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Life cycle assessment of bioenergy production from orchards woody residues in Northern Italy

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ABSTRACT

In the alpine Autonomous Province of Bolzano (NE Italy), about 40% of the biomass used for bioenergy production is currently imported. This share is expected to further increase in the near future owing to growing renewable energy needs. The residual biomass harvestable from the local agronomic sector, mostly based on the cultivation of apple, is a promising option to supply relatively cheap bioenergy feedstock. In this study, we investigate the use of woody residues from apple orchards (apple orchard's woody residues, AWRs) for the production of bioenergy using the life cycle assessment (LCA) methodology. The system boundaries include the harvesting and chipping of AWRs, their transport to the energy plant and conversion into heat and power in a gasification unit. The life cycle inventory (LCI) data rely on field measurements for AWRs harvesting and chipping operations, as well as for their chemical and energy characterization. In the life cycle impact assessment (LCIA) phase, we consider various environmental impact categories like climate change, acidification, fossil depletion, and others. We benchmark the outcomes with two alternative reference systems based on fossils fuels.

Our results show that the energy production using AWRs generally presents better environmental indicators than the reference systems, although some trade-offs exist. For instance, whereas the bioenergy system saves up to about 85% of greenhouse gas (GHG) emissions and about 95% of nonrenewable resources, it is usually associated with higher toxicity impact potentials.

1. Introduction

Although mitigation of climate change is a global challenge, active protection of the climate and of the local environment is closely linked to a sustainable energy policy. The Alpine Regions show high levels of awareness regarding climate change. The Climate Action Plan, issued in 2009, requires the development of specific energy strategies based on local and regional conditions and resources (Permanent Secretariat of the Alpine Convention, 2011; Provincia Autonoma di Bolzano, 2011). A common action is to incentivize sustainable local bioenergy chains and promote efficient energy conversion technologies.

In the Autonomous Province of Bolzano (NE Italy) about 40% of wood used today for bioenergy production is imported, especially from Austria and southern Germany (Provincia Autonoma di Bolzano, 2011). The intention of the Province is to increase the bioenergy use from local biomass sources, in order to reduce the Province's dependency on external energy supplies, trigger innovation and boost employment in marginal lands (Provincia Autonoma di Bolzano, 2011). In this area, the additional biomass recovery from local forest is limited by the economic profitability of forest operations (Provincia Autonoma di Bolzano, 2009), and by concerns regarding the negative effects that an excessive forest exploitation could cause on ecosystem services, such as the protection of human beings and infrastructures against natural hazards (e.g. rockfall, landslides and avalanches), cultural, recreational and aesthetic services, etc. (Provincia Autonoma di Bolzano, 2008; Radtke et al., 2014).

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The local agronomic sector, largely based on the cultivation of apple (*Malus domestica*), represents a promising potential option of alternative biomass that is underexploited at the moment. Orchards require annual and cycling cultural operations (i.e. annual pruning and tree removals at the end of the fruit producing cycle) which produce woody biomass material such as branches, trunks and rootstocks. Currently, the trunks of cut trees are used as firewood to feed house-stoves or boilers in the farmers' houses. Pruning residues are grinded and left on the field, whereas rootstocks are sent to compost plants or to the landfill. The exploitation of this residual biomass stream (apple woody residues, AWRs) for energy purposes could represent an option for the diversification of farmer's incomes, besides the possibility to limit the fossil fuel use (Brassard et al., 2014).

Understanding the environmental impacts of bioenergy chains based on woody biomasses has been an important focus of research in the last years. Life cycle assessment (LCA) is an important tool for assessing environmental burdens associated with bioenergy production, "by identifying energy and materials used as well as waste and emissions released to the environment" (Cherubini and Strømman, 2011). LCA is increasingly adopted by legislative documents, including the European Directive 2009/28/CE (European Commission, 2009). Several papers investigated the greenhouse gas (GHG) emissions and energy balances of different bioenergy chains based on forest wood and residues (Cowie et al., 2006; Daystar et al., 2012; Guest et al., 2011; Jungmeier et al., 2002; Valente et al., 2011), or from fast growing species like short rotation coppice (Ericsson et al., 2014; Fantozzi and Buratti, 2010; Njakou Djomo et al., 2013; Sandilands et al., 2009). Many papers also tested the environmental performance of bioenergy based on agricultural residues (mainly cereal straws) (Cherubini and Ulgiati, 2010; Giuntoli et al., 2013; Khatiwada and Silveira, 2011; Luo et al., 2009; Nguyen et al., 2013; Sastre et al., 2014; Whitman et al., 2011; Yang and Chen, 2014). However, woody agricultural residues, such as woody residues from fruit cultivation, have so far received comparable little attention. Some authors (Bessou et al., 2013; Cerutti et al., 2014) reviewed several LCA studies of fruit production systems achieving important insights on how to perform the analysis, but focussing on the main fruit product and not explicitly considering the life cycle of woody residues. Some papers assessed technological, economical and fuel characterization aspects of agricultural woody residues (Magagnotti et al., 2013; Picchi et al., 2013; Spinelli et al., 2012; Velázquez-Martí et al., 2011a, 2011b, 2011c), but we are aware of only one published LCA study investigating a bioenergy chain based on woody residues from apple cultivation (Boschiero et al., 2015). In addition to the well-known LCA methodological issues (Cherubini, 2010; Gnansounou et al., 2008), LCA results can also be very dependent on local aspects and case-specific conditions, which makes the case for undertaking region-specific LCA case studies (Finnveden et al., 2009; Hellweg and Mila i Canals, 2014).

