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LCA of a multifunctional bioenergy chain based on pellet production

D. Ruiz[a], G. San Miguel[a,*], B. Corona[a], F.R. López[b]

[a] Department of Chemical and Environmental Engineering, Industrial Engineering Faculty (ETSII), Universidad Politécnica of Madrid, José Gutiérrez Abascal 2, 28006 Madrid, Spain

[b] Department of Agroforestry Science and Technology, School of Agricultural Engineering and Forestry, Universidad de Castilla Mancha, Avenida de España, s/n, 02071 Albacete, Spain

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ABSTRACT

This paper investigates the environmental performance of a multifunctional bioenergy chain for the provision of domestic heat using Life Cycle Assessment methodology. The analysis is based on a commercial pellet plant located in Spain and incorporating a Combined Heat and Power system based on Organic Rankine Cycle technology that also produces electricity that is sold to the grid. The base scenario involves using pine wood both from forests and wood processing activities. This situation is compared against a conventional pellet plant with no Combined Heat and Power, using poplar wood from a Short Rotation Coppice plantation and also using the ash produced in the pellet plant as a surrogate fertilizer. The base scenario has also been compared against domestic heat provision from conventional systems based on natural gas, diesel and electricity. The results have shown that the most impacting activities in the life cycle of the bioenergy chain are primarily attributable to the pellet making process, followed by biomass production, biomass transport and finally pellet combustion by the final user. Incorporation of the Combined Heat and Power system to the pellet plant has a very limited influence on the environmental performance of the system since the power generation capacity is very limited and environmental savings from power generation are offset by detrimental effects associated with extra biomass consumption. For a conventional pellet plant, the normalized impact value obtained using International Reference Life Cycle Data System methodology is 2.78 E − 04 µPt (vs 2.85 E − 04 µPt for the base scenario). A similar bioenergy chain based on poplar wood from a Short Rotation Coppice generates higher environmental impact in water resource depletion. This impact category has a decisive weight after normalization, making this alternative highly unfavorable (5.50 E − 04 µPt). Utilizing the ash fraction produced in the pellet plant as a surrogate fertilizer implies low environmental benefits (2.71 E − 04 µPt).

When compared against heating systems based on diesel, natural gas or electricity (heat pump), the pellet system benefits from reduced impacts on global impact categories like climate change, ozone depletion and Cumulative Energy Demand. However, the bioenergy system performs worse on local impact categories such as particulate matter formation, human toxicity, photochemical ozone formation, freshwater eutrophication and land use. Normalized impact values suggest that the bioenergy system is the least favorable environmental option (2.85 E − 04 µPt) as compared to heating systems based on diesel, natural gas or electricity (5.72 E − 05 µPt, 5.15 E − 05 µPt and 1.99 E − 04 µPt respectively).

1. Introduction

Lignocellulosic biomass is a renewable and widely available energy resource suitable for the generation of heat, power and fuels. However, its low energy density, heterogeneous nature and disperse geographic distribution pose economic and technical limitations to a more extensive commercial utilization both in industrial and domestic applications [20]. Pelletizing is a form of mechanical densification that allows the transformation of raw lignocellulosic resources into a uniform bio-fuel product with superior combustion properties and improved performance in terms of handling, transportation, storage and combustion performance. Although pellet making has been practiced in Europe since the 1970s, this activity has gained popularity primarily over the last decade as a result of a regulatory framework that has promoted the use of renewable and locally available energy resources, high fossil fuels prices and also the introduction of quality standards (ISO/TC 238, CEN/TC 335) that facilitate its commercialization in a global market and its utilization in modern automatic energy systems

* Corresponding author.
E-mail address: g.sanmiguel@upm.es (G. San Miguel).

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[37,39].

At present, most of the biomass employed for commercial pellet making derive from forest management (tree trunks and branches from a wide range of species such as pine, eucalyptus, poplar, oak, beech), agriculture (stumps and pruning residues) and industrial activities (chips and sawdust from wood processing) [37]. The quality of these resources is not always high and consistent, and the availability may pose limitations to meet a growing demand. An alternative receiving increasing attention involves the sustainable cultivation of fast growing species as energy crops [1]. Poplar has been widely investigated for use in Short Rotation Coppice (SRC) plantations due to its capacity to re-sprout from its stump, fast growth rate and resistance to frost [32]. One drawback of using SRC poplar for pellet making relates to difficulties in the debarking of the raw biomass, due to the small diameter of the tree trunks and the limited mechanical consistency of the bark itself. The incorporation of this bark may result in pellets with higher ash contents than those produced from conventional debarked wood [10].

Despite its renewable nature, bioenergy systems generate environmental impacts that need to be identified, quantified and managed accordingly. Life Cycle Assessment (LCA) methodology has been widely used to evaluate the environmental performance of energy systems including those based on biofuels [5,14,33]. In general terms, bioenergy systems based on residual resources are associated with reduced impacts on certain categories like global warming, depletion of fossil resources and land acidification [40]. However, this environmental profile may change in biofuel chains supported by energy crops due to the consumption of fertilizers and phytosanitary products, extensive water use and other energy requirements [31,43].

