Resources, Conservation and Recycling 110 (2016) 61–73

Contents lists available at ScienceDirect

Resources, Conservation and Recycling

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

A model for improving sustainable green waste recovery

Dirk Inghels[a,b,*], Wout Dullaert[a], Jacqueline Bloemhof[c]

[a] VU University Amsterdam, De Boelelaan 1105, 1081HV Amsterdam, The Netherlands
[b] University of Antwerp, Institute of Transport and Maritime Management Antwerp (ITMMA), Kipdorp 59, 2000 Antwerp, Belgium
[c] Wageningen University, PO Box 8130, 6700 EW Wageningen, The Netherlands

ARTICLE INFO

Article history:
Received 28 November 2015
Received in revised form 24 February 2016
Accepted 9 March 2016
Available online 26 March 2016

Keywords:
Multi-objective optimization
Flanders
Biomass
Sustainability
Performance evaluation
Green waste valorization

ABSTRACT

Green waste, consisting of leaves, wood cuttings from pruning, and grass collected from parks and gardens, is a source of biomass that can be used for material and energy valorization. Until recently, the EU-Waste Directive 2009/28/EC allowed green waste to be used as feedstock only for compost. This paper presents a framework for examining the most sustainable processing options for green waste valorization in terms of the triple bottom line, People–Planet–Profit. A mathematical model is presented that optimizes profit, as well as environmental and social impact. Four processing options are compared and analyzed: composting, partial separation of wood cuttings prior to composting, partial separation of chopped wood cuttings in the sieve overflow after composting, and a combination of the last two options. Computational results for a Belgian case demonstrate that the optimal sustainable recovery solution is to separate a fraction of the wood cuttings in the sieve overflow for use as green energy feedstock. Additionally, if sufficiently large subsidies are available to separate wood cuttings prior to composting, the optimal solution shifts to one of partially separating the cuttings both prior to composting and in the sieve overflow, and then using the combined cuttings for energy valorization. Whenever cuttings are partially separated the remainder of the green waste is composted.

1. Introduction

Since the Industrial Revolution, the global economy has grown rapidly through the use of mainly non-renewable raw materials as feedstock for products and energy; this has led to the depletion of non-renewable stocks. Over the last decade, this insight has been a stimulus for governments and other involved stakeholders, particularly in Western, developed countries, to begin a transition toward a sustainable society. We define sustainability in business processes as the combined economic, environmental, and social optimum of manufacturing alternatives that take into account constraints, such as technological limits or legislation, also known as the triple bottom line (TBL) approach to People–Planet–Profit optimization (Kleindorfer et al., 2005). Government regulations and legislation play an important role in this transition and in the coordination of the complex trade-offs between economic, environmental, and societal factors (Tang and Zhou, 2012). Quantitative models are rarely used to support such decisions (Seuring, 2013; Dekker et al., 2012). This paper presents a quantitative model that enables policymakers to examine different waste processing alternatives and to identify their most sustainable options, given the relative importance assigned to people, planet, and profit. Without reducing more general application, this paper proposes a sustainability assessment model for optimal green waste recovery. The proposed model can also be applied to select the optimal recovery process from a set of alternatives for other types of waste and biomass feedstock, such as food or wood waste, or lignocellulosic biomass (see e.g. Sharma et al., 2013 for an overview of conversion methods).

Green waste consists of wood cuttings from pruning (hereafter, cuttings), leaves, and grass collected after gardening. The cuttings are desirable for both composting and energy production since dry wood has an energy content of 18,600 MJ/ton (McKendry, 2002). When used as co-firing in a power plant, dry wood can generate on average 1650 kWhe/ton. Until recently, green waste could be used only for compost in the EU. The current version of the EU Waste Directive 2008/98/EC (EP&C, 2008) permits separating a portion of green waste cuttings for energy recuperation if doing so can be shown to be a more sustainable option. Nevertheless composting remains the most common option to recover material from the organic fraction of municipal solid waste because of the possibility to use compost as a fertilizer (Cesaro et al., 2015).

* Corresponding author at: VU University Amsterdam, De Boelelaan 1105, 1081HV Amsterdam, The Netherlands.
E-mail addresses: Dirk.Inghels@vu.nl (D. Inghels), Wout.Dullaert@vu.nl (W. Dullaert), Jacqueline.bloemhof@wur.nl (J. Bloemhof).

