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Life Cycle Energy Assessment of Pneumatic Waste Collection Static Systems: A Case Study of Energy Balance for Decision-Making Process

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Waste collection presents a significant influence in the environmental sustainability of municipal solid waste (MSW) management. Conventional door-to-door collection consumes high amounts of fuel for waste transportation, thus generating significant direct greenhouse gas emissions (GHG). Pneumatic collection emerges as an alternative to conventional trucking system, comprised by an underground network of long distance pipelines that carries MSW fractions to a central collection plant where the waste is collected and compacted. Such systems represent a way of arranging waste collection in densely populated urban areas and have recently been used in the design of smart cities to control waste flows. While this technology apparently reduces direct air emissions, suffers from large energy demand derived from vacuum production for waste suction. This work compares both conventional door-to-door and pneumatic collection systems from a life cycle approach, obtaining that the latter accounts for 5 and 3 times more energy demand and CO_2-eq. emissions than conventional collection, respectively. Results suggests that the electricity consumption and the origin of electricity have a significant influence on the results, since vacuum production is responsible for more than 99 % of the total impacts for pneumatic scenario, while diesel for trucking accounts to around 70 % of the conventional system impacts. Greener electricity mixes and less energy consuming materials are required in order to ensure the environmental sustainability of pneumatic systems.

1. Introduction

By 2050 it is expected that around 70 % of the population will move to urban areas, constituting vast cities. Such cities will require a smart sustainable infrastructure to manage citizens' needs and offer fundamental and more advanced services (Anagnostopoulos et al., 2017). Under such framework, the efficient management of waste is essential to ensure the sustainability of smart cities. In particular, waste collection accounts nowadays for 50-75 % of the total municipal solid waste (MSW) costs and is one of the life cycle phases that influences the environmental sustainability of waste management (Teerioja et al., 2012). The method used for MSW collection compromises the recovery of the wastes. The conventional management of wastes rely on the manually collection from open containers placed in the street for its transport in heavy trucks, passing through residential areas. Wastes are long-distances transported to processing or disposal facilities, while consuming fuel that generates air emissions and economic and public health costs. While sewer pipelines are now extensively used to minimize the costs and negative impacts of removing liquid sanitary wastes, most cities still depend on trucks for removing municipal solid waste (Miller et al., 2014).

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One alternative to conventional MSW trucking collection is pneumatic transportation. This technique consists on the transportation of waste through an underground network of long distance pipelines to a central collection plant. The transportation is conducted using vacuum and each fraction is directed into its own container, for later full containers be transported to final processing and disposal sites by trucks (Punkkinen et al., 2012). Pneumatic waste collection systems have been already used in hospitals for decades and hundreds of municipal-scale pneumatic collection systems have been installed in Europe and Asia. This method reduces the need for trucking collection, noise and odour effects, thus presenting potential space savings and apparently lower GHG emissions related to fuel consumption. However, the system is unsuitable for large items, hazardous waste and liquid waste. Taking into account the great influence of energy on costs and related environmental impacts, it is necessary to research on actual energy use across existing installations. So too is further research on improving energy efficiency, so that energy balances throughout the life cycle could contribute to optimize the operation of these facilities.

2. Methodology

Life-cycle assessment (LCA) is a tool to assess the potential environmental impacts and resources used throughout a product´s life-cycle (Margallo et al., 2016). LCA has been widely applied to the evaluation and comparison of waste management strategies and activities from the system perspective (Pisoni et al., 2009). Some studies specifically focus on the role of the waste collection and transportation phase in the waste management system, demonstrating the significance of such stages when assessing the environmental sustainability of alternative waste management approaches. The reported LCA study is carried out in accordance with the requirements of the ISO 14040 (2006a) and ISO 14044 (2006b) international standards. According to them, LCA should be applied in 4 stages: (a) definition of the goal and scope of the study, (b) life cycle inventory (LCI); (c) life cycle impact assessment (LCIA) and (d) interpretation. The impact assessment method follows the ILCD/PEF recommendations v1.09 for determining the global warming potential (GWP). The consumption of Primary energy resources (net calorific value) is determined according to PE International (2014) life cycle inventory.

