ARTICLE IN PRESS

Waste Management xxx (2014) xxx–xxx

Contents lists available at ScienceDirect

Waste Management

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

Life cycle costing of waste management systems: Overview, calculation principles and case studies

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ARTICLE INFO

Article history:
Received 29 July 2014
Accepted 31 October 2014
Available online xxxx

Keywords:
Waste management
LCA
Cost
Economy
LCC
Welfare economy

ABSTRACT

This paper provides a detailed and comprehensive cost model for the economic assessment of solid waste management systems. The model was based on the principles of Life Cycle Costing (LCC) and followed a bottom-up calculation approach providing detailed cost items for all key technologies within modern waste systems. All technologies were defined per tonne of waste input, and each cost item within a technology was characterised by both a technical and an economic parameter (for example amount and cost of fuel related to waste collection), to ensure transparency, applicability and reproducibility. Cost items were classified as: (1) budget costs, (2) transfers (for example taxes, subsidies and fees) and (3) externality costs (for example damage or abatement costs related to emissions and disamenities). Technology costs were obtained as the sum of all cost items (of the same type) within a specific technology, while scenario costs were the sum of all technologies involved in a scenario. The cost model allows for the completion of three types of LCC: a Conventional LCC, for the assessment of financial costs, an Environmental LCC, for the assessment of financial costs whose results are complemented by a Life Cycle Assessment (LCA) for the same system, and a Societal LCC, for socio-economic assessments. Conventional and Environmental LCCs includes budget costs and transfers, while Societal LCCs includes budget and externality costs. Critical aspects were found in the existing literature regarding the cost assessment of waste management, namely system boundary equivalency, accounting for temporally distributed emissions and impacts, inclusions of transfers, the internalisation of environmental impacts and the coverage of shadow prices, and there was also significant confusion regarding terminology. The presented cost model was implemented in two case study scenarios assessing the costs involved in the source segregation of organic waste from 100,000 Danish households and the subsequent co-digestion of organic waste with animal manure. Overall, source segregation resulted in higher financial costs than the alternative of incinerating the organic waste with the residual waste: 1.6 M€/year, of which 0.9 M€/year was costs for extra bins and bags used by the households, 1.0 M€/year for extra collections and −0.3 M€/year saved on incineration.

1. Introduction

Over the past decade, increasingly rigorous and systematic documentation of societal consequences related to solid waste management has been required by authorities, technology developers and other stakeholders. This has placed increasing emphasis on the holistic assessment of waste management, in particular on environmental impacts. Meanwhile, the Life Cycle Assessment (LCA) of waste management systems has matured significantly (Laurent et al., 2014a,b; Finnveden et al., 2009), and it is now regularly accepted as a useful source of support for overall decision-making in many countries (Carlsson Reich, 2005). While waste LCA provides a systematic framework for accounting for environmental impacts associated with waste management, most decisions related to the real-life implementation of waste technologies in modern societies are affected by economic constraints. For decision-makers, the lack of a balanced economic assessment alongside traditional LCA results therefore limits the value of the LCA itself, as economic priorities are then de-coupled from environmental aspects.

The economic characteristics of waste management have been addressed in the literature, related either to specific waste management technologies (for example Vinyes et al. 2012; Teerioja et al. 2012; De Feo and Malvano, 2012; Coelho and De Brito,

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http://dx.doi.org/10.1016/j.wasman.2014.10.033
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2013) or to overall waste systems (for example Ricci, 2003; Larsen et al. 2010).

Regarding collection costs, Teerioja et al. (2012) applied a social life-cycle cost analysis, determining that the pneumatic collection system in their study was six times more expensive than a traditional door-to-door waste collection system for a specific area (0.2 km^2 with 20,000 citizens/km^2 and 2000 tonnes of MSW per year). In addition, Groot et al. (2013) developed a comprehensive cost model (including financial and carbon costs) to demonstrate that: (1) the source separation of plastic packaging waste (PPW) was over two times more expensive than post-separation and (2) for source separation options, curbside collection was 2.5 times more expensive than drop-off. Eriksson et al. (2005) assessed the welfare economics of different waste systems applied to easily degradable waste (EDW), plastic and paper. They found that incineration was better than composting and anaerobic digestion for EDW, and it was comparable to recycling for plastic and paper. While these studies naturally reach a variety of conclusions based on differences in framework conditions, very few of them include (1) details of cost calculation principles for the involved waste technologies, as in Groot et al. (2013), (2) details on assessment focus, definitions of system boundaries and assumptions, as in Carlsson Reich (2001) and Eriksson et al. (2005), or (3) clear, transparent terminology for describing assessment principles (for example Vigsø, 2004; Carlsson Reich, 2001; Eriksson et al., 2005). This clearly not only limits the transparency of these studies and the subsequent applicability of the results, but it also illustrates that the economic assessment of waste management systems is a relatively under-developed field.