http://dx.doi.org/10.1016/j.resconrec.2016.03.013
0921-3449/

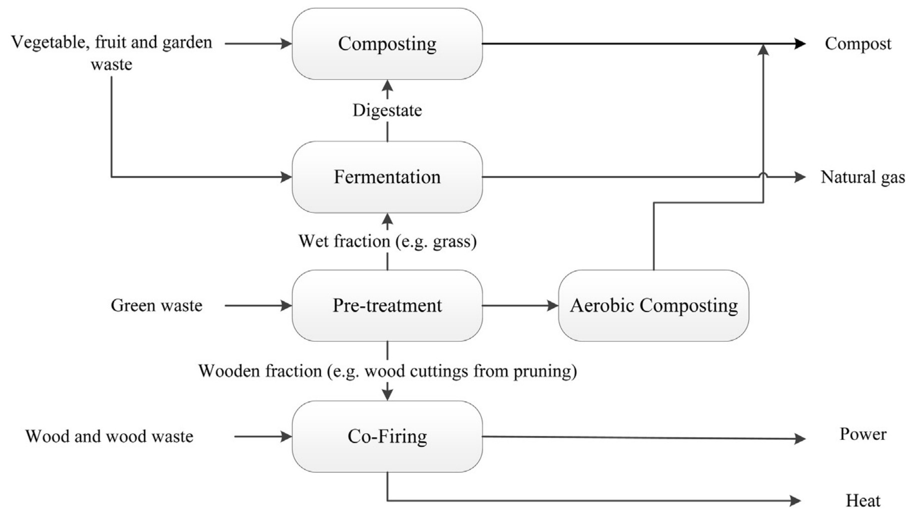

Fig. 1. Alternative green waste recovery processes.

To better explain the problem setting and the need for a quantitative model to assess sustainability effects, consider the main options for green waste material/energy recovery depicted in Fig. 1. Green waste composted in open air, so-called *aerobic composting* (AC), results in compost only. It is also possible to separate some of the wooden fraction of the green waste to be used for co-firing in power plants, depicted as "*Pre-treatment*" in Fig. 1. When used in combined heat power (CHP) installations, the wooden mass of the green waste can produce both power and heat. The remaining fraction of the green waste can be fermented by means of an *anaerobic digestion* (AD) process, which results in biogas that can be added to a natural gas grid after upgrading. The digestate of the AD process then can be composted. The same fermentation process is also applicable for vegetable, fruit and garden (VFG) waste. In many cases, co-digestion of green waste with VFG waste improves energy yield and is more economically viable (Braber, 1995).

Anaerobic digestion (AD) of green waste as biomass feedstock for renewable energy sources (RES) is not economically viable (Pick et al., 2012).

By using a multi-objective mathematical model, this paper will examine the sustainability of the following recovery options for processing green waste: (a) composting, (b) separation of wooden mass prior to composting, (c) separation of wooden mass after composting, and (d) separation of wooden mass prior to and after composting. The separated wooden mass can be used for co-firing in coal power plants generating power and heat.

Using a portion of green waste for energy recuperation could help EU member states, such as e.g. Belgium and the Netherlands, comply with the EU Directive 2009/28/EC (EP&C, 2009)[1] on the promotion of renewable energy resources. EU-targets for the overall share of energy from renewable sources by 2020 have already been reduced for Belgium (13%) and the Netherlands (14%), given their geographical position which results in average sunshine, average wind speed, almost no possibilities to generate hydro power, and limited biomass stocks in combination with highly dense populations. According to the latest figures of Eurostat (2015) both countries still have a huge gap to close. Additional biomass feedstocks such as green waste can help to close this gap. For this paper, we will use Flanders, the northern region of Belgium, as a case. In 2012, Flanders implemented the EU Waste Directive 2008/98/EC (EP&C, 2008) as part of a new Flemish waste directive VLAREMA (Flemish Government, 2012).

Vanneste et al. (2011) showed that the valorization of wood waste in large-scale combined heat power (CHP) systems and co-firing in coal plants offers the largest CO_2 reduction per TJ wood waste for Flanders. The Flemish public Waste Agency, OVAM (2009) already demonstrated the economic feasibility of partially separating cuttings from green waste if at least 15% of the cuttings could be used for energy valorization. However, this study ignored the quantitative environmental and social impacts for the different green waste recovery alternatives examined.

Although co-firing of biomass reduces CO_2 emissions compared to regular power production (Baxter, 2005), co-firing of biomass with coal is generally more expensive than dedicated coal systems. Moreover, co-firing also has some known drawbacks such as fuel preparation, handling and storage, milling and feeding problems, different combustion behavior, possible decreases in overall efficiency, deposit formation (slagging and fouling), agglomeration, corrosion and/or erosion, and ash utilization. The impact of these difficulties depends on the quality and percentage of biomass in the fuel blend. One of the measures to alleviate the difficulties of co-firing is the application of biomass pre-treatment used to modify biomass properties of e.g. density. The higher cost of pre-treatment needs to be evaluated against improved fuel operability (handling, storage, transportation) and operability of the boiler and combustion process (Maciejewska et al., 2006).

The discussion on co-firing illustrates the importance of an integrated approach toward sustainable waste valorization. This paper does not focus on a single waste recovery process as such. Rather, it aims at selecting the waste recovery process that performs best from a triple bottom line perspective.

The remainder of this paper is as follows. Section 2 presents a literature review on sustainable value recovery and sustainability assessment modeling. Section 3 defines the problem statement. Section 4 introduces the model and Section 5 reviews the results. Finally, in Section 6 the research findings are discussed and suggestions for further research are made.

2. Literature review

Sustainable development came on the global agenda as an answer to environmental degradation, lasting poverty, and underdevelopment. The Brundtland Commission (WCED, 1987) defined

[1] By 2020, so-called 20-20-20 climate targets aim to effect a 20% reduction in EU greenhouse gas emission from 1990 levels, raise the share of EU energy consumption produced from renewable resources to 20%, and improve the EU's energy efficiency by 20%.