2.1 Goal and scope

The goal and scope have to include the intended application of the study, the system boundaries, the functional unit and the level of detail to be considered. The goal of this work is to compare the primary energy demand and the carbon footprint of conventional door-to-door waste collection to its hypothetical pneumatic alternative waste collection systems by means of LCA.

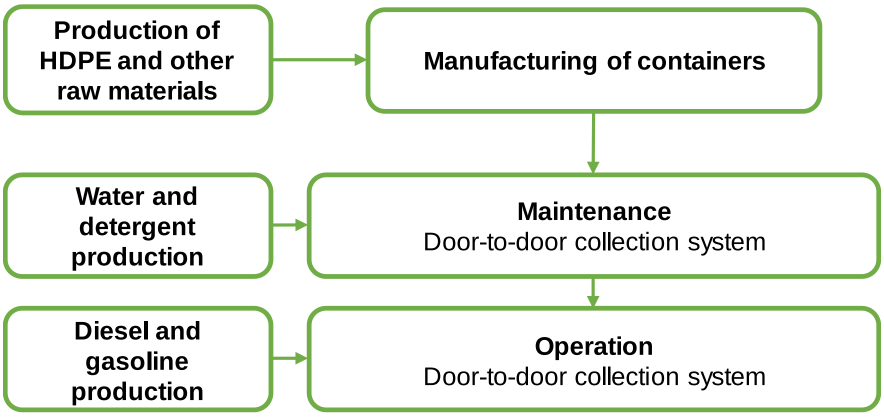

Figure 1: System boundaries of the door-to-door collection scenario

The system boundaries determine which unit processes shall be included within the LCA. In this case, the processes are studied from cradle to gate, which comprises the manufacturing, operation and maintenance stages as shown in Figures 1 and 2. The manufacturing of components includes the extraction and treatment of the raw materials, i.e. stainless steel cold rolled and high density polyethylene (HDPE) for bins and/or pipes production. The use stage considers the operation and maintenance of the system, considering the transporting of waste flows from bins to waste collection plant. The stage of manufacture of the waste collection plant was excluded from the analysis, since it can be reasonably assumed that, when expressed per unit of waste treated, their contribution to the waste management life cycle will be minimal, compared to the environmental impacts caused by other processes involved, and considering the long useful life of these infrastructure. The manufacture and installation of the waste collection plant was also excluded from the analysis, since it can be reasonably assumed that, when expressed per unit of waste treated, their contribution to the waste management life cycle will be minimal, compared to the environmental impacts caused by other processes involved, and considering the long useful life of these infrastructure.

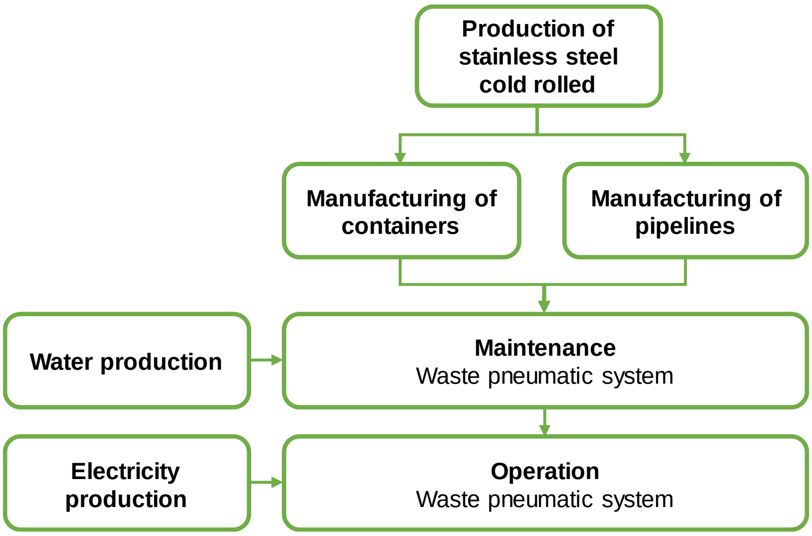

Figure 2: System boundaries of the pneumatic waste collection scenario

The functional unit is the quantified performance of a product system for use as reference unit based on ISO 14040 guidelines (2016a). In this work in particular, the collection and transportation of one tonne of MSW for Spain as an input to the system under study is selected as functional unit (FU).

