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# Life cycle assessment (LCA) of a pneumatic municipal waste collection system compared to traditional truck collection. Sensitivity study of the influence of the energy source

Marta Chàfer [a, b], Francina Sole-Mauri [a], Aran Solé [c], Dieter Boer [d], Luisa F. Cabeza [a, *]

[a] *GREiA Research Group, INSPIRES Research Centre, University of Lleida, Pere de Cabrera s/n, 25001, Lleida, Spain*
[b] *CIRIAF-Interuniversity Research Center on pollution and environment Mauro Felli, Via G. Duranti 63, 06125, Perugia, Italy*
[c] *Department of Mechanical Engineering and Construction, Universitat Jaume I, Campus del Riu Sec s/n, 12071, Castelló de la Plana, Spain*
[d] *Departament d'Enginyeria Mecànica, Universitat Rovira i Virgili, Av. Països Catalans, 26, 43007, Tarragona, Spain*

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## ABSTRACT

The study of waste management strategies is increasing worldwide due to the necessity of a more sustainable environment. In this framework, guaranteeing cleaner energy is the key parameter for cleaner production, especially for reducing the emissions of greenhouse gases and other pollutants to the environment, which are directly related to the types of the energy sources used. Through the methodology of LCA it can help in the study of the environmental part. This study is based on the methodologies ISO 14040 and 14044 for obtaining quantitative results on the environmental impact, from cradle to grave, of different waste collection systems. A sensitive study of the influence of the energy source on the life cycle assessment (LCA) is analysed for six different waste collection systems (trucks - electric, gas, diesel, diesel-electric, gas-electric - and stationary pneumatic waste collection) and five energy sources (Spanish energy mix 2008, hydropower, photovoltaic, wind, and a renewable energy mix). The results show that the energy source has a big impact in the results of the LCA with variations up to 80%. The environmental impact of each collection system depends strongly on the source of the energy used and thus, decision-makers should consider the energy source and the expected evolution of energy mix when considering the best waste collection systems from an environmental point of view. In a framework with a majority of fossil-sourced energy, the truck collection shows lesser environmental impact, due to its lower electricity use, whereas in a renewable energy environment, the stationary pneumatic waste collection shows better performance.

## 1. Introduction

There is an increasing awareness of the importance of energy use and a growing concern about its source. Ellabban et al. (2014) stated that the limited sources of fossil fuels, in addition to the need to reduce greenhouse gases emission, increased the request for renewable resources, which, in principle, can exceed the world energy demand. In that context, cleaner production is based upon holistic and preventative approaches, which if implemented society-wide can help in progressing towards more sustainable societies (Yong et al., 2016).

In the short term, the set of EU and national specific policies that promote renewable energies (RES) drive a significant penetration of RES in power generation (EC, 2016). By 2020, RES in power generation are projected to increase to 35.5% (RES-E indicator51) or 37.2% of net electricity generation, of which 52% are projected to be variable RES (wind and solar). Policies on promoting RES also indirectly lead to energy efficiency gains; in statistical terms many RES, such as hydro, wind and solar PV, have an efficiency factor of 1; thus, the penetration of RES in all sectors, in particular in power generation, induces energy savings in primary energy terms (EC, 2016).

The increase in the world population, a greater consumption of food and products is related to a more important generation of wastes causing impacts on the environment, which compromise a sustainable future (Severo et al., 2018). Waste management, especially waste collection, has a significant effect on the environmental

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* Corresponding author.
*E-mail address:* lcabeza@diei.udl.cat (L.F. Cabeza).

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sustainability of a society. As the world population becomes more urbanized and affluent, the increase of waste generation is putting enormous pressure on local governments (Khandelwal et al., 2019; Rodrigues et al., 2018). Solid waste management is one of the key parameters in cities and countries since the effects of waste mishandling are well known (Bogner et al., 2008; Miller et al., 2014). For that reason, nowadays ensuring cleaner production is a key factor in cities.

According to Pérez et al. (2017a) solid waste management has two differentiated parts, the collection, and the treatment or disposal, nevertheless other studies considered a first step, the temporary storage (den Boer et al., 2007). Regarding the collection, most cities still rely on trucks to move municipal solid waste from the city to the treatment facilities. However, in the last twenty years the pneumatic waste collection has been attracting a lot of attention and some cities have started to use it (Miller et al., 2014).

The costs and benefits of pneumatic collection vs. conventional truck waste collection were described in Miller et al. (2014). Those authors stated that the costs and impact of specific pneumatic installations will vary a lot depending to the pneumatic design characteristics (such as number of tonnes managed, number of waste fractions, length of tube network, number of inlets, etc.) and the conventional system characteristics (distances between garage, route, dump site, truck type, waste generation density, etc.). Punkkinen et al. (2012) listed as benefits of pneumatic waste collection systems the reduction of local $CO_2$ emissions, less congestion, and less noise due to the reduction of trucks circulation; general improvement of hygiene, reduction of contamination, odours and pests, and potentially positive effects on both residential and occupational safety.

However, the pneumatic waste collection should also be evaluated from an environmental point of view. Within this context, life cycle assessment (LCA) is an available tool recognized as being able of capturing and addressing the complexities and interdependencies, which typically characterise modern integrated waste management systems (Blengini et al., 2012) Evaluating the environmental performance would help decision-maker in selecting the best management strategy with minimum impacts on the environment (Khandelwal et al., 2019). Different authors have performed different LCA in different locations with different systems, as summarized below.

Iriarte et al. (2009) used LCA to compare the overall impact potential environmental impact of three waste collection systems in dense urban areas: mobile pneumatic, multi-container, and door-to-door systems. Those authors concluded that at the urban level the collection system with lower impact is the multi-container one, and that the door-to-door system has the highest energy demand, 57% higher than the multi-container and 38% higher than the pneumatic one.

Aranda Usón et al. (2013) compared a stationary pneumatic waste collection system with a truck collection system in the neighbourhood of Valdespartera (Zaragoza, Spain). Trucks, in this case, used diesel fuel. Results showed that, when operating at loads close to 100%, the pneumatic collection system had the best environmental performance than the conventional system. Those authors discuss that the emissions avoided are higher than those generated. Thus the net performance has a negative value. However, when operating at low load, under design capacity, the conventional system is shown to be a better alternative.

Traditional waste collection systems have also been compared using LCA. For example, Rives et al. (2010) compared the characteristics of the waste container model that they evaluated as most relevant. The waste containers compared were the container model (done with HDPE or steel) varying volume and weight. Authors found that HDPE containers had a higher impact than the steel ones and that the bigger containers had less impact than the small ones.

Pérez et al. (2017b) estimated the carbon footprint of a truck waste collection system for the specific case of Madrid, but unlike the previous studies, actual data about the fleet, fuel consumption, journeys, and collected waste mass was used. The situation in Madrid in 2013 was compared to that in other Spanish cities and to past scenarios in Madrid. The collection systems considered in this paper were the use of compressed natural gas-powered trucks, diesel-powered trucks, and tone where it is considered that the gas used by the trucks comes from the anaerobic digestion of the collected organic wastes. The authors concluded that the carbon footprint of the municipal solid waste collection and transport fleet is conditioned by the boundary conditions of the system and the initial assumptions set for each study, as well as by the local, regional and national conditions to which they apply. The main differences involve the life cycle stages considered and the type of data used in the LCI.

Peri et al. (2018) highlighted the role of the transportation of waste in the evaluation of the environmental impact exerted by a MSW management system, which also said that the transportation segment affects up to 50% of the whole environmental impact. A pneumatic waste collection system seems to be the most promising system, but there are some points that need further research to assess its impact.

Turconi et al. (2013) provided a review of important emissions from electricity generation technologies based on a critical review of 167 existing LCA in the literature. The authors concluded that the incorrect or inappropriate use of emission data and LCA results might generate wrong conclusions, being the most critical aspects affecting the results the functional unit definition, the LCA method used, and the allocation principle. The pneumatic waste collection system, with its suggested potential for increasing hygiene and safety levels in waste collection, is an example of an innovative waste collection technology. This system also reduces the need for vehicle transportation in collection areas, thus reducing noise and congestion effects and presenting potential space savings (Kogler, 2007). In addition, Oh et al. (2016) confirmed that in South Korea, the value of per capita generation of general waste in a city with a pneumatic waste collection system showed 147.73 g/(day·capita), which is 20% less than that with trucks delivered (185 g/(day·capita)).

When evaluating different waste collection systems in terms of LCA for the same area and using real data, it can be seen the electricity has high impact in all scenarios studied, to the extent that electrical collection trucks resulted with higher impact than their diesel equivalents. When assessing this in detail, the database used in that study, Ecoinvent v.3.0, obtained the energy source data from the energy mix for Spain of 2008. The environmental impact associated with the electricity consumption depends on the production method and emission factor of the power used. Hidalgo et al. (2018) also studied the impact of the waste collection system in Barcelona and highlighted that vacuum system needs more electrical energy but fewer fossil fuels when compared with the traditional trucks collection system.

