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Wood-based bioenergy value chain in mountain urban districts: An integrated environmental accounting framework

Natasha Nikodinoska [a], Elvira Buonocore [a], Alessandro Paletto [b], Pier Paolo Franzese [a,*]

[a] Laboratory of Ecodynamics and Sustainable Development, Department of Science and Technology, Parthenope University of Naples, Centro Direzionale, Isola C4, 80143 Naples, Italy
[b] Council for Agricultural Research and Economics – Consiglio per la ricerca in agricoltura e l'analisi dell'economia agraria –Forest Monitoring and Planning Research Unit (CREA-MPF), Trento, Italy

HIGHLIGHTS

- The Sarentino bioenergy value chain (North Italy) was investigated.
- A multi-method environmental accounting framework was implemented.
- Environmental costs and impacts of a forest bioenergy chain were assessed.
- Indicators show a good environmental performance and sustainability.
- Linking wood industry and energy production could lower the environmental burden.

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ABSTRACT

Using wood biomass for bioenergy production in mountain urban settlements can represent a win–win strategy when it combines a continuous energy provision to households with a sustainable management of local forests, also boosting rural development and stakeholders' cooperation. In this study, we implemented a multi-method environmental accounting framework aimed at investigating environmental costs and impacts of a bioenergy value chain located in Sarentino Valley (North Italy). This assessment framework encompasses material, energy, and emergy demands as well as main emissions generated at each step of the chain: (1) forestry, (2) logistics, and (3) conversion.

The resulting global to local ratios of abiotic material calculated for forestry, logistics, and conversion subsystems show that the global (direct and indirect) consumption of abiotic matter was respectively 3.6, 3.2, and 7.6 times higher than the direct material demand. The Energy Return on Energy Investment (EROI) of wood biomass and wood chips production (37.1 and 22.4) shows a high energy performance of these processes, while the EROI of heat generation (11.35) reflects a higher support of human-driven inputs. The emergy renewable fraction, ranging from 77% to 37% across the value chain, shows a high use of local renewable resources in the bioenergy value chain. The total CO_2 emissions of the bioenergy value chain (4088 t CO_2 yr^{-1}) represent only 7.1% of the CO_2 sequestration potential of the Sarentino Valley forest ecosystem, highlighting the capability of the local forests to offset the CO_2 emissions released by the value chain. The scenario analysis indicates that using both local sawmill residues and local forest wood chips to power the heating plant could further lower the environmental burden of the bioenergy chain, maximizing local and renewable resources use while reducing waste disposal.

The multi-method environmental accounting framework provided a large set of performance and sustainability indicators useful for both local managers and policy makers in charge of ensuring a sustainable management of local forests and energy security of urban settlements.

1. Introduction

1.1. Scientific background

Currently, energy agendas at European [1,2] and Italian national level [3,4] promote renewable energy alternatives and a higher use

* Corresponding author.
E-mail address: pierpaolo.franzese@uniparthenope.it (P.P. Franzese).

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of bioenergy to address the increasing concerns about fossil fuel supply, energy security and diversification, and climate change mitigation [5,6]. Among different renewable energy options, wood biomass shows a high potential to support bioenergy production chains, especially in mountain urban areas [7,8].

An increased use of wood biomass and residues from forestry activities and wood industry could reduce the exploitation of non-renewable resources, lowering impacts on ecosystems and their services, also enhancing local energy supply, rural development and sustainable schemes of natural resources management [8–11]. This is especially the case of bioenergy from forests located in mountain districts, typically characterized by low population density and large forest areas.

Bioenergy from agricultural crops and residues, forestry and wood residues, and municipal wastes currently accounts for about two-thirds of the total renewable energy in Europe [12]. This figure is expected to rise as a response to the commitment of European Union (EU) countries to increase up to 20% the share of renewable energy by 2020 [13]. In this context, the use of forest biomass for bioenergy production represents an important alternative as it has been estimated that the EU's forest biomass supply could increase by 11% from 2010 to 2030 [14].

In particular, Italy has committed to cover 20% of the final energy consumption by renewable energy by 2020. In 2013, bioenergy represented 15% of the power generation from renewables and 71% of the thermal generation from renewables [15].

According to the Italian Biomass Association [16], the setup of sustainable forest management plans for energy purposes, and use of best available technologies and working practices could lead to a higher wood energy availability.