The aim of this study is to assess the environmental performance of using AWRs as bioenergy feedstock in the Bolzano Province. The system produces heat and power from orchards residues, using primary data for the agricultural operations, and it is scaled to the annual volumes of residues produced in the entire Province. The main objectives of the study can thus be summarized as follows: 1) to collect and provide site-specific data of the field operations for the life cycle inventory analysis; 2) to assess the GHG emissions and other environmental impacts derived from the whole value chain; and 3) to compare the innovative AWRs bioenergy chain with two reference system based on fossil-fuels.

2. Materials and methods

2.1. Goal and scope definition

The primary goal of this study is to carry out an analysis of the life cycle environmental impacts of the electricity and heat produced in a hypothetical gasification-CHP plant, fed with AWRs. This study aims to answer the following questions: i) what are the impacts generated by the assessed bioenergy system in the whole Province?, ii) what are the main processes of the bioenergy chain that contribute to the impact categories considered?, iii) does the bioenergy system produce environmental benefits when compared to reference systems mainly based on fossil fuels?

2.2. Functional unit

The functional unit of the analysis is one operational year. In one year, 50.9 $GWh_{el}\ y^{-1}$ (gigawatt hour electricity per year) of electricity and 79.4 $GWh_{th}\ y^{-1}$ (gigawatt hour heat per year) of heat are produced from gasifying the AWRs of the Province in the CHP plant described below. In order to facilitate the comparison with other energy sources and other studies in the literature, we also show the results on a per unit basis, i.e. per megajoule of useful energy (MJ_{ue}), per megajoule of electricity (MJ_{el}) and per megajoule of heat (MJ_{th}) produced.

2.3. System description and data inventory

This study examines one hypothetical bioenergy chain based on a gasification-CHP plant using AWRs as feedstock. Two reference systems are considered for comparison. The systems are schematized in Fig. 1, and they are described in the following sub-sections. Data obtained from direct field measurements are used for the majority of the field foreground processes. Literature data are used to complement the field data, and the Ecoinvent v2.0 database (Swiss Centre For Life Cycle Inventories, 2007) is used for the background processes.

2.3.1. Bioenergy system

Field measurements were conducted in winter 2013 in selected apple orchard sites to sample biomass yields, composition, and process operations. The pruning residues potentially available in the whole Province are estimated to be about 19,261 tonnes of dry weight (t_{dw}) per year, and the wood from removed trees are estimated to be on average 18,052 t_{dw} per year (see Prando et al., 2014a for more details). Table 1 shows the potential yields and the results of the chemical and energetic analysis of the biomass.

Boschiero et al. (2015) show that there are two main different options on how agricultural residues can be assessed in LCA. Essentially, they can be considered either as by-product or as co-product. In the first case, only the downstream processes should be included in the assessment. On the other hand, when agricultural residues are interpreted as co-products, the impacts deriving from up-stream processes (i.e. the crop cultivation phases) are also to be accounted for. In this study, we consider AWRs as by-products, following common practice in the published studies and as explicitly suggested by Baumann and Tillman (2004).

The bioenergy system starts with the biomass harvesting (Fig. 1a). After the pruning operation, residues are collected and chipped immediately with a shredder (Spinelli et al., 2012). Field trials were conducted to assess the diesel consumption of the shredder coupled with a dump bin for chipping and harvesting the prunings. The trials took place in March 2014, on a surface of 20 ha in the land-tenure of the Laimburg Research Centre for Agriculture and Forestry (46° 22′ 59″N, 11° 17′ 18″E). Detailed information

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