2.2 Data collection

LCI is one of the most effort-consuming steps of an LCA and consists on the collection of the relevant input and output data for the assessed systems (Garcia-Herrero et al., 2017). Hereafter, the data sources and main assumptions for both scenarios under study are explained.

2.2.1 Door-to-door collection

Primary data were obtained from the Spanish Ministry of Environment and Rural and Marine Affairs (MERMA, 2011), while secondary data were sourced from PE International database (2014). The fuel consumption rates were estimated at 3.98 and 0.07 L of diesel and gasoline per collected tonne of waste (MERMA, 2010). Emission factors for transport were assumed at 2.51 and 2.21 kg CO2-eq per litre of diesel and gasoline, respectively (MAPAMA, 2016). Energy demand and emission factors for fuel production were taken from PE International database (2014). Based on MERMA (2011), containers requirements are estimated at 0.107 m3 per FU. All fractions have been assumed to be deposited in a polyethylene high density (HDPE) bin, which has been modelled assuming the following composition: 74.75 % HDPE, 21.57 % steel and 3.68 % styrene-butadiene-rubber (Table 1). A lifetime of 7.5 y has been assumed for containers. The bin is considered to be washed 6 times per y, using 0.35 kg of detergent per m3. The LCI of the system is shown in Table 2.

Table 1: Life cycle inventory for the high polyethylene density (HDPE) container. Units expressed per m^3 container per y, considering a 7.5 y lifetime

Input	Units	Quantity
HDPE	kg·m^3 container	4.61
Steel	kg· m^3 container	1.33
Styrene-butadiene-rubber	kg· m^3 container	0.227
Detergent	kg· m^3 container	2.22
Water	m^3· m^3 container	84.7

Table 2: Life cycle inventory for door-to-door collection system. Units expressed per functional unit (FU) of the study, which 1 t of waste entering the system

Input	Units	Quantity
Container	$m^3 \cdot FU^{-1}$	0.108
Diesel	$L \cdot FU^{-1}$	3.98
Gasoline	$L \cdot FU^{-1}$	0.07

2.2.2 Pneumatic collection

Primary data were provided by Ecoembes and the two main companies that manage the pneumatic system in Portugal and Spain, Envac Iberia and Ros Roca. Secondary data were taken from the literature and PE International database (2014). Data collection is explained according to three main infrastructure stages in the system: waste collection plant, central collection points and underground pipes. LCI is displayed in Table 3.

- Waste collection plant

The waste collection plant is the infrastructure where all the waste gathered in the collection points is carried through the network of underground pipes. Then, waste is compacted and deposited in a container until it is full. The energy consumed in the system is due essentially to the suction and compaction waste operation from the waste collection plant. The suction stage is estimated to work 3,500 h/y at 220 kW. The average compaction demand is established at 15 kW for 1,100 h annually.

- Central collection points

The central collection points refers to the different bins located in public streets or indoors, where citizens can deposit the different waste fractions. Bins are connected to the underground network by means of valves, whose environmental impact has been assumed negligible in comparison to the rest of the system. The number of bins per collection point depends on the separate waste fractions managed (Ros Roca, 2011). Only one fraction has been considered in this study. A 9 y lifetime is assumed for the bins (Hernandez, C., 2010). Two different containers composed the system: a sidewalk container, entirely made of stainless steel, and an indoors bin, made of stainless steel and a small fraction of fiberglass and aluminium (Envac, 2010). Both containers have been assumed to be constituted entirely by stainless steel. According to Ecoembes (2011), 70 bins per collection point are located, each weighting 40 kg (Medina, 2009).

- Underground pipes

The underground network of pipes consists of stainless steel pipes with and average length of 1 km per station line and an inner diameter of 50 cm and 12.5 mm of thickness. On the inside of these pipes a stream of air is running transporting waste bags at a speed of 90 km/h. A 30 y lifetime is considered for them (Medina, 2009).