Regarding pellet making, several studies have been published describing the environmental performance of this practice using different biomass resources including wood residues and byproducts from forestry management [15,24,26,35], the wood processing industry [4,15,24,28] and agricultural activities [25]. Reported GHG emissions ranged between 5 and 20 g CO_2 eq/MJ, depending not only on technical aspects of pellet production (biomass pre-treatment requirements, transportation, plant efficiency and technology) but also on methodological issues in the application of LCA (such as scope and impact allocation approach). One additional paper published by Fantozzi and Buratti [13] describes the LCA of pellet production from a poplar SRC using damage-oriented indicators, not considering the calculation of characterized impact values.

In all these publications, pellets are produced in conventional plants where heat required to dry the raw biomass comes from the combustion of low quality biomass (typically tree tops, branches and bark) in a conventional boiler. However, modern installations tend to incorporate Combined Heat and Power (CHP) systems that allow higher energy efficiencies and improved overall economics of the pellet making process. Another aspect not considered in these analyses relates to the potential application of the ash fraction generated in the pellet plant. The use of this mineral fraction as a fertilizer implies not only economic profits but also environmental benefits depending on the impact allocation approach considered.

The aim of this paper is to quantify the environmental performance of a biofuel chain based wood pellets for use in residential heating using life cycle methodology [22,23]. The main contribution of this paper is to combine, under the same methodological criteria (databases used, impact categories evaluated, calculation hypothesis, etc.), the analysis of biofuel chain based wood pellets considering alternative scenarios regarding plant design (conventional boiler vs. modern CHP system), biomass type (pine, poplar) and origin (forest management, wood processing industry and SRC), and the utilization of ash from the biomass boiler as a surrogate for synthetic fertilizers. The results have been compared against domestic heat production from three conventional energy carriers like natural gas, diesel and electricity. The analysis is based on data from a state of the art commercial installation located in southern Spain.

Other contributions related to the use of characterization factors recommended by the International Reference Life Cycle Data System – ILCD handbook [17]. This guide supports the calculation of indicators for different impact categories in terms of their effects on human health, natural environment and availability of resources in a common integrated framework providing robustness and coherence to the analysis.

2. Methodology

The methodology employed in this LCA is based on ISO 14044:2006 [23], which recommends a system expansion approach in the analysis of multifunctional systems. Hence, in the scenarios where more than one product is generated (pellets, electricity, fertilizer) the impacts associated with the biofuel chain have been attributed solely to the final pellets. Subsequently, the environmental impacts saved as a result of by-products generated in each scenario have been subtracted from those attributed to the pellet system. Saved emissions associated with power generation have been calculated considering the mix of marginal technologies for electricity production in Spain, as suggested by Ekvall and Weidema [9] and Weidema et al. [41].

2.1. Goal and scope

Fig. 1 illustrates the life cycle diagram of the bioenergy system considered in this investigation. The analysis has been structured considering the following life cycle phases: a) biomass production, b) biomass transport, c) pellet plant, d) pelleting & power generation, e) pellet distribution, and f) pellet combustion. The differences between the pine and poplar pellets are shown in Fig. 1 by means of differentiated arrows for each biomass flow used for pellet production. The inventory section provides details about the elements considered in each of these phases.

The bioenergy system analyzed in this paper is based on a state-of-the-art commercial facility located in the Albacete region (Castilla La Mancha, Spain) with capacity for the production of 30,000 t/yr (wet matter basis) of pellets. As shown in Table 1, the real pellet output for the period considered (two full years between 2013 and 2014) was 13% below nominal capacity due to commercial and technical limitations. The plant has a CHP system based on a 3.9 MW_{th} thermal oil boiler that burns the biomass fractions not suitable for pellet making. The hot oil feeds an Organic Rankine Cycle (ORC) for power generation that pours residual heat from the condensation stage into a drying belt, which is used to reduce moisture content in the biomass intended for pellet making. The lifetime of the installation is 25 years.

The objectives of this investigation are to quantify and evaluate:

- the environmental impacts associated with the life cycle of a bioenergy chain based on pine wood pellets produced both from forest management and wood processing activities and their consumption for domestic heating,
- the environmental significance of using biomass from a dedicated energy crop (poplar SRC) for pellet making,
- the environmental and energy implications associated with incorporating a CHP system based on ORC technology for power generation in the pellet plant,
- the environmental consequences of using the inorganic fraction (slag ash) produced by the biomass boiler in the pellet plant as a fertilizer, and
- the performance of the bioenergy system based on pellet making for domestic heat generation against conventional energy systems based on fossil fuels and electricity.

The Functional Unit (FU) considered in this analysis is 1 MJ of net energy produced by a wood pellet domestic boiler. This is equivalent to 64.0 g of pellets when assuming an average heating value (LHV) of 18.84 MJ/kg and a boiler efficiency of 83%.