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Life-Cycle Assessment of coal–biomass based electricity in Chile: Focus on using raw vs torrefied wood

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ABSTRACT

In this article, the environmental impacts associated to cofiring coal with forest biomass for electricity production in Chile are analyzed for: (i) untreated pine pellets and (ii) torrefied-pretreated pine pellets. Results show that energy production from cofiring coal/untreated wood pellets or coal/torrefied pellets, featured significant reductions in environmental impacts, as compared with pure coal plants. Indeed, reductions in acidification (28–26%), abiotic depletion (15–7%), eutrophication potential (15–12%), global warming potential (16–6%), photochemical oxidation (28–23%), human toxicity (17–15%), terrestrial ecotoxicity (12–9%), and marine aquatic ecotoxicity (17–15%) were obtained when untreated or treated pellets were used as a substitute for coal. Moreover, the environmental profile of torrefied pine evidenced its low impact per energy unit, in most of the studied categories except for eutrophication and marine aquatic ecotoxicity, for which the harvesting, logistic chain and torrefaction processes were the most important contributors.

Introduction

Energy security concerns, excessive fossil fuel consumption, increasing pollutant emissions and incipient and worrisome climate change are the main drivers for more aggressive development of renewable energy sources. In this framework, forest biomass is a potential candidate to replace fossil fuels from their current applications, based on its abundance, renewability, carbon neutrality, and the possibility of conversion to higher-value-added products. Forest biomass is near neutral in CO_2, as some authors argued that the growing trees absorb the CO_2 emitted during combustion creating a closed carbon loop (Bracmort, 2013). Nevertheless, it has also been demonstrated that the quantity and composition of greenhouse gasses (GHG) produced in biomass-based power generation systems depends upon the type of feedstock and the way it is burned (Weisser, 2007; Royo et al., 2012). Accordingly, the introduction of such resource into traditional energy matrices should be done from the sustainable perspective by integrating technical and environmental principles.

Chile has experienced a fast economic growth in the last decades featuring an average increase in energy demand around 94 PJ/y between 2009 and 2013 (MinEnergía, 2014). Electricity production in Chile heavily relies on imported fossil fuels, with coal-fired power plants accounting for about a third of total installed capacity (viz. 3541 MW in Sept. 2015), driven by low natural gas and coal prices. This framework resulted from an economic-based decision procedure, supported by the low prices of natural gas and coal. Nevertheless, it has been envisaged that such dependence on volatile international energy prices represents a threat to the country's stability (MinEnergía, 2013), hence actions should be taken to change the *status quo* by considering national resources.

With more than 15 million hectares of native and forest plantations and a yield of 20–40 m^3/ha/y, Chile has one of the largest and productive forested areas in Latin America (Berg et al., 2013; CONAF, 2014). Forest management and processing, generates approximately 4 million of tonnes/year of woody residues which is equivalent to 14,000 GWh/y of energy, enough to replace an important fraction (viz. 25%) of the internal coal demand (Berg et al., 2013). Currently, the installed capacity for electricity production from biomass amounts to nearly 5% of its estimated potential, and these are mostly designed to meet internal energy demand in paper and wood industries (Martínez-Saperas, 2014). Therefore, there is an interesting opportunity to transform the local energy matrix into a more sustainable one.

Among several options, integrating forest biomass to coal-fired power plants is an attractive option to revamp current installations. Indeed, this alternative offers a number of advantages, such as lower

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investment risks, greater efficiency, low costs and easiness to implement. As a result, the number of traditional coal fired boilers turned into biomass co-firing plants around the world has increased, from 152 to 241 in only 5 years (Al-Mansour and Zuwala, 2010; IEABCC, 2012). Most common practice is to develop the combustion of coal and biomass in air-fluidized bed reactors, where particles are suspended in a bed of ash, sand or limestone (Oka and Anthony, 2004). Cofiring with biomass usually occurs at temperatures between 800 and 1000 °C; with maximum up to 1400 °C, when the process is carried out in pulverized-coal boilers, but the feeding of untreated biomass in these systems is rather complex and impractical (Kalisz et al., 2008). According to Baxter (2005), cofiring ranked as the best option for countries that are looking for ways to reduce global warming, because it brings environmental benefits such as reduction of CO_2, SO_2 and also NO_x for some biomass types. Nevertheless, such transformation is not a straightforward process and it has both, technical and environmental burdens. Biomass features a number of technical constraints as compared with solid fossil fuels, such as higher biodegradability, higher moisture content, lower energy density, discrete distribution, lower grindability and hydrophilic (Almeida et al., 2010). On the other hand, main environmental concerns are related to land use, transport and distribution chains and, on ensuring a long-term availability of biomass with the required quality at a competitive cost (Cambero and Sowlati, 2014). Pretreatment of bio-resources by physical, biological or thermochemical methods, may help to mitigate problems associated to variable fuel quality. Furthermore, if the treatment leads to the increment of the energy density, the cost and environmental impacts per energy unit of transported fuel may decrease. In this respect, torrefaction is an emerging thermal biomass pretreatment method that has the ability to reduce biomass heterogeneity, increase its energy density and reduce hygroscopic behavior, and fibrous nature. This process is defined as mild pyrolysis and takes place between 200 and 320 °C (Bergman, 2005; Chew and Doshi, 2011; Batidzirai et al., 2013; Nhuchhen et al., 2014). Throughout torrefaction, the tenacious fiber structure of the original biomass is largely destroyed through the breakdown of hemicellulose and, to a lesser degree, cellulose and lignin molecules, so that the material becomes brittle and easier to grind (Phanphanich and Mani, 2011). With the removal of oxygen-rich lighter volatile fraction, the highest heating value (HHV) of the remaining material gradually increases at expenses of a mass reduction, retaining around 90% of its initial HHV. Key torrefaction reaction products include solids in the form of char, ash and volatiles (gasses and organic vapors) (Prins et al., 2006; Bates and Ghoniem, 2012; Kiel et al., 2012). Technical studies have shown that 20% of coal could be substituted by torrefied biomass, without the need for further significant investments, thus contributing to a reduction in fossil carbon emissions (Lempp, 2013).