At regional level, South Tyrol (North Italy) set more ambitious climate and energy targets: increase of energy efficiency and reduction of CO_2 emissions by using renewables up to 75% of the total energy sources by 2020, and up to 90% by 2050 [17]. Currently, the local energy production is based on the following energy sources: 49% fossil fuels, 39% hydropower, and 12% other renewables. In the same region, bioenergy based on wood biomass as feedstock accounts for 21% of the total renewable energy production, second only to hydropower accounting for 76% [18]. In South Tyrol, 71 district heating plants are mainly powered by local wood biomass and residues from forest supply chain, generating annually 693 GW h of heat distributed to various municipalities and hamlets. Regarding the local consumption, about 13% is supplied by wood-based bioenergy [18]. Recent statistics on forest management and harvesting operations in South Tyrol region show that, on average, the annual wood felling rate ($1.6\ m^3\ ha^{-1}$) amounts to 30% of the annual increment ($5.5\ m^3\ ha^{-1}$) of the regional forests, far below the potentially sustainable use of wood for timber industry and energy generation [19,20].

Several studies have been conducted to assess the sustainability of wood-based bioenergy.

Lindner et al. [21] developed a tool for sustainability impact assessment of forest-wood-chains in Germany. Ingrao et al. [22] explored the use of agricultural and forest biomass for food, materials, and energy, and the implications for the development of a possible post carbon and bio-based economy. Le Truong and Gustavsson [23] investigated the primary energy efficiency and cost of small scale district heating plants, using conventional (e.g., combined heat and power plant) and emerging technologies (e.g., biomass-based organic Rankine cycle). Kinoshita et al. [24] and Viana et al. [25] studied the woody biomass supply potential and geographical availability for energy purposes in Japan and Portugal, respectively. Fitzpatrick [26] performed an environmental sustainability assessment of using forest wood biomass for heat generation in Ireland. Shabani and Sowlati [27] used a mixed non-linear programming model for tactical value chain optimization of a forest biomass power plant in Canada. Kanianska et al. [28] applied material flow accounting for the assessment of bioenergy and energy savings in Slovakia and the Czech Republic. Forsius et al. [29] modeled the impacts of forest bioenergy use on ecosystem sustainability in Southern Finland. Kukrety et al. [30] assessed sustainable forest biomass potential and bioenergy implications for the northern Lake States region in the United States.

Previous studies have addressed different environmental, economic, and social aspects related to the use of forest biomass for energy purposes in urban settlements located in Italian mountain valleys.

Martire et al. [31] performed a sustainability impact assessment for local energy supplies' development in the alpine area of Lake Como (North Italy).

Valente et al. [32] performed a life cycle assessment (LCA) to explore environmental and socio-economic impacts related to forest wood energy production in Fiemme Valley (North Italy).

Buonocore et al. [33] assessed environmental costs and impacts of forestry activities in Fiemme and Fassa Valley by using a multi-method approach to environmental accounting.

Cavalli and Grigolato [34] used a Geographic Information System (GIS) approach to implement geographical and cost-supply analysis estimating a sustainable amount of logging residues for potential energy use in Pinè Valley (North Italy). Zambelli et al. [35] developed a GIS decision support system (GIS-DSS) for regional forest management to assess biomass availability for renewable energy production in Trentino Province (North Italy), whereas Emer et al. [36] used the GIS approach to compare biomass feedstock supply and demand in different regions in North Italy.

Fagarazzi et al. [37] investigated both the economic and financial feasibility as well as the CO_2 emissions of two types of forest biomass-based plants providing heat to households located in two mountain valleys in Tuscany region (Central Italy). Sacchelli et al. [8] explored socio-economic and environmental efficiency of a wood-residues energy chain in an Alpine area by developing and applying a decision support model based on multi-objective linear programming and spatial analysis. Using the same model, Sacchelli et al. [38] quantified the potential amount of woody biomass from the forest sector at local, regional, and national scale in Italy, and estimated the potential trade-off between the provision of several forest ecosystem services and bioenergy production.

Häyhä et al. [39] assessed, mapped, and valued the bundle of forest ecosystem services including the amount of fuelwood for bioenergy, also exploring the possible trade-offs occurring when maximizing the exploitation of provisioning services in Fiemme and Fassa Valley (e.g., timber, wood chips).

Nikodinoska et al. [40] used the Strengths Weaknesses Opportunity Threats (SWOT)–Analytical Hierarchy Process (AHP) analysis to identify and quantify actual and potential benefits and drawbacks of bioenergy value chain perceived by different categories of stakeholders in Sarentino Valley (North Italy).

1.2. Need and novelty of the study

In spite of the broad and interdisciplinary cited literature, an effort is still required to fully explore costs, impacts, and benefits of wood-based bioenergy production processes. Previous studies on bioenergy systems explored the performance of forestry operations or the efficiency of wood-based thermal plants, most often using a conventional LCA approach focusing on emissions and potential environmental impacts [32,33,37]. Instead, in this study, we implemented and applied a multi-criteria and multi-scale environmental accounting framework exploring the performance and sustainability of a bioenergy value chain from several different viewpoints: (a) money costs, (b) energy costs, (c) material costs,