Therefore, the comparison, using real data, of a static pneumatic waste collection plant with the collection of different truck systems has never been carried out. To fill this gap, in this study the pneumatic waste collection system in Barcelona (Spain) has been environmentally compared to the collection with five different truck collection systems: diesel, gas, and electric trucks, together with hybrid ones (both diesel and gas-hybrid trucks). Moreover, in this study the effect of the electricity source and its associated environmental impact and its relative shares of loads due to the electricity consumption of different waste collection systems was analysed. Compared to the baseline result for the energy mix for

Spain in 2008 (scenario 1), the energy source impact in the LCA of municipal waste collection, by considering 100% hydropower (scenario 2), 100% photovoltaic (scenario 3), 100% wind (scenario 4), and a renewable energy mix (scenario 5).

## 2. Methodology

### 2.1. Considered waste collection systems

The study was carried out for the case study of the area of 22@, in Barcelona. 22@, also known as 22@Barcelona and Districte de la innovació (Innovation district), is the corporative name given to an urban renewal area in Barcelona. From 2001 to 2009, the resident population in 22@Barcelona grew 22.8%, from 73,464 inhabitants to 90,214. This increase is 15% higher than the average for the city of Barcelona, which experienced a growth of 8% between 2001 and 2009. The average growth for the metropolitan area in this time period was 13.7% and for Catalonia, 17.9% From 2007 to 2014 the population grew 3.69%, closer to the growth of the city during the same period (Barcelona, 2018; "Barcelona Catalonia," 2018).

Two different waste collection systems were considered, a pneumatic system and the traditional truck collection (Fig. 1). Both systems were located in the same area of Barcelona and to reach the same endpoint, a recycling facility endpoint located at Gorchs Lladó street 134, Barberá del Vallés in Barcelona.

The pneumatic collection system uses waste collection points, which can be outside or inside a building, where the waste is thrown, and it is moved through a transport network, mainly formed by pipes, to a collection centre (Fig. 2). In the collection site, the residue is pressed by fractions to reduce the amount of air before its final transport to the endpoint, which is usually a municipal waste treatment plant. This is the case for stationary pneumatic systems. On the other hand, there are mobile pneumatic systems which use trucks to transport the waste from a group of containers to the truck. Then, the truck moves to the next suction point, where the action is repeated until all the containers are emptied.

During the process of pneumatic collection fans, cyclones, compactors, and more industrial machinery type equipment that consume electricity should be considered. By means of a control system, the collection process is initiated by creating an airflow that sucks the waste from its waste collection point to the collection centre. Once the waste reaches the collection centre, it is separated according to the fraction to which it corresponds (organic, packaging, paper and cardboard, or unsorted) and it is pressed by fraction in the container that will be used for its subsequent transport to a treatment plant by trucks.

In addition, the building has a biofilter that allows filtering the air, which is collected in the collection central, by its passage through a base of poplar bark, which only requires a minimum consumption of water to maintain humidity and that it is a sustainable environmental option to purify the air of particles or odours before being poured into the atmosphere.

The traditional urban waste collection system is based on trucks that perform an urban route collecting each fraction of waste that is then transported to an urban waste treatment plant. In this system, different scenarios were considered varying the type of truck according to the fuel used. The five scenarios considered were: diesel trucks, diesel-electric hybrid trucks, gas trucks, gas-electric hybrid trucks and fully electric trucks. In addition, the total number of containers of each fraction of the area under study was also quantified.

In this collection system, trucks leave the truck park to go to the first container, and do their route stopping at each container of the fraction they are collecting. In each island of containers and for each fraction, the container is emptied and the waste pressed inside the truck. When the truck reaches the filling coefficient established (usually 75% - defined by the manufacturers) it goes to the waste treatment plant. The truck will make as many trips as necessary to complete the collection in the area assigned and finally returns to the truck park. The number of kilometres travelled for each fraction type is presented in Table 1 and the total waste collected per day in Table 2, as provided by the operating company.

The assumptions considered of the systems are the following: For all the systems, the worst case scenario is chosen when the required information is not available in the database.

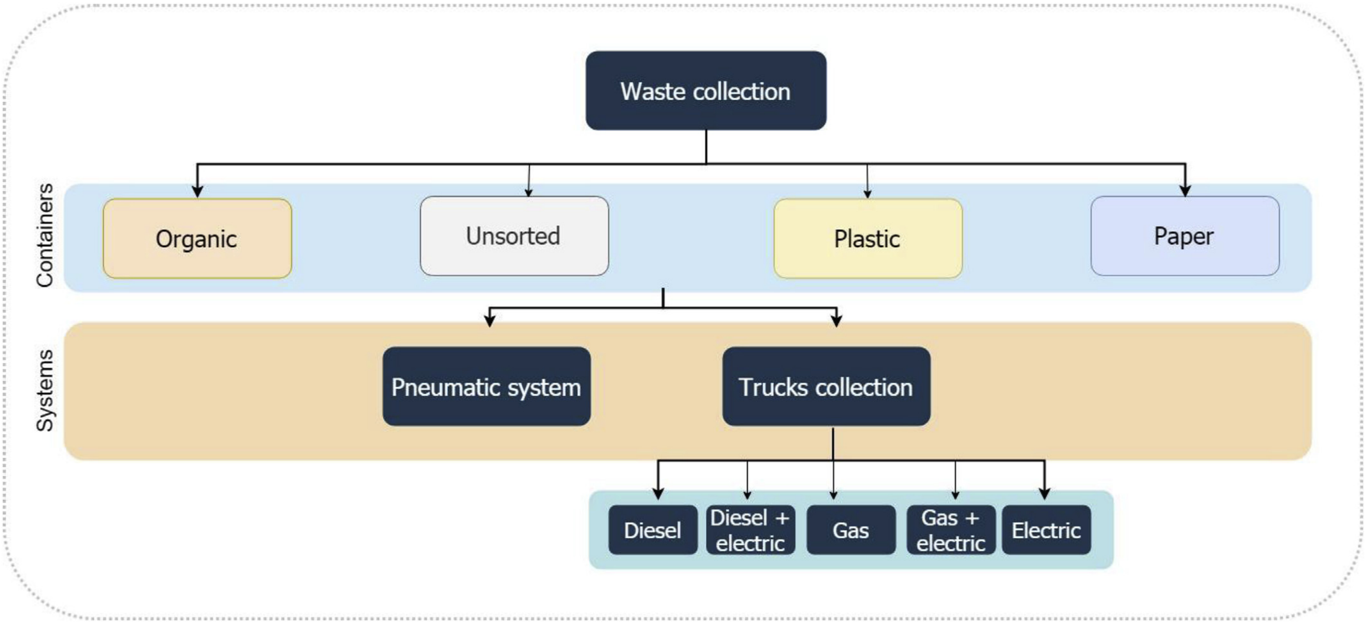


**Fig. 1.** Waste collection systems studied.

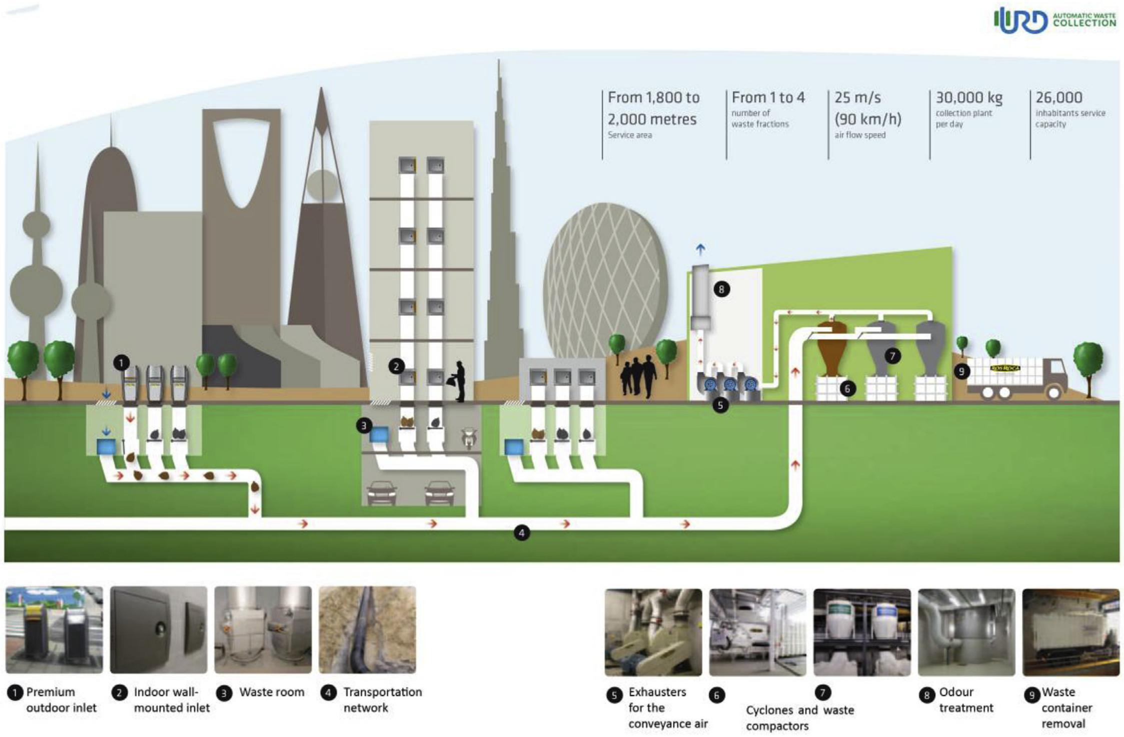


**Fig. 2.** Pneumatic waste collection system.

**Table 1**
Distance (km) travelled by the trucks collecting wastes.

| Waste fraction | km travelled in the city (collecting) | km travelled by road[a] |
|---|---|---|
| Organic | 26.5 | 196.5 |
| Paper | 59.5 | 124.5 |
| Plastic | 51.5 | 88.5 |
| Unsorted | 33.0 | 124.5 |

[a] Distance travelled from the Central of trucks to the containers of the 22@ + distance from the city to the landfill.