Table 3: Life cycle inventory for the pneumatic system

Input	Units	Quantity
Stainless steel cold rolled	$Kg \cdot FU^{-1}$	0.0487
Electricity	$MJ \cdot FU^{-1}$	437.58
Water	$m^3 \cdot FU^{-1}$	0.0001

3. Results

Results for the LCIA are shown in Figure 2. Regarding energy indicator, pneumatic collection exhibits the largest primary energy demand, estimated at 1,291 MJ/t collected waste. This involves a 5.3 times higher dependency on energy resources than the conventional door-to-door collection. The reason of such difference lies mainly in energy requirements for vacuum production, which accounts for 99.74 % of the total energy embedded in the process. Regarding conventional collection, diesel production for trucking is responsible for 70 % of the primary energy demand, while the rest is mainly attributed to the production and maintenance of containers.

The difference between both scenarios is less dramatic regarding GWP, since pneumatic collection accounts for 3 times more CO2-eq emissions than conventional collection (Figure 2b). Again, electricity production for vacuum production accounts for the majority of impacts (99.5 %). Conversely, door-to-door collection is essentially penalised by diesel combustion, which represents 74 % of the GWP. These results for GWP agree with the findings of Punkkinen et al. (2012) for Finland, which also estimated a 3 times larger CO2-eq emissions for the pneumatic system.

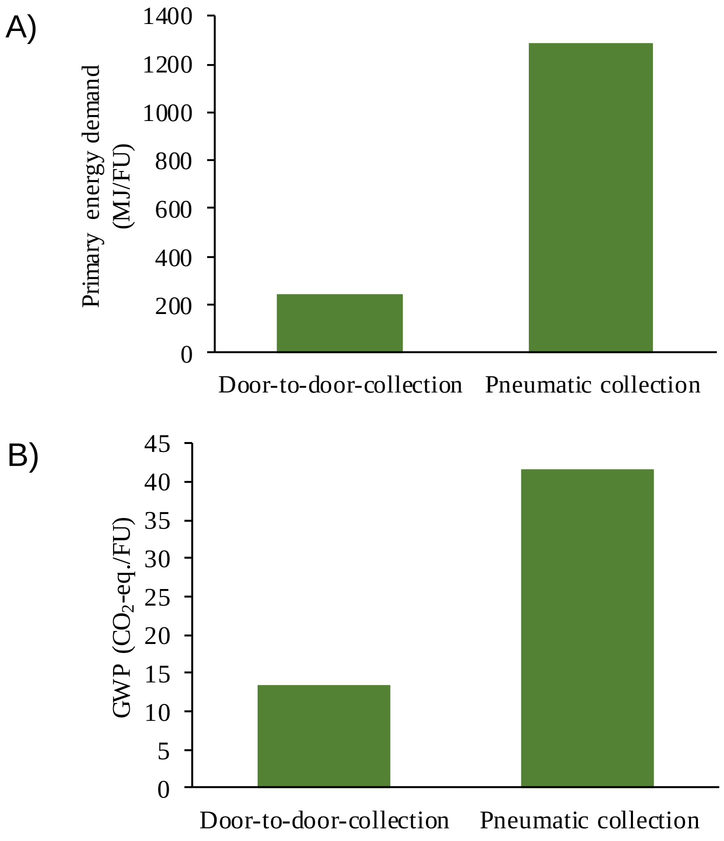

Figure 2: A) Results for primary energy demand. B) Results for global warming potential (GWP). Estimations expressed per functional unit (FU)

As shown, results indicate that replacing the prevailing system with pneumatic waste collection would increase primary energy demand and GWP. The electricity requirements of pneumatic system for vacuum production presents a major influence on the results of the study. Consequently, reducing the dependency on non-renewable resources for electricity production is key in order to ensure the sustainability of the system. Although the pneumatic collection system offers some advantages in terms of service quality and quality-of-life benefits, energy demand and GWP depends on specific local circumstances.

4. Conclusions

According to the results of the study, the implementation of a pneumatic system in a hypothetical Spanish city, would increase the dependency on energy resources and the emissions of greenhouse gases 5 and 3 times with regard to the conventional door-to-door collection system, respectively. The electricity requirements for vacuum production are the main responsible for such results, sharing more than 99 % of the impacts under study. Reducing energy consumption for waste transport through the underground system and using a more environmentally friendly electricity mix seem the main improvement measures to ensure the sustainability of the pneumatic process. This study contributes to decision-making in waste management strategies and enables the introduction of the environmental variable in the design model of smart cities. In addition, this study comprises the basis for the future optimisation of pneumatic collection as hybrid systems feed by renewable energies.

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