Renewable and Sustainable Energy Reviews 92 (2018) 823–833

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

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

Uncovering energy use, carbon emissions and environmental burdens of pulp and paper industry: A systematic review and meta-analysis

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ARTICLE INFO

Keywords:
Pulp and paper
Life cycle assessment
Meta-analysis
Straw-based pulp

ABSTRACT

The pulp and paper industry, which provides cellulose pulp and paper, bio-based energy and chemicals, is one of the largest energy consumers, greenhouse gases (GHG) and pollutant emitters among manufacturing industries. Although the environmental impact of the pulp and paper industry has been extensively studied, life cycle assessment (LCA) results have not yet reached a consensus. By means of a systematic review and meta-analysis, this article contributes to the quantification and harmonization of the life cycle environmental impacts of pulp making and paper making systems. Based on the screening of 45 cases of paper making and 18 cases of pulp making, we found that 1 t of paper results in about 950 kg carbon dioxide (CO_2) equivalent (CO_2-eq) GHG emissions on average. However, there are distinct differences between countries and pulp and paper categories. The dominant factor influencing GHG emissions is energy use. In paper making, the pulp making process is responsible for 62% of energy use, 45% of GHG emissions, 48% of acidification potential, and 49% of eutrophication potential. The kg CO_2-eq emissions of three different types of pulp were as follows: Kraft, 508 kg CO_2-eq/t; chemi-mechanical, 513 kg CO_2-eq/t; and recycled pulp, 408 kg CO_2-eq/t. Excluding emissions from electricity and steam production, the convergence of carbon emissions is observed within the same categories of pulp. Straw-based pulp caused far more environmental impact than any other type because of the intensive inputs in agricultural activities as well as in the pulp making process. This research highlighted the inconsistencies in functional units, system boundaries, and methodologies and carbon neutrality assumptions in different LCA studies of pulp and paper making. Future studies should focus on the environmental impact of straw-based pulp making, system boundary unification, and calculation of biogenic carbon emissions.

1. Introduction

Paper making includes two main processes: pulp making and paper formation. In the pulp making process, under a certain temperature and pressure, cellulose is extracted from the wood or straw by chemicals. In the paper formation process, the pulp is converted into paper by adding coatings and fillers. Both pulp making and paper formation processes involve intensive resources and energy inputs as well as greenhouse gases (GHG) and pollutant emissions. Therefore, the pulp and paper industry contributes substantially to total energy use and GHG emissions. Pulp and paper industry is involved in both fossil fuels and renewable energy in most countries. Taking Kraft pulping for example, in the cooking process, large quantities of fossil-based energy are needed for digesting the lignocellulose. On the other hand, in the alkaline recovery process, cellulose is burnt to produce renewable energy, which could be used to produce pulp and paper. In some cases, the renewable energy produced in alkaline recovery process could meet all the energy needed in pulping process, and causing a net positive global warming

Abbreviations: AP, Acidification Potential; CMP, Chemi-mechanical pulp; CO_2-eq, CO_2 equivalent; EP, Eutrophication Potential; GHG, Greenhouse Gas; GWP, Global Warming Potential; IQR, Interquartile Range; LCA, Life Cycle Assessment; PO_4^{3-}-eq, Phosphate equivalent; SCP, Super Calendared Paper; SO_2-eq, SO_2 equivalent

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https://doi.org/10.1016/j.rser.2018.04.036
Received 6 May 2017; Received in revised form 13 March 2018; Accepted 14 April 2018
1364-0321/

potential [1]. Energy quantification and optimization has been a major issue in pulp and paper industry to foster low carbon and green industry and promote sustainable development goals (SDGs) put forward by the United Nations (UN) [2], such as responsible consumption and production and climate action. Globally, many efforts have been devoted to energy conservation [3] and water pollution reduction [4] and hazard reduction [5] in the pulp and paper industry from government, academia, and industry. For instance, the pulp and paper industry has been listed as one of the key industries for emission permit systems in China.

Many studies have focused on quantification of energy use, material inputs, and pollution emissions in the pulp and paper industry. Globally, the pulp and paper industry contribute 5.7% of industrial final energy use [6], and it ranks as the fourth largest GHG emitter and is responsible for 9% of GHG emissions of manufacturing industries [7]. In China, the pulp and paper industry accounted for 1.7% of industrial energy demand in 2010 [8], and ranks among the top 10 for GHG emissions in the 39 industrial branches [9], with energy consumption being the largest contributor [10]. In European Economic Area member countries, the pulp and paper industry accounted for 5% of the total final energy use, and 15% of the final energy use in the industrial sector in 2010 [11]. In Germany, pulp and paper industries account for 9% of the industrial energy demand and 2.5% of all the energy-related GHG emissions [12].