The economic assessment of waste management systems and technologies involves three context-specific challenges: (1) which type of costs should be assessed (for example private or social costs), (2) for whom should these costs be assessed (for example facility operators, households, public entities or entire systems) and (3) which cost calculation principles should be applied for the individual waste technologies included in a system? Traditionally, private costs (expenses in real money flows incurred by any stakeholder, also called internal costs) are addressed in financial assessments, while social costs (i.e. the sum of private and externality costs) are included in socio-economic assessments (Nordic Council of Ministers, 2007). Waste management systems involve stakeholders with significantly different interests: (1) waste generators (for example households), (2) waste facility operators and (3) waste authorities. The financial costs of a waste management service are often paid by the waste generators (either by waste fees or through taxes), and waste operators are typically involved only in selected parts of the management chain and may consider only costs associated with relevant facilities. On the other hand, authorities, such as local governments, may be interested mainly in the socio-economic aspects of the waste management system. Existing cost assessments of waste systems in the literature offer a wide range of stakeholder's foci and associated cost calculation principles but provide limited guidance on how to assess systematically economic aspects of complex multi-stakeholder waste systems and at the same time relate these findings to LCA results.

Very few examples of combined economic and environmental assessments exist in the literature. Typically, economic assessments are carried out separately from the LCA, most often employing different system boundaries and assumptions (Hunkeler et al., 2008; Swarr et al., 2011; Norris, 2001; Carlsson Reich, 2005), while integrating economic and environmental aspects of waste management within a single assessment has been discussed only in a few cases (for example Carlsson Reich, 2005; Dahlbo et al., 2007). While a variety of approaches to cost assessment have been proposed in the literature (for example Economic Assessment, Financial Assessment, Total Cost Assessment and Cost Benefit Analysis), Life Cycle Costing (LCC) has been suggested as a consistent framework for combining LCAs and economic assessments, involving three types of LCC assessments (Hunkeler et al., 2008): Conventional, Environmental and Societal. A Conventional LCC represents traditional financial assessments (i.e. accounting for marketed goods and services) carried out typically by individual companies focusing on their "own" costs. The Environmental LCC[1] expands the Conventional LCC, in order to be consistent with the system boundaries of the LCA. This is also a financial assessment, albeit costs incurred by all the affected stakeholders are included. The Societal LCC further includes externality costs (i.e. it "internalises" environmental and social impacts by assigning monetary values to the respective effects), by using accounting prices. Societal LCCs may also be characterised as "socio-economic" or "welfare-economic" assessments. The three types of LCC thereby offer an overall framework for systematic economic assessments either in combination with LCAs or as stand-alone indicator.

Based on LCC principles and terminology, this paper aims at providing a consistent and comprehensive framework for the economic assessment of waste management systems. This is achieved by (1) developing systematic cost models for all main activities related to waste management (for example source segregation, collection, treatment and final disposal) based on transparent technical parameters associated with the involved technologies, (2) implementing the cost model framework on two selected case study examples illustrating the management of household waste and (3) on this basis, evaluating applicability and identifying critical methodological aspects related to LCC on waste management systems.

2. Methodology

2.1. Terminology

The naming principles introduced by Hunkeler et al. (2008) and Swarr et al. (2011) were applied in this study. Overall, costs can be distinguished between "internal" and "external," whereby internal costs are monetary costs occurring both inside and outside the waste management system, while external costs (also termed "externality" costs) occur outside the economic system (also called "non-marketed goods/services" because they have no direct monetary value in the market). Internal costs can be measured either in market prices or in factor prices, the latter are market prices excluding transfers (taxes, subsidies, fees and duties used to distribute income between different agents in society, but which do not represent any resource reallocation) (Nordic Council of Ministers, 2007). The sum of internal costs and external costs represents social costs, here defined as society's costs for managing waste (Porter, 2002). The cost model differentiates between three types of costs: (1) budget costs, (2) transfers and (3) externality costs. Budget costs and transfers are characterised as internal costs, while externality costs, as the name suggests, are external. Budget costs are included in all three LCC types, transfers only in Conventional and Environmental LCCs and externality costs only in Societal LCCs. Table 1 provides an overview of cost types related to solid waste management.

Budget costs are incurred by waste agents, for example households, as waste generators or technologies/facilities operating within the waste system. Budget costs can be either "one-off" occurring once in the lifetime of a technology (for example capital investment or back-end costs), or recurring (for example

[1] The name "Environmental LCC" is used to emphasize that this type of assessment is intended to be consistent with an environmental assessment, i.e. LCA.

Please cite this article in press as: Martinez-Sanchez, V., et al. Life cycle costing of waste management systems: Overview, calculation principles and case studies. Waste Management (2014), http://dx.doi.org/10.1016/j.wasman.2014.10.033