- Pneumatic waste collection: The construction of pneumatic pipes has been considered as perforations 0.5 m deep. After 30 years pipes, manholes, valves, and mailboxes will not be removed. Lifetime of 50 years of the building of the collection centre is considered. The equipment of the plant is considered to be recycled at the end of their lifetime and replaced throughout the 30-year operation considered. Real data was used for electricity and water consumptions.
- Traditional truck collection: Diesel trucks were assumed to weight 940 kg, while hybrid diesel-electric trucks had two engines, the diesel engine with 700 kg and the electric one with 637 kg. Gas trucks were assumed to have a power of 206 kW, while hybrid gas-electric trucks had two engines, the gas engine with 105 kW (since the indicator was not available in the database, a 206 kW engine was considered - worst case scenario) and an electric one The period of the replacement of the trucks is considered every 9 years and the batteries of electric and hybrid trucks every 10 years. The containers, every 5 years. The area of the truck park has an is 10700 m2 and a useful life of 50 years. This LCA does not consider the location of the manufacturing industries and the transport between the industries and Barcelona is not considered. weighing 637 kg. Finally, the electric truck was assumed to have an electric engine of 637 kg - The maintenance of parts of the containers was not taken into account since it is minimal due to the replacement every 5 years. However, cleaning was considered. The fuel consumption is considered different for each different truck operation. The hypothesis of the end-of-life phase was for containers, all trucks, building of the collection centre (dismantling) and compressed air dryer.

## 2.2. Description of the scenarios

To the best of the authors knowledge, the consideration of the effect of the energy source and its environmental implications has never been analysed before in the study of the waste collection systems. In order to analyse the effect of the use of different sources of energy, five scenarios were chosen, each of them consists of a

**Table 2**
Total waste collected per day.

| Waste fraction | Container volume ($m^3$) | Container filling percentage (%) | Number of containers | Waste density ($kg/m^3$) | Collected waste quantity (ton/day) |
|---|---|---|---|---|---|
| Organic | 2.2 | 75 | 68 | 400[a] | 44.9 |
| Paper | 3.2 | 75 | 71 | 85 | 14.5 |
| Plastic | 3.2 | 75 | 71 | 45 | 7.7 |
| Unsorted | 3.2 | 75 | 76 | 90 | 16.4 |

[a] The density of the organic waste fraction in Barcelona is very low because it has a high percentage of impurities.

different source of electrical energy:

### 2.2.1. - Scenario 1. Spanish national energy mix (2008)

Ecoinvent database uses the Spanish national energy mix. However, the one used by the database is from the year 2008. When comparing such national energy mix with the energy mix in Spain from 2016 (España, 2016) in Fig. 3, it is clear that more renewable energy is produced today in Spain than in 2008. Moreover, the European Council is asking for at least 27% share of renewable energy consumption in 2030 in its 2030 Framework for climate change and energy. Therefore, one can only expect that the contribution of renewables will keep on growing.

It is important then to take into consideration that the energy mix used in this study includes less renewable energy sources than the reality, and thus, in this scenario the environmental impact is overestimated.

### 2.2.2. - Scenario 2: 100% hydropower

The second scenario considers that the source of energy is 100% hydropower. Ecoinvent database considers the production of 2 kWh of electricity in a pumped storage power plant. The calculation is based on data from reservoir hydropower and extrapolated to Spanish conditions.

The study carried out by Gaurard and Romerio (Gaudard and Romerio, 2014) concludes that hydropower appears to have a promising future. When compared to other power generation systems, it scores quite high in terms of environmental impact.

The relative contribution of hydro generation in Spain remains rather constant at 30% of total net generation, with small hydro slightly increasing (Ministry of Energy, 2016). Hydropower includes infrastructures such as dams or run-of-river plants. Previous studies done on LCA for hydropower link its impact to the building of the required infrastructures and provision of materials and are related to the dam size and generation capacity (Gagnon et al., 2002; Goralczyk, 2003; Suwanit and Gheewala, 2011).

### 2.2.3. - Scenario 3: 100% photovoltaic

A 100% photovoltaic (PV) generation is another scenario. Ecoinvent database considers the production of grid-connected low voltage electricity with a 3 kWh building integrated PV module in Spain in 2008.

PV generation is expected to grow drastically worldwide in many decarbonizing scenarios. In many countries the promotion of PV technology was set to an important goal which was aligned with decreasing of PV generation costs. Undoubtedly, the solar industry would be the best choice for future energy demand because of its availability, cost effectiveness, accessibility, capacity and efficiency compared to other renewable energy sources (Kannan and Vakeesan, 2016). In Europe, generation from PV contributes 4.8% in net generation by 2020. Beyond 2020, PV generation continues to increase up to 7% in 2030 and 11% in 2050 (EC, 2016). In Spain PV has an important growth during the early 2000s reaching 2.9% of the primary energy, but CSP (concentrated solar power) generation should also be mentioned, since its contribution to the Spanish primary energy generation was 2% in 2016 (Govermnent, 2016).

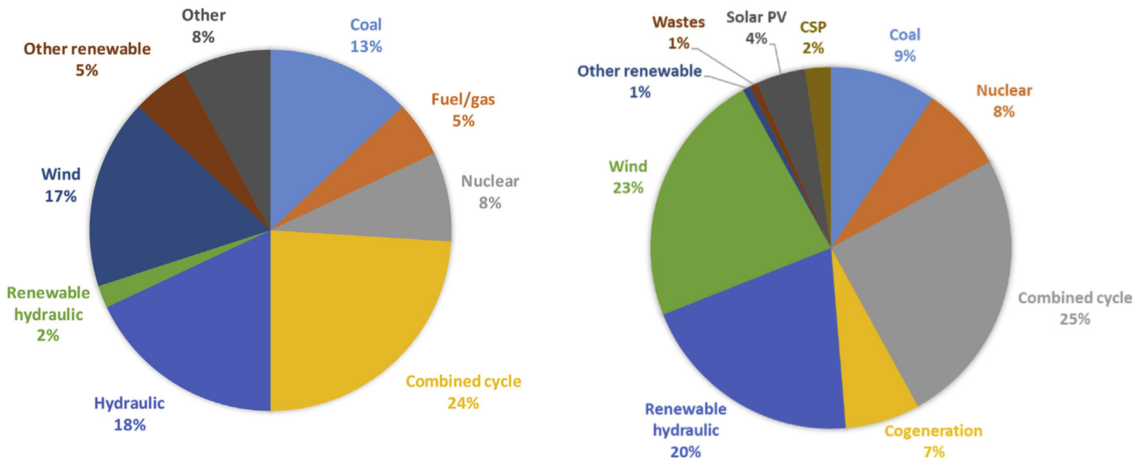
Previous LCA studies are related to the environmental impact to the infrastructure, in particular to the solar cells, while the impact of operation or maintenance is considered to be almost negligible. However, PV technologies improved vastly in the last decades and the actual solar cells are more efficient than the ones that were built only a few years ago.

### 2.2.4. - Scenario 4: 100% windpower

This scenario considers 100% wind power generation. Ecoinvent database considers the production of high voltage electricity at onshore grid-connected wind power plants with a capacity of less than 1 MW in Spain in 2008.

In Europe, wind provides the largest contribution from RES supplying 14.4% of total net electricity generation in 2020, rising to 18% in 2030 and 25% by 2050 (EC, 2016). In Spain, in 2016 wind generation contributed to 17.8% of the primary energy (Ministry of Energy, 2016).

Lenzen and Munksgaard (2002) reviewed the LCA studies published before 2002 to determine the causes for the variation in the results of wind power environmental impact and found that it was very difficult to compare studies when parameters such as lifetime, load factor, power rating, country of manufacture (impact of the energy used) differ from one to another. Afterwards, the variability in the assessment of the wind power LCA has continued, with variations found in the literature. Raadal et al. (2011) found that the impact decreases with increased capacity factor, from 33.8 to 8.3 kg $CO_2$-eq/MWh. However, the largest capacity factor (36–55%) is usually associated with offshore locations with larger infrastructure which leads to a slightly higher impact that the second one (36–45% capacity factor).