Because of the high energy consumption and high GHG emissions factors, considerable research has focused on improving the energy efficiency and reducing the GHG emissions in the pulp and paper industry. Most of these studies were conducted at the national or regional scale. The quantifications of energy use and GHG emissions provide a basis for further analysis. Energy use and GHG emissions over a long-time series have been calculated in China [10], Sweden [13] and globally [14]. The historical trajectory of energy efficiency and GHG emissions intensity were analyzed and the influencing factors were identified through various decomposition methods [15]. Some studies even projected the demand for pulp and paper production and the related GHG emissions in the future for Asia [16]. New technologies were applied to examine potential to reduce energy use and GHG emissions. The contribution of policy and technological changes in energy saving and GHG emission mitigation has been further explored in European countries, such as the application of an emission trading system [17] or carbon capture and storage techniques [18] for reducing GHG emissions. Some studies have explored the economic perspective of the technological application, utilizing economic models to study the cost of new technology application in energy saving and mitigation of GHG emissions. The cost of energy saving and carbon emission reductions in the USA was analyzed in [6], the water related issues in a Mexican mill in [19]. Combined with the resource endowment, a study has analyzed the optimization strategies of different countries in reducing GHG emissions [11]. Research has also analyzed policies in driving energy saving and GHG emission reduction [20].

Most studies take place at the national or regional level, and mostly only energy-related GHG emissions are included, while GHG emissions from other sources such as chemicals, transportation, and biomass are neglected. Because of the huge heterogeneities between different plants and the difficulties in obtaining detailed information for each plant, it is difficult to calculate the GHG emissions for a country from a life cycle perspective. The national scale calculation gives a rough picture of the GHG emissions of the pulp and paper making industry in certain countries or regions. However, it fails to reveal the “true” emissions from a life cycle perspective, and it is not easy to explore the emissions from a higher resolution and to identify the processes specifically contributing to GHG emissions. Country or regional level analyses are only focused on GHG emissions and energy use, while other environmental impacts, such as acidification potential (AP) and eutrophication potential (EP) are not quantified. At the same time, life cycle perspectives of multi environmental impacts assessment are conducted at the plant scale to complement the regional and country scale research.

As a powerful tool for environmental impact quantification, life cycle assessment (LCA) is intensively employed in environmental impact assessment in the pulp and paper industry. There are over 100 studies published concerning different processes of pulp and paper making in different countries, including pulp making [21], paper making in Portuguese mill [22], evaluating chemical-, mechanical-, and bio-pulping processes and their sustainability characterization in, newsprint in Canada [23], forestry processes [24], waste water treatment [25], and sludge management [26]. Some international organizations, such as the European Association of Carton and Carton board Manufacturers [27], regularly publish the life cycle carbon emissions of pulp and paper making in specific areas. The pulp and paper industry has been involved in varieties of feedstock, technological routes and product categories, which leads to diverse environmental impact evaluation results. The further analysis of these results could not only help to identify the trend of previous studies and provide a benchmark for comparison, but also identify the hotspots in environmental impacts in the pulp and paper industry. However, the systematic analysis of those evaluation results is scarce. To the best of the author's knowledge, there are few studies systematically analyzing and comparing the life cycle environmental impacts of pulp and paper production. There is a great need to systematically analyze the status of the life cycle environmental impacts of pulp and paper making to provide a benchmark for future studies.

In this article, we conduct a meta-analysis by systematically analyzing the life cycle environmental impacts of pulp and paper making reference to the published LCA studies. Meta-analysis, which was firstly used in medicine sciences, is a commonly used tool in scientific research to combine and analyze the results of multiple individual studies to derive an estimate closer to the common truth [28]. Meta-analysis is a useful method by which to understand the general status and prevailing trend of the topic of interest [29]. In our meta-analysis, the total and average main environmental impacts of pulp and paper, which are the fundamental results of LCA studies, were first revealed. This basic information provides the foundation for further analysis. Based on the overall results, the discrepancies among different categories of pulp and paper as well as different countries were analyzed. To promote the further development of LCA on the pulp and paper industry, drawbacks of current studies and suggestions for further studies are presented. We aimed to provide a benchmark for life cycle environmental impacts of pulp and paper making and provide suggestions for future studies.

This article is not just a literature review on LCA of pulp and paper making. Rather, it concludes by providing a meta-analysis and systematic review of environmental impact profiles of the pulp and paper industry. The article is structured as follows: data and methodology are presented in Section 2; the main results are described in Section 3; and Section 4 and Section 5 show discussions and conclusions respectively.

2. Data and methodology

LCA has been extensively deployed in environmental evaluation of bio-oriented products, including production of resources such as electricity [30], bioethanol [31,32], and chemicals [33]. The environmental impacts of pulp and paper making at enterprise scale are typically quantified through an internationally standardized LCA method. Here, we reviewed LCA studies concerning pulp and paper based on a comprehensive search of the literature published in English. Two rounds of review have been used to select the targeted studies based on the following principles. In the first step, only studies that quantified pulp and paper making in physical units for environmental impact categories and excluded those with non-physical functional units in the USA [34] and Brazil [35]. Second, we only included studies that provide specific figures for environmental impacts and exclude those that provide only relative contributions between different processes [36]. We also excluded studies from flyers and presentations and other unqualified studies with inadequate description of the data sources and