Kong et al., 2016). Thus, the development of these emerging technologies and their deployment will be a key element in the environmental cost mitigating measures.

The majority of the studies available in the scientific literature analyses the environmental impacts related to the pulp and paper industry and the potential improvements, i.e. environmental impacts reduction, resulting by specific measures, such as the use of a cleaner energy, non-virgin materials, as well as the recycling of pulp and paper by-products (Counsell and Allwood, 2007; Holmberg and Gustavsson, 2007; Zhang et al., 2012; Brogaard et al., 2014; Cheung and Pachisia, 2015; Bousios and Worrell, 2017; Kong et al., 2017).

Also in line with other studies (Wiegard, 2001; Dias et al., 2002; Holmgren and Henning, 2004; Dias et al., 2007; Murphy and Power, 2007; Schmidt et al., 2007; Merrild et al., 2008), Poopak and Reza (2012) calculated the potential environmental benefits of using non-virgin material (i.e. bagasse) instead of wood in paper and pulp factory in Iran. Moreover, Krishna Manda et al. (2012) proved that the use of new coatings (micro or nano TiO_2), in combination with the different pulp types, brings savings in wood, energy, GHG emissions and other environmental impacts in comparison with conventional printing and writing paper.

Conversely, several studies are focused on improvements in energy efficiency in the paper industry. Lopes et al. (2003) assessed that the Eucalyptus pulp and paper production (in Portugal) is a large consumer of energy throughout the paper life cycle; therefore, the substitution of heavy fuel oil by natural gas in the pulp and paper production processes seems to be environmentally positive. Ruohonen et al. (2010), Hong et al. (2011), Fleiter et al. (2012) and Faubert et al. (2016), evaluated that cleaner process technologies (such as heat recovery in paper mills and the use of innovative paper drying technologies) can significantly improve energy efficiency in the pulp and paper industry, which in turn can lead to lower carbon emissions.

In general, most of the papers assesses that the largest supply-side environmental costs are generated by the industrial processing activities, due to high energy and water consumption as well as to the significant use and release of chemicals and combustion products. Only a minor role is played by forestry activities that supply the raw feedstock, although forestry management practices certainly affect both the final productivity and the energy balance, through the amount and use efficiency of the farm inputs (Dias et al., 2007; Silva et al., 2015).

Nevertheless, a limited number of studies have evaluated the forestry activities in terms of resource quality and resource generation costs from a supply-side point of view (Doherty, 1995; Campbell and Brown, 2012; Viglia et al., 2013; Buonocore et al., 2014; Nikodinoska et al., 2016, among others). In any case, all of them have a specific focus on environmental costs and impacts due to the exploitation of forest ecosystem services. In order to have a deeper understanding of the whole pulp and paper production chain, this study aims to include a wider and holistic viewpoint, properly including all direct and indirect interactions with the environment.

To this purpose, the Emergy Accounting method (EMA) is very appropriate for the evaluation of the efficiency, effectiveness and sustainability of the papermaking process under different perspectives (resource quality, time and spatial scales, fossil energy and material consumption, environmental and human-driven support). The concept of Emergy (spelled with an "m") was introduced to measure the cumulative environmental support to a process. EMA allows evaluating the environmental performance of the investigated system on the global scale of biosphere by taking into account free environmental inputs (e.g., solar radiation, wind, rain, geothermal flow), human-driven material and energy flows, as well as the indirect environmental support embodied in human labor and services (Nikodinoska et al., 2016).

By means of EMA performance indices, this study aims to assess the environmental sustainability associated to the production of office paper, so as to identify those process steps that require the highest environmental support. Moreover, the study explores the sensitivity of results to three forest management scenarios − namely Spruce/Pine, Eucalyptus and Poplar plantations for raw material supply − in order to identify the wood-biomass alternative that can be considered more environmentally sustainable for paper production. In addition, the marginal costs of achieving higher energy and material efficiency are investigated, with a special focus placed on the identification of the costs of energy input flows on additional demand for environmental services.

2. Materials and methods

2.1. The emergy accounting

Emergy is defined as all the available energy (exergy) previously used up at the time-space scale of the biosphere directly and indirectly to make a product or service expressed in units of solar equivalent joule (sej)[1] (Odum, 1996). It overcomes the obstacles of the different quality of energy and material flows used in a process by converting them into solar emjoules, sej, by means of equivalency factors (Brown and Ulgiati, 2016a,b; Brown et al., 2016). EMA considers all systems to be networks of energy flows to and among systems components and determines the emergy value of all flows, storages, and components involved. In so doing, the environmental support provided by biosphere to each step or component of the network is quantified in comparable units and performance indicators can be computed. Most often, evaluation methods in environmental and ecological economics estimate the value of ecosystems as well as of resource flows exchanged in anthropocentric terms, while emergy tries to capture the eco-centric costs and value of a system and its dynamic. It attempts to assign environmental values to ecological and economic resources, flows and services, based upon a theory of energy flows in system ecology and its relation to system's survival (Ulgiati and Brown, 1998). These characteristics makes EMA a powerful tool when assessing the resource use environmental performance through a larger spatial and time window than the traditional Embodied Energy Analysis (EEA) (IFIAS, 1974). EEA of a product is concerned with the depletion of fossil energy, and therefore process inputs of material and energy flows which are not directly accounted for in terms of fossil and fossil equivalent resources are generally disregarded. Resources provided for free by the environment, for instance

[1] In the last Emergy Conference (Gainesville, January 2016) a decision was made about emergy units nomenclature. Instead of seJ (capital J), referred to "solar equivalent joule", the unit will be sej (small cap, not capital j), referring to "solar emjoule". Only when referring to the baseline the unit remains seJ (capital J), in order to underline the existence of equivalence factors among the three driving forces of biosphere (solar, deep heat, gravitational). Further clarifications in Brown et al. (2016), Brown and Ulgiati (2016a,b).