(a) Energy mix 2008 (b) Energy mix 2016

**Fig. 3.** Spanish energy mix in 2008 and 2016 (España, 2009, 2016).

### 2.2.5. - Scenario 5: renewable energy mix

Seeing the energy mix in Spain in 2016 (España, 2016) a hypothetical future energy mix is designed in this study by considering a contribution of 20% hydroelectricity, 30% PV, and 50% wind. In the future energy mix in Spain, the contribution of hydroelectricity is not expected to grow much more than that of today, since the resources are mostly used (IDAE, 2011), therefore 20% hydro is considered. Solar and wind are expected to grow, but the wind contribution should be higher than the solar one, following the 2016 energy mix and literature studies (García Sánchez et al., 2013), therefore 30% PV (Ecoinvent does not include CSP yet but as mentioned above it is a contributor to the Spanish energy mix) and 50% wind are considered.

The objective of the Spanish Renewable Energy Plan is that by 2020 at least 20% of gross final energy consumption in Spain will come from the use of renewable sources, as indicated in the EU Directive.

## 2.3. LCA methodology

The LCA methodology was used to quantify and compare the potential environmental impacts of the different municipal waste management scenarios. This study was based on ISO 14040 and ISO 14044 standards (ISO 14040, 2006; ISO 14044, 2006). According to these standards, an LCA includes four main steps: goal and scope, analysis inventory, life-cycle impact analysis, and interpretation of the results.

**Table 3**
Inventory of the infrastructure of the pneumatic system – manufacturing phase.

| Component | Quantity | Material | Total |
|---|---|---|---|
| Exterior collection points | 240 | Aluminium casting | 15120 kg |
| | | Carbon steel | 14160 kg |
| | | Stainless steel | 34080 kg |
| | | Rubber | 72 kg |
| | | Polycarbonate | 24 kg |
| | | Polyamide 6.6 | 72 kg |
| Interior collection points | 22 | Stainless steel | 484 kg |
| | | Rubber | 6.6 kg |
| Butterfly valves | 12 | Stainless steel | 504 kg |
| | | Aluminium | 48 kg |
| Gate valves (for waste circulating pipes) | 15 | Stainless steel | 990 kg |
| | | Aluminium | 120 kg |
| | | Nylon | 30 kg |
| Gate valves (for air pipes) | 58 | Stainless steel | 1624 kg |
| | | Aluminium | 290 kg |
| | | Rubber | 17.4 kg |
| Mufflers | 58 | Stainless steel | 1450 kg |
| | | Rock wool | 29 kg |
| Clapper valves (for pipes in each collection point) | 240 | Stainless steel | 38880 kg |
| | | Aluminium | 1200 kg |
| | | Rubber | 960 kg |
| Clapper valves (other parts of the system) | 22 | Stainless steel | 3520 kg |
| | | Aluminium | 110 kg |
| | | Rubber | 88 kg |
| Pipes 9 mm thickness and 498 mm diameter | 75 m | Stainless steel[a] | 8049.6 kg |
| Pipes 6 mm thickness and 498 mm diameter | 910 m | Stainless steel[a] | 65325.6 kg |
| Pipes 3 mm thickness and 498 mm diameter | 5500 m | Stainless steel[a] | 198608.4 kg |
| Horizontal drilling | 6.5 km | – | 6.5 km |
| Vertical drilling | 2.5 m | – | 0.0025 km |
| Electrical panel | 122 | Glass reinforced plastic | 244 kg |
| Corrugated pipe | 13 km | – | 13 km |
| 3G16 electric cable | 9.75 km | – | 9.75 km |
| Profibus DP 3G10 data cable | 1.3 km | – | 1.3 km |
| Pneumatic tubbing | 1.95 km | – | 1.95 km |
| Building | 435 $m^2$ | – | 261 $m^2$ |
| Cyclone | 3 | Carbon steel | 5700 kg |
| | | Aluminium | 30 kg |
| | | Rubber | 6 kg |
| Diverter | 2 | Carbon steel | 920 kg |
| | | Aluminium | 16 kg |
| | | Rubber | 6 kg |
| | | Stainless steel | 276 kg |
| Compactor | 3 | Carbon steel | 2250 kg |
| Fan | 3 | Carbon steel | 15840 kg |
| | | Weathering steel | 2160 kg |
| | | Aluminium | 2160 kg |
| Compressor | 2 | – | 6 units |
| Refrigerator - compressed air dryer | 1 | Carbon steel | 120 kg |
| | | Aluminium | 30 kg |
| Cathodic protection | 1 | Carbon steel | 150 kg |
| | | Polycarbonate + polyesther | 30 kg |
| Crane | 1 | Carbon steel | 24600 kg |
| Biofilter filling | 1 | Poplar bark | 240 $m^3$ |
| Truck | 10.3 ton | – | 1 |
| Containers | 4 | Carbon steel | 45600 kg |

[a] Density = 7740 kg/m.$^3$.

**Table 4**
Inventory of the pneumatic system – operational phase.

| Component | Quantity | Energy carrier | Consumption | Total |
|---|---|---|---|---|
| Electric panel | 4 | Electricity | 968 kWh/year | 116185 kWh |
| Cyclone | 1 | Electricity | 691 kWh/year | 20748 kWh |
| Fans | 3 | Electricity | 202876 kWh/year | 18258851 kWh |
| Compactor | 1 | Electricity | 1942 kWh/year | 58262 kWh |
|  | 2 | Electricity | 2913 kWh/year | 174786 kWh |
| Compressor | 1 | Electricity | 41495 kWh/year | 1244878 kWh |
| Refrigerator - compressed air dryer | 1 | Electricity | 7227 kWh/year | 216810 kWh |
| Crane | 1 | Electricity | 17719 kWh/year | 531578 kWh |
| Cathodic protection | 1 | Electricity | 21681.00 kWh/year | 650430 kWh |
| UPS | 1 | Electricity | 12448 kWh/year | 373452 kWh |
| Biofilter | 1 | Water | 20 l/day | 219000 kg |
| Truck | 1 | Diesel[a] | 0.4 l/km – 80 km/day | 249999 kg |
| Container cleaning | 1 | Water | 100 l/day | 1095000 kg |

[a] Density = 0.832 kg/l.

### 2.3.1. Objectives and scope

The aim of this study is to determine the environmental performance of two municipal wastes collection systems and to perform a sensitivity analysis of different municipal wastes collection system with five different scenarios regarding the energy source. LCA is considered from cradle to grave.

**Table 5**
Inventory of the truck system – manufacturing (others).

| Component | Quantity | Total |
|---|---|---|
| Organic container | 68 | 48960 kg |
| Paper container | 71 | 59641 kg |
| Plastic container | 71 | 59641 kg |
| Unsorted container | 76 | 68400 kg |
| Cleaning truck (8 tons) | 1 | 43278.3 kg |
| Building | 10700 $m^2$ | 6420 $m^2$ |
| Crane | 1 | 24600 kg |
| Hydraulic elevator | 4 | 5940 kg |
| Blowtorch | 1 | 4.5 kg |
| Tensor | 1 | 6.9 kg |
| Drill | 1 | 195 kg |
| Cleaning hydrojet | 1 | 186 kg |
| Pit | 1 | 35970 kg |
| Smoke extractor | 4 | 26880 kg |
| Air compressor | 1 | 3 units |
| Van | 1 | 3.3 units |

*Density = 2200 kg/$m.^3$.

The main assumptions of the two systems considered were:

- Glass collection and recycling is not studied because of a lack of data.
- The construction and maintenance of the roads for the truck system are neglected due to the lack of information to include it. However, Gschösser (2011) did a complete assessment of the environmental impact of roads and pavements, and the fact that the construction and maintenance of the roads are not considered underestimates the environmental impact for the truck system (Gschösser, 2011).

## 2.4. Functional unit

The functional unit provides a common basis for the comparison of results (ISO 14044, 2006). The most comomonly used functional unit in LCA is 1 ton of waste (Khandelwal et al., 2019). Thus, the functional unit of this study was 1 ton of generated MSW per year in the 22@Barcelona with a lifetime of 30 years, in order to compare the different systems and moreover in order to compare with other authors (Barreto-Lins et al., 2017).