Although cofiring biomass (untreated or torrefied) could be a more sustainable way to produce energy from wood in existing facilities, there are still some environmental concerns that need to be evaluated, such as emissions profiles, global warming potential, acidification, ozone depletion, eutrophication, ecotoxicity, etc. along the whole biofuel life cycle.

Life Cycle Assessment (LCA) is a stepwise methodology to evaluate impacts associated to a product, technology or stage in a process. LCA includes the attributes or aspects of the natural environment, human health and resources associated to a product's life from raw material acquisition to processing, manufacturing, use and, finally, disposal (ISO 14044, 2006). There are several reports on the application of LCA to analyze the cofiring of woody biomass (Table 1) in Europe and Asia, and references of such analysis in Latin America and especially in Chile are scarce.

Works in Table 1 vary in detail and scope but all of them concluded that each case should be analyzed individually, because site specific regional, demographical and economic characteristics influence the environmental performance and impacts of technologies.

Most LCA studies on torrefaction, mainly focus on its integration to cofiring for electricity generation and, there is still a knowledge gap on the environmental comparison between torrefied biosolid and coal (Al-Mansour and Zuwala, 2010; Tabata et al., 2011; Huang et al., 2013; Tsalidis et al., 2014). This study addresses this issue for the Chilean case, presenting the environmental profile of torrefied biomass for its future application in different systems such as electricity generation, cement industry, gasification and integrated gasification–Fischer Tropsch systems. Additionally, the use of torrefied biomass as blend fuel for electricity generation in coal-fired thermal plants is also presented.

Pinewood (*Pinus radiata*) is used here as the biomass feedstock, since this species accounts for more than 60% of forest plantations in the country (CONAF, 2014). Most inventory data for torrefaction and cofiring plants were obtained in pilot-scale experiments, whereas complementary upstream and downstream data were acquired using Ecoinvent database and sequential modeling (Arteaga-Pérez et al., 2015). Experimental results for cofiring were extrapolated to a 250 MWe plant, considering a negligible effect of coal substitution (up to 20%) on energy efficiency, temperature profiles and flue gas composition.

Methods

The SimaPro v8.0.2 and CML2 baseline 2000 v2.05, world 1995 model were used in this study. The CML2 was originally developed by the "Centre for Environmental Studies (CML)" at the University of Leiden, the Netherlands, in 1992. The impact categories included in this method are: abiotic depletion (ADP), acidification (AP), eutrophication (EP), global warming (GWP), ozone layer depletion (ODP), human toxicity (HTP), fresh water ecotoxicity (FAETP), marine aquatic ecotoxicity (MAETP), terrestrial ecotoxicity (TETP) and photochemical oxidation (POCP).

LCA methodology

The LCA methodology is thoroughly described elsewhere (Guinée, 2001). Here, a brief summary of the main LCA stages is presented below

Goal and scope definition

The aim of this LCA is to compare alternative processes for power production using woody biomass as fuel substitute in coal-fired power stations. Two scenarios are analyzed using a cradle-to-gate approach: (i) cofiring of coal with 20% (energy basis) of untreated wood pellets and (ii) cofiring of torrefied wood pellets with coal under the same replacement ratio. Both cases are compared with installed coal-fired power stations in Chile, based on all impact categories included in the CML baseline 2000 model. The choice of both scenarios is in line with Chilean government decision to substitute 10% of fossil-based electricity production by renewables by 2024 (MinEnergía, 2013). As mentioned above, cofiring is a simple and low cost alternative to take advantage of forest residues as fuels for electricity production in Chile. Moreover, torrefaction is a very promising process to increase quality, compatibility and competitiveness of forest resources in comparison to coal. Accordingly, the environmental profile of non-pelletized torrefied material is studied and compared with that of coal.

System boundaries

The cradle-to-gate boundaries of coal and biomass for power generation in thermal stations are shown in Fig. 1.

The biomass chain included production, harvesting, transportation, pelletization, cofiring and electricity generation. In the case of pretreated biomass, boundaries are extended (dashed lines area) to the torrefaction plant. *P. radiata* was used as reference to estimate the impacts of forestry production process, which included plantation establishment, management, harvesting and transportation. Transport of pesticides and fertilizers was not considered here, since preliminary estimations showed that associated environmental burdens were