### 2.4.1. Impact analysis

The Ecoinvent v3.0 database was used to obtain the environmental impacts associated with the materials, transport and energy

**Table 6**
Inventory of the truck system – manufacturing (2 trucks).

| Materials | Diesel |  |  | Diesel + electric |  |  | Gas |  |  | Gas + electric |  |  | Electric |  |  |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  | Quantity [kg/truck][a] | RR[b] [years] | Total [kg][a] | Quantity [kg/truck][a] | RR[b] | Total [kg][a] | Quantity [kg/truck][a] | RR[b] | Total [kg][a] | Quantity [kg/truck][a] | RR[b] | Total [kg][a] | Quantity [kg/truck][a] | RR[b] | Total [kg][a] |
| Diesel engine | 940 | 3.3 | 62666 | 700 | 3.3 | 4666 | – | – | – | – | – | – | – | – | – |
| Electric engine | – | – | – | 637 | 3.3 | 4246. | – | – | – | 637 | 3.3 | 4246 | 637 | 3.3 | 4246 |
| Gas engine | – | – | – | – | – | – | 1 unit | 3.3 | 6.6 units | 1 unit | 3.3 | 6.6 units | – | – | – |
| Battery | – | – | – | 700 kWh | 6 | 8400 kWh | – | – | – | 700 | 6 | 8400 | 3100 kWh | 6 | 372000 kWh |
| Chassis | 7640 | 3.3 | 50933 | 7000 | 3.3 | 46666 | 6450 | 3.3 | 43000 | 7000 | 3.3 | 46666 | 7400 | 3.3 | 49333 |
| Aluminium | 3404 | 3.3 | 22694 | 3404 | 3.3 | 22694 | 2372 | 3.3 | 15820 | 3404 | 3.3 | 22694 | 3360 | 3.3 | 224000 |
| Carbon steel | 3404 | 3.3 | 22694 | 3404 | 3.3 | 22694 | 2372 | 3.3 | 15820 | 3404 | 3.3 | 22694 | 3760 | 3.3 | 25066 |
| Hydraulic oil | 324 | 3.3 | 2161 | 324 | 3.3 | 2161 | 226 | 3.3 | 1506 | 324 | 3.3 | 2161 | 320 | 3.3 | 2133 |
| Rubber | 405 | 3.3 | 2701 | 405 | 3.3 | 2701 | 282 | 3.3 | 1883 | 405 | 3.3 | 2701 | 400 | 3.3 | 2666 |
| Copper | 243 | 3.3 | 1621 | 243 | 3.3 | 1621 | 169 | 3.3 | 1130 | 243 | 3.3 | 1621 | 240 | 3.3 | 1600 |
| HDPE | 243 | 3.3 | 1621 | 243 | 3.3 | 1621 | 169 | 3.3 | 1130 | 243 | 3.3 | 1621 | 240 | 3.3 | 1600 |

[a] kg otherwise stated in the table.
[b] RR – replacement rate.

**Table 7**
Inventory of the truck system – operation (30 years).

| Component | Energy carrier | Consumption | | | | km circulated | | Total |
|---|---|---|---|---|---|---|---|---|
| | | Yearly | Stopped | Circulating in town | Circulating on the road | Town | Road | |
| Diesel truck organic waste | Diesel[a] | – | 16.7 l/day | 0.6 l/km | 0.4 l/km | 26.5 km/day | 196.5 km/day | 1001369.6 kg |
| Diesel truck paper waste | Diesel[a] | – | 32.1 l/day | 0.6 l/km | 0.4 l/km | 59.5 km/day | 124.5 km/day | 1044188.5 kg |
| Diesel truck plastic waste | Diesel[a] | – | 21.3 l/day | 0.6 l/km | 0.4 l/km | 51.5 km/day | 88.5 km/day | 774885.1 kg |
| Diesel truck unsorted waste | Diesel[a] | – | 26.7 l/day | 0.6 l/km | 0.4 l/km | 33 km/day | 124.5 km/day | 862026.0 kg |
| Diesel + electric truck organic waste | Diesel[a] | – | 0 l/day | 0.6 l/km | 0.4 l/km | 6.6 km/day | 196.5 km/day | 749273.5 kg |
| | Electricity | – | 60.9 kWh/day | 1 kWh/km | 0 kWh/km | 19.9 km/day | 196.5 km/day | 888729.4 kWh |
| Diesel + electric truck paper waste | Diesel[a] | – | 0 l/day | 0.6 l/km | 0.4 l/km | 14.9 km/day | 124.5 km/day | 528232.4 kg |
| | Electricity | – | 116.7 kWh/day | 1.2 kWh/km | 0 kWh/km | 44.6 km/day | 124.5 km/day | 1849578.2 kWh |
| Diesel + electric truck plastic waste | Diesel[a] | – | 0 l/day | 0.6 l/km | 0.4 l/km | 12.9 km/day | 88.5 km/day | 387021.2 kg |
| | Electricity | – | 77.6 kWh/day | 1.4 kWh/km | 0 kWh/km | 38.6 km/day | 88.5 km/day | 1449971.6 kWh |
| Diesel + electric truck unsorted waste | Diesel[a] | – | 0 l/day | 0.6 l/km | 0.4 l/km | 8.3 km/day | 124.5 km/day | 495036.4 kg |
| | Electricity | – | 97 kWh/day | 1.4 kWh/km | 0 kWh/km | 24.8 km/day | 124.5 km/day | 1446878.3 kWh |
| Gas truck organic waste | CNG[b] | – | 16.7 kg/day | 0.5 kg/km | 1.2 kg/km | 26.5 km/day | 196.5 km/day | 15361.5 m$^3$ |
| Gas truck paper waste | CNG[b] | – | 32 kg/day | 0.5 kg/km | 1.5 kg/km | 59.5 km/day | 124.5 km/day | 14569.1 m$^3$ |
| Gas truck plastic waste | CNG[b] | – | 21.3 kg/day | 0.5 kg/km | 2.1 kg/km | 51.5 km/day | 88.5 km/day | 13306.4 m$^3$ |
| Gas truck unsorted waste | CNG[b] | – | 26.6 kg/day | 0.5 kg/km | 1.8 kg/km | 33 km/day | 124.5 km/day | 15241.7 m$^3$ |
| Gas + electric truck organic waste | CNG[b] | – | 0 kg/day | 0.5 kg/km | 1.2 kg/km | 6.6 km/day | 196.5 km/day | 13791.5 m$^3$ |
| | Electricity | – | 69.9 kWh/day | 1 kWh/km | 0 kWh/km | 19.9 km/day | 196.5 km/day | 888729.4 kWh |
| Gas + electric truck paper waste | CNG[b] | – | 0 kg/day | 0.5 kg/km | 1.5 kg/km | 14.9 km/day | 124.5 km/day | 11360.2 m$^3$ |
| | Electricity | – | 116.7 kWh/day | 1.2 kWh/km | 0 kWh/km | 44.6 km/day | 124.5 km/day | 1849578.2 kWh |
| Gas + electric truck plastic waste | CNG[b] | – | 0 kg/day | 0.5 kg/km | 2.1 kg/km | 12.9 km/day | 88.5 km/day | 10899.7 m$^3$ |
| | Electricity | – | 77.6 kWh/day | 1.4 kWh/km | 0 kWh/km | 38.6 km/day | 88.5 km/day | 1449971.6 kWh |
| Gas + electric truck unsorted waste | CNG[b] | – | 0 kg/day | 0.5 kg/km | 1.8 kg/km | 8.3 km/day | 124.5 km/day | 12951.6 m$^3$ |
| | Electricity | – | 97 kWh/day | 1.4 kWh/km | 0 kWh/km | 24.8 km/day | 124.5 km/day | 1446878.3 kWh |
| Electric truck organic waste | Electricity | – | 60.9 kWh/day | 1 kWh/km | 2.2 kWh/km | 26.5 km/day | 196.5 km/day | 5588825.3 kWh |
| Electric truck paper waste | Electricity | – | 116.7 kWh/day | 1.2 kWh/km | 3.6 kWh/km | 59.5 km/day | 124.5 km/day | 7002470.3 kWh |
| Electric truck plastic waste | Electricity | – | 77.6 kWh/day | 1.4 kWh/km | 4.1 kWh/km | 51.5 km/day | 88.5 km/day | 5662135.5 kWh |
| Electric truck unsorted waste | Electricity | – | 97 kWh/day | 1.4 kWh/km | 3.9 kWh/km | 33 km/day | 124.5 km/day | 6891930.0 kWh |
| Building | Electricity | 100072 kWh/year | – | – | – | – | – | 3002160 kWh |
| | Water | 4159000 l/year | – | – | – | – | – | 124770000 kg |
| Cleaning organic container | Water | 1440 l/year | – | – | – | – | – | 43200 kg |
| Cleaning paper container | Water | 240 l/year | – | – | – | – | – | 7200 kg |
| Cleaning plastic container | Water | 240 l/year | – | – | – | – | – | 7200 kg |
| Cleaning unsorted container | Water | 720 l/year | – | – | – | – | – | 21600 kg |
| Cleaning truck | Diesel[a] | – | – | – | 1.6 l/km | – | 51.5 km/day | 750697 kg |

[a] Density = 0.832 kg/l.
[b] Density = 0.005 m$^3$/kg.

employed in the study (Frischknecht et al., 2007). The quantitative indicators used were the Eco-Indicator 99 and the IPCC2003 GWP. The Eco-indicator 99 defines the “environment damage” in three categories: Human health, Ecosystem quality, and Resources. The standard Eco-indicator values can be regarded as dimensionless figures. As a name it is used the Eco-indicator point (Pt) (Baayen, 2000). To quantify the environmental impacts, different kinds of indicators are possible, categorized in two groups: mid-points and end-points. The first group classifies impacts into environmental themes such as global warming potential, acidification potential, ozone depletion potential, etc. This method generates a more complete picture of the ecological impact, but requires some knowledge of LCA to interpret the results (Audenaert et al., 2012). The second group translates environmental impacts into issues of concern (typically reflect damage at one of three areas of protection which are human health, ecosystem quality and resources). Within this research the Eco-indicator 99 is used, a damage oriented method since the main objective of the study is the influence of the energy source. Of all the emissions, extractions and land use in all processes, the damage they cause to human health, ecosystem quality and resources is calculated. At the end, these three categories are combined into a single score. As said by Hauschild and Huijbregts (Hauschild et al., 2017) the endpoint characterisation is easier to interpret in terms of relevance of the environmental flows.

On the other hand, it was used the IPCC 2013 Indicators, the Global proposed by the Intergovernmental Panel on Climate Change (IPCC), which quantify the climate change impacts of greenhouse gas emissions due to human activities by aggregating them into a common unit, e.g. $CO_2$-equivalent (IPCC, 2014).

### 2.4.2. Analysis inventory

The inventory is a list of all substances involved in the process. Each system was evaluated separately. Tables 3–7 show the inventory of the waste collection systems studied. The inventory of the pneumatic system was obtained from the company Urban Refuse Development, and the of the truck collection system from Urbaser, S.A, Ilnet UTE (Romero Polo, SA and Valoriza-Sacyr, S. A) and Ros Roca, SA.

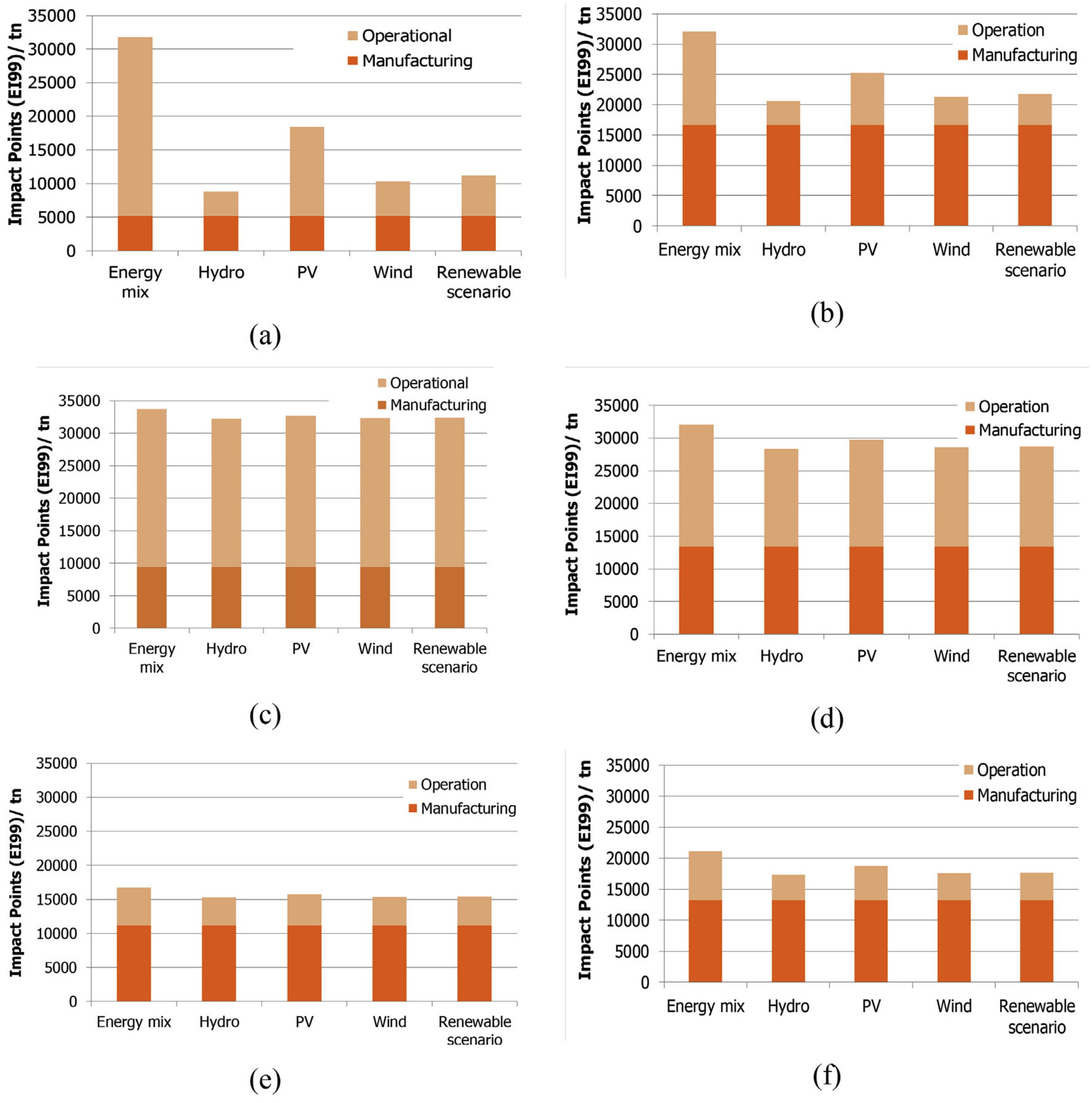


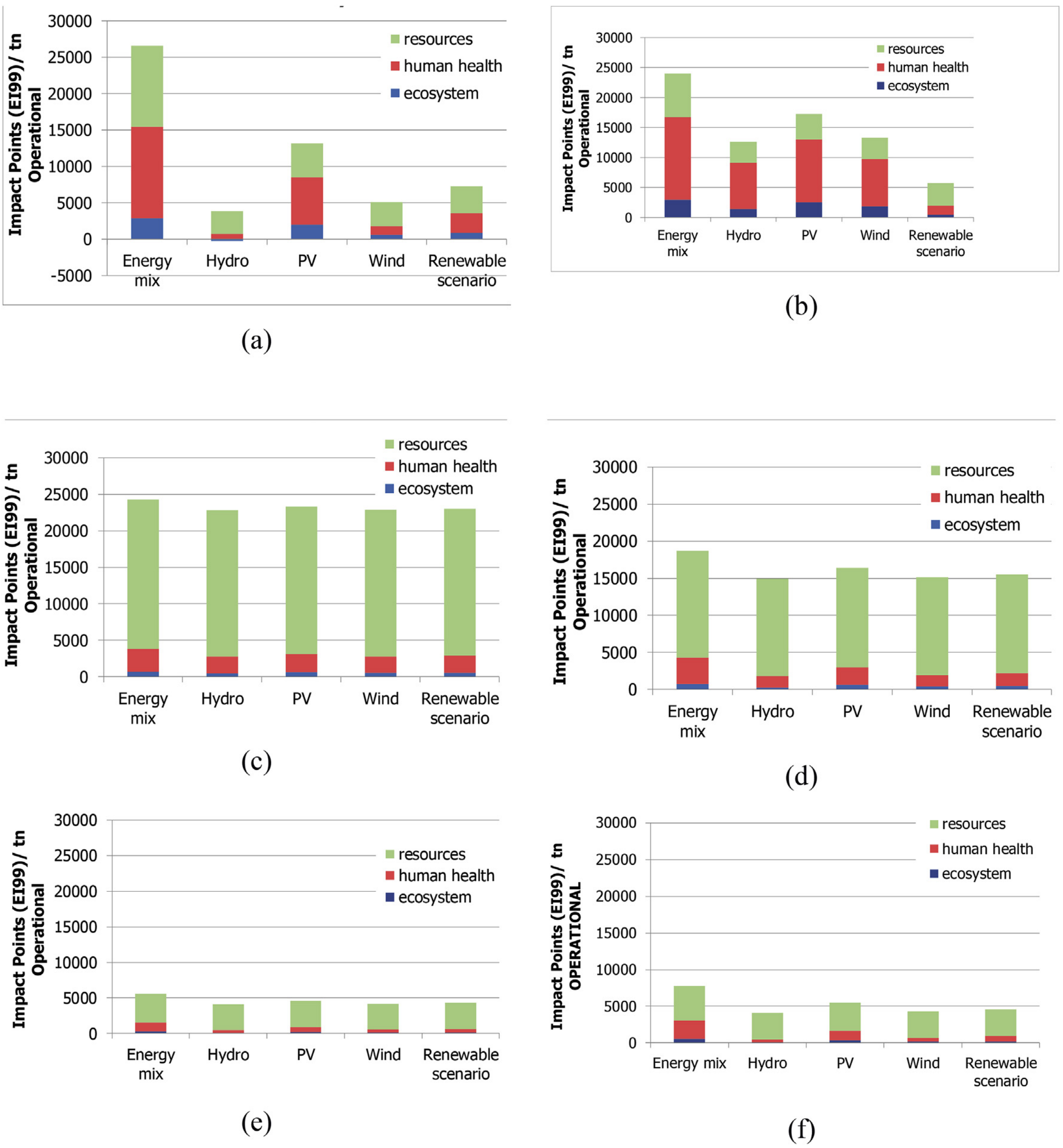
**Fig. 4.** Eco-Indicator 99 total impact points for the different waste collection systems studied comparing different electricity generation sources. (a) Pneumatic; (b) electric trucks; (c) diesel trucks; (d) diesel-electric trucks; (e) gas trucks; and (f) gas-electric trucks.

## 3. Results and discussion

Fig. 4 shows the total impact points (all categories) assessed with the Eco-Indicator 99 for all systems compared in each scenario studied. In this figure the main objective was to study the difference between systems by the global environmental effects. The results were divided between manufacturing and operational phase. The part of the authors interested was the operational phase since is the one which changes the most when varying the energy source. When talking about the total impact points in the operational phase results show clearly that the energy mix 2008 penalizes the pneumatic waste collection system (26565 points) the most compared to any other truck collection system. The pneumatic waste collection system decreases from 26565 impact points in the energy mix scenario to 7276 impact points with the renewable scenario, but with a minimum with the hydro scenario (3607 impact points); this means a reduction of one third. Regarding traditional trucks, in the energy mix scenario the highest results were shown by diesel trucks, electric trucks, and hybrid diesel-electric truck. Even electric trucks also have a high impact with the energy mix scenario other scenarios in electricity generation shows a significant reduction.

Moreover, the impact of the operational and manufacturing phases can be assessed with the Eco-invent 99 indicator for all systems and scenarios studied. Fig. 3 shows that, as expected, in all systems the manufacturing impact does not change when comparing different electricity generation scenarios, and that all the differences highlighted above are due to the operation phase of operation.

Fig. 5 details the results of the operational phase of all studied systems. Here, it is differentiated by scores per each of the three comprehensive damage categories (human health, ecosystem



(a)

(b)

(c)

(d)

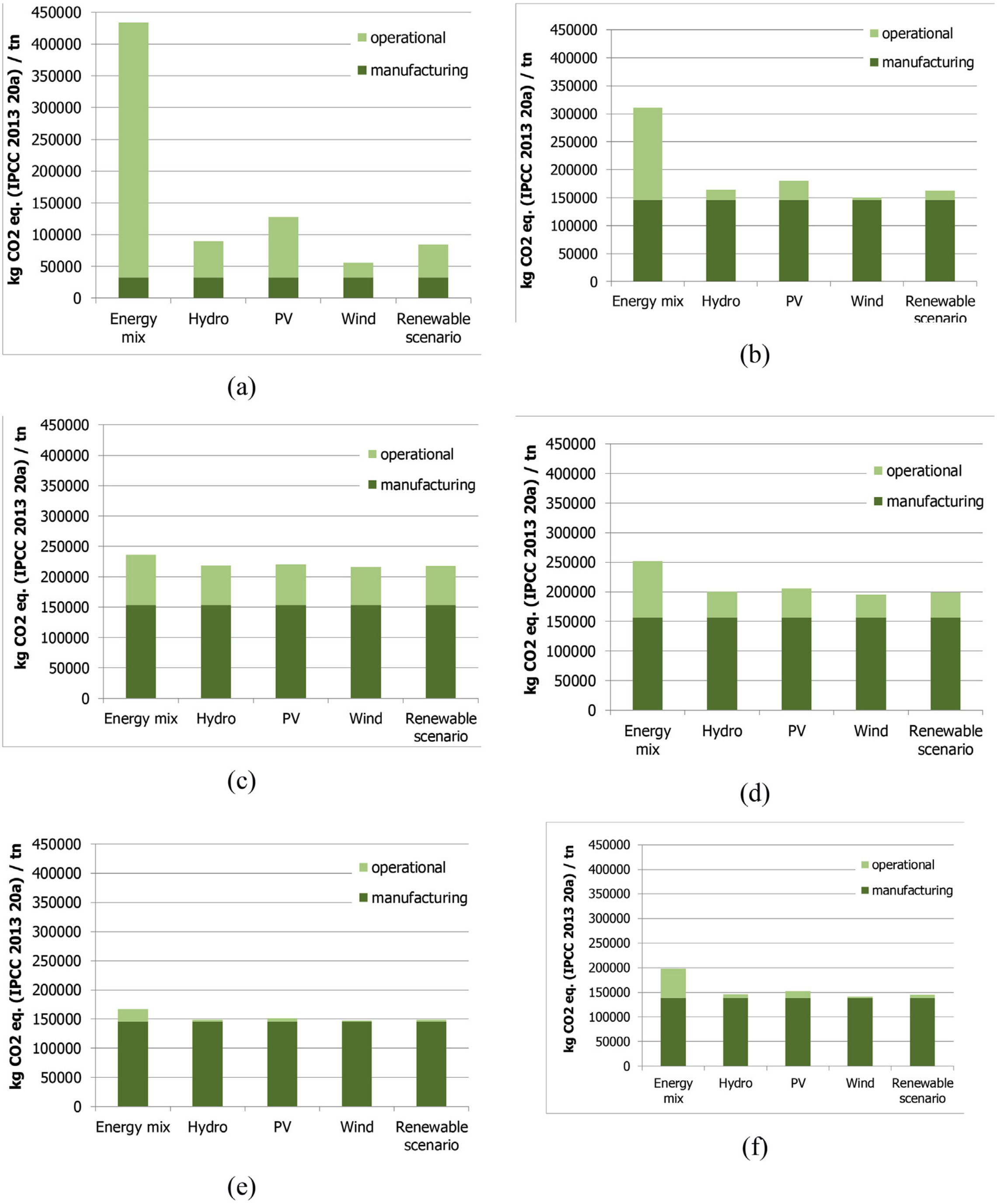
(e)

(f)

**Fig. 5.** Eco-Indicator 99 operational categories impact points for the different waste collection systems studied comparing different electricity generation sources. (a) Pneumatic; (b) electric trucks; (c) diesel trucks; (d) diesel-electric trucks; (e) gas trucks; and (f) gas-electric trucks.

quality, and resources). Very small differences can be seen between diesel trucks, gas trucks, and their hybrids, but when the electricity generation scenario changes, it can be noticed that the resources category is the one with highest impact in all of them. On the other hand, electric trucks show a high decrease in the impact points when a more renewable scenario is implemented. Moreover, electric trucks have a high impact in the category human health when the scenarios energy mix, hydro, PV and wind source are considered; but in the renewable scenario this impact is drastically lower. Finally, when the pneumatic waste collection system is assessed, as it happened with electric trucks, when going to a more renewable electricity generation scenario, there is a reduction of more than 70%.

Fig. 6 and Fig. 7 shows the results of the LCA when using the IPCC 2013 20a and IPCC 2013 100a indicators are used. Very similar comments and conclusions can be withdrawn in this case, but here the differences between the pneumatic waste collection system and the trucks collection systems are even higher than before. The impact of the operational phase in the energy mix scenario is much higher than that in the other scenarios; here the renewable scenario gives impacts much more similar to the hydro, PV, and wind ones. In the pneumatic collection system, changing from the energy



(a)

(b)

(c)

(d)

(e)

(f)

**Fig. 6.** IPCC 2013 20a impact for the different waste collection systems studied comparing different electricity generation sources. (a) Pneumatic; (b) electric trucks; (c) diesel trucks; (d) diesel-electric trucks; (e) gas trucks; and (f) gas-electric trucks.

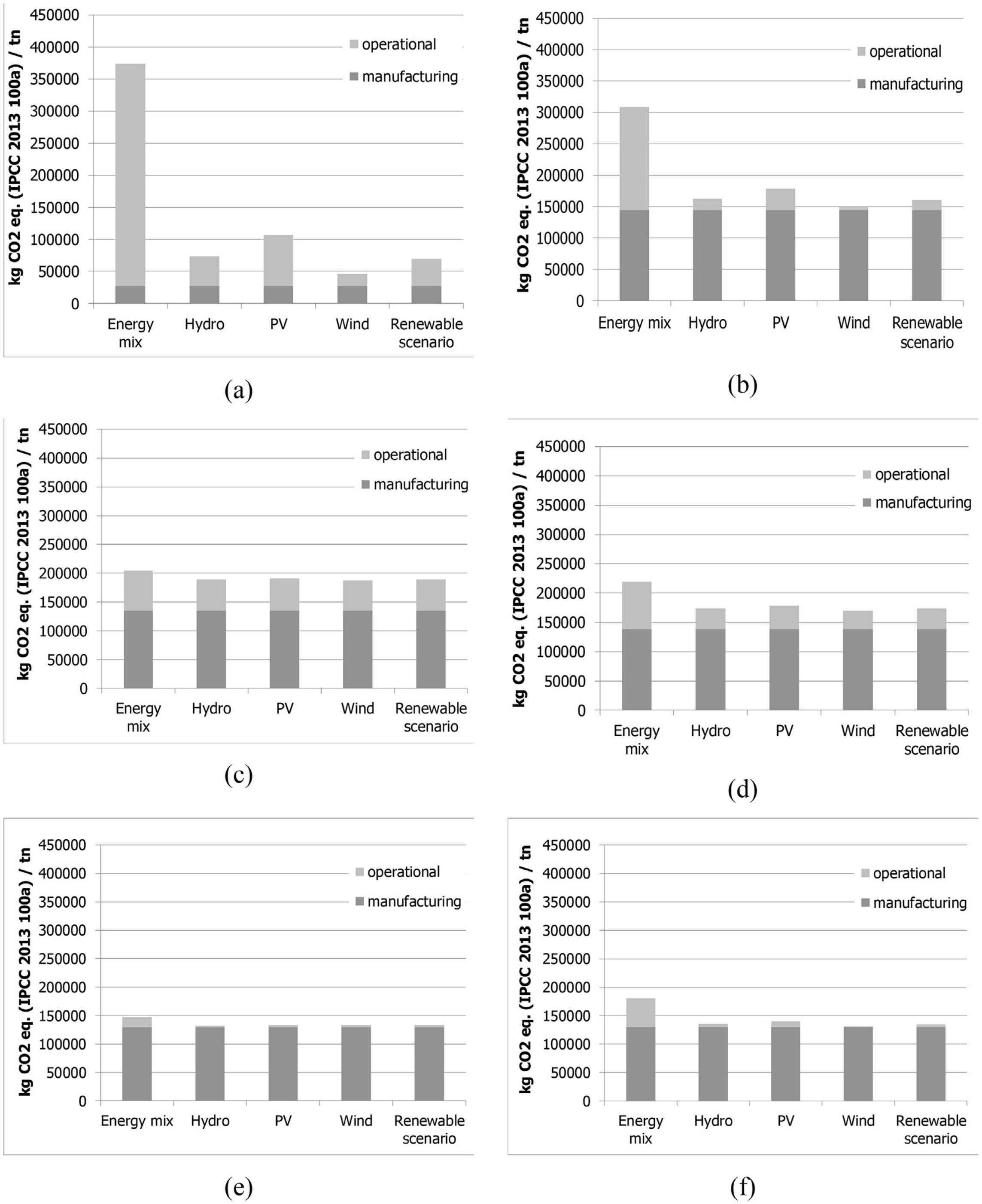
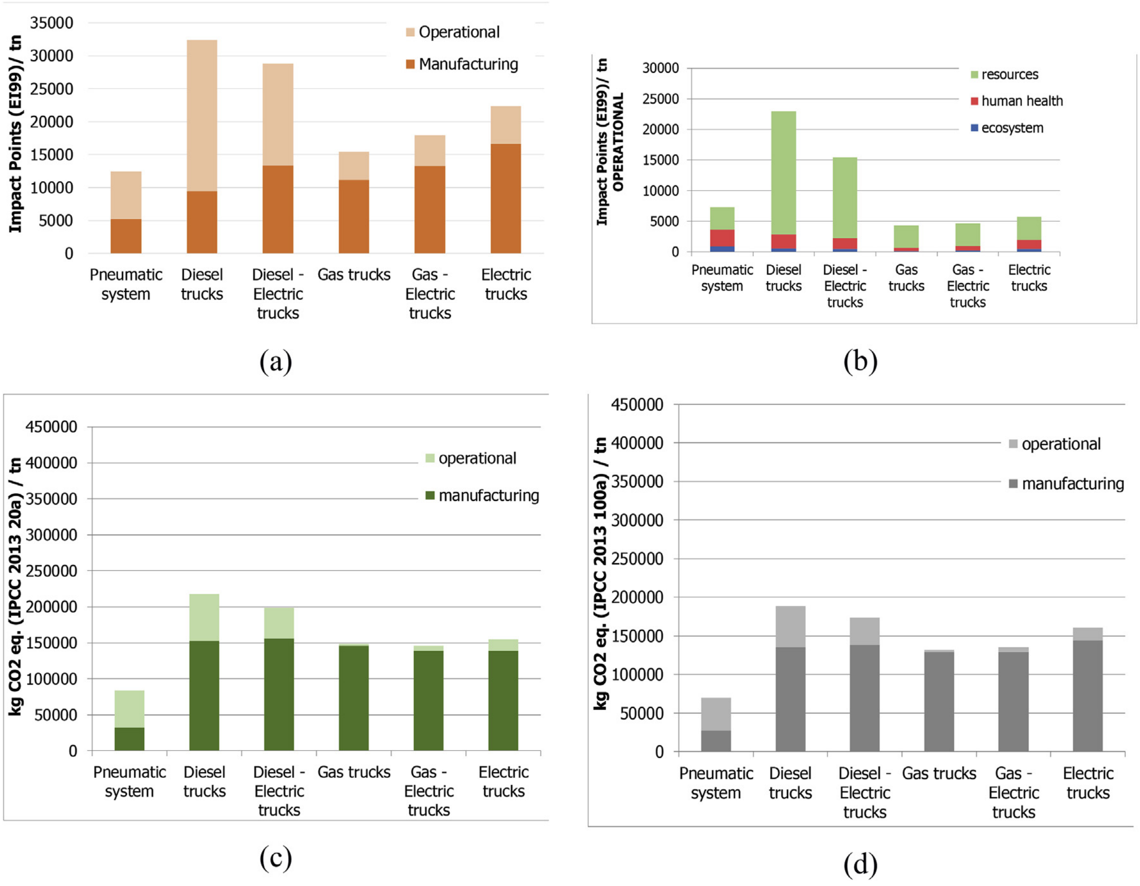


**Fig. 7.** IPCC 2013 100a impact for the different waste collection systems studied comparing different electricity generation sources. (a) Pneumatic; (b) electric trucks; (c) diesel trucks; (d) diesel-electric trucks; (e) gas trucks; and (f) gas-electric trucks.

mix scenario to a renewable scenario means a reduction of 81% in kg $CO_2$eq/tn emissions both in the IPCC 2013 20a impact accounting and the IPCC 2013 100a one, while in the electric trucks the decrease is of 48%.

Results agree with the study of López et al. (2009) who compared the GHG emissions from diesel, biodiesel, and natural gas waste collection trucks and concluded that gas trucks are those that the global environmental impact was lower. Even electric cars are being studied and improved, since the manufacturing part (i.e. batteries) have the highest impact of all the trucks studied. That affirmation agrees with the study of Garcia Sanchez et al. (2013) which compared four type of Buses in Madrid and even the GHC emissions are better with electric cars, the impact of the batteries need to improve. Another weakness is the low range that electric vehicles can do, a solution should be hybrid vehicles, or series hybrids, are also a good alternative to electric trucks, particularly for long distance uses or for larger cars (as trucks), because they have a higher range from a smaller battery capacity, and therefore a lower price (Mahmoudzadeh Andwari et al., 2017). The same author affirmed that electric vehicles would probably be the most suitable



(a) (b)

(c) (d)

**Fig. 8.** Renewable mix scenario results comparing the different waste collection systems studied. (a) Eco-Innovation 99 total impact points, (b) Eco-Indicator 99 operational categories impact points, (c) IPCC 2013 20a impact, and (d) IPCC 2013 100a impact.

for urban, small to medium-sized vehicles, while hybrid vehicles, and fuel-cell vehicles appear to be more applicable for the longer-ranged and larger vehicles.

Finally, just to have a clearer comparison of the impact of the different waste collection systems under the different scenarios studied, the results for the renewable energy scenario (considering a contribution of 20% hydroelectricity, 30% PV, and 50% wind in the electricity generation) are presented in Fig. 8. All impact indicators studied show the same trend: the pneumatic waste collection system has the lowest total impact and the operation phase impact is similar to the electrical trucks, and the gas and gas-electric trucks; and the diesel and diesel-electric trucks have a higher impact in the operation phase.

## 4. Conclusions

In processes with high energy consumption, the selection of the energy source has a big impact in its evaluation. This paper confirms that this is also true for LCA of waste collection systems, especially when a pneumatic system is considered, due to its high electricity consumption in fans. Different energy sources scenarios were evaluated, with a higher contribution of renewable energy than that used by the Ecoinvent database, which for the case of Spain uses the energy mix of 2008. From the scenario studied, the more realistic one is the hypothetical renewable energy scenario proposed, since it is a mix of renewable energy sources (hydro, PV – considering CSP, and wind). Diesel trucks utilization should be reconsidered since the resources (mineral extraction and fossil fuels) have the highest impact in that system. Due to its lowest emissions, compressed natural gas stands its best chance to be a go-to fuel choice in trucks. Regarding the waste collection system done by trucks, the message given by Nordelof et al. (2014) was confirmed in this study, if the global electricity production is made clean and essentially free from emissions of fossil carbon, these vehicles can reach their full potential in mitigating global warming. Finally, this study confirms that the pneumatic waste collection system is the best from an LCA point of view, if renewable electricity is used.

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