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CARBON FOOTPRINT OF MUNICIPAL SOLID WASTE COLLECTION IN THE TREVISO AREA (ITALY)

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Abstract

Carbon Footprint (CF) is an environmental indicator used in Life Cycle Assessment (LCA) that allows measuring the total amount of CO_2 emissions caused directly or indirectly by an activity or accumulated through the life cycle stages of a product (ISO 14064-14067).
In this article CF was used to analyse and assess the environmental impacts of the resources used for the collection of municipal solid waste by the company Contarina S.p.A. Contarina oversees waste management for part of the Treviso province (Italy), serving about 260,000 appliances in 50 municipalities distributed in the territory.
The presented case study assessed CF of year 2015 related the whole fleet involved in door-to-door collection of municipal solid waste without taking into account treatment processes. In addition, a future scenario, in which part of the current fleet is replaced by compressed natural gas engine (CNG) based vehicles, was assessed and compared to the current status. The CF was performed by adapting the SimaPro software from PRè, one of the most widely used LCA software since the nineties, by introducing fuel based analysis and creating CNG lorries. The analysis aimed at improving sustainability of Contarina's services while fostering an informed development and testing of new technologies aimed at reducing its overall greenhouse gas emissions.

Key words: carbon footprint, transport, waste management, sustainability

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1. Introduction

Solid waste management (SWM) is a complex process composed by various components among which waste collection is one of the main contributors as far as costs and environmental emissions (Chalkias and Lasaridi, 2009; Schiopu and Gavrilescu, 2010). According to Chalkias and Lasaridi (2009) waste collection contributes up to 40% of total costs of municipal SWM regardless variations due to location, labor costs, population and population density while, as far as emissions, those from waste collection vehicles are the most predominant in SWM systems due to their fuel-intensive nature. Focusing the analysis on the collection process is therefore necessary in order to develop sustainable waste management systems able to minimize environmental emissions in a cost-effective way (NREL, 1995).

Among the tools currently available to evaluate the environmental emissions' impact of waste collection, the Carbon Footprint (CF) is constantly gaining more and more attention (Bamonti et al., 2016; Pandey et al., 2011). Wiedmann and Minx (2008) defined CF as a measure of the exclusive total amount of carbon dioxide emissions that is directly and indirectly caused by an activity or is accumulated over the life stages of a product, conceptually being a global warming potential indicator. CF is one of the instruments which are

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currently used for sustainability assessment, it also corresponds to the “Global warming” impact category in Life Cycle Assessment (LCA) which aims at evaluating environmental impacts due to development, use and disposal of goods and services (Ghinea et al., 2014; ISO, 2006a).

All Greenhouse Gases (GHG) included in the Kyoto protocol (ISO, 2006b) are considered as part of CF: Carbon dioxide (CO_2), Methane (CH_4), Nitrous Oxide (N_2O), Hydrofluorocarbons group (HFC_s), Perfluorocarbons group (PFC_s) and Sulfur hexafluoride (SF_6). All those gasses are mainly generated by energy processes; among all CO_2 is the major contributor to the greenhouse effect because of the amount annually produced (WRI/WBCSD, 2004) and for this reason it was decided to adopt the kilogram of CO_2 equivalent ($kgCO_{2eq}$) as CF’s unit of measure (Franchetti and Apul, 2013) as also one of the common practice with other carbon footprint measures and tools (Bacenetti and Fiala, 2016).

CO_{2eq} is obtained by multiplying emissions of the different GHG by their Global Warming Potential (GWP) (ISO, 2006b) which represents the ratio between warming produced by the gas in a specific time frame (usually 100 years) and warming produced in the same period by the same mass of CO_2 (ISO, 2006b). It represents the contributions caused by all gases to the overall greenhouse effect including both the radiation characteristics of the gaseous molecules (i.e. to the diverse ability to absorb different wavelengths of solar radiation and specifically, infrared radiation) and their time of persistence in the atmosphere (Franchetti and Apul, 2013). A generic model for assessing the waste collection process CF on the basis of distance or customer number demonstrated not to be feasible due to the limited amount of information regarding vehicles’ fuel consumption and operating conditions as well as the infinitely many different working environments and conditions (Agar et al., 2007). While consistent efforts have been performed in characterizing waste collection processes as reported in (Farzaneh et al., 2009; Ivanič, 2007; Sandhu et al., 2014; Sandhu et al., 2016), the multifaced nature of the system consisting in different lorries fleets, route conditions, house density and dumping systems imposes case specific assessments and characterizations (Agar et al., 2007). Even though the Waste tool developed by the Universita Autonoma de Barcelona (Sevigné Itoiz et al., 2013) could have been a feasible solution, the authors decided to perform anyway a specific assessment by adopting one of the most widely used LCA software (i.e. SimaPro) to obtain more precise results.

The objective of this study was to establish the annual environmental impact, by means of CF, of the solid waste collection process of Contarina S.p.A. in the province of Treviso, Italy, and to investigate its possible reduction by simulating a hypothetical scenario where most of the door-to-door service vehicles is turned from Diesel to Compressed Natural Gas (CNG) powered engines.

2. Case studies

2.1. Description

Contarina S.p.A. is a municipally participated company (i.e. a company in which the municipality is a shareholder) in charge of waste collection, management and disposal for part of the Treviso province, including the Municipality of Treviso. The managed area is about 1300 square meters with a population of nearly 554000 inhabitants served by different vehicles’ typologies according to the peculiarities of their residential areas. The door-to-door service spreads among 50 municipalities summing up to more than 260000 households.

Door-to-door waste collection follows a schedule which allows collecting all different waste typologies like non-recyclable, wet, glass/plastic/cans, vegetable, paper and cardboard (Artuso et al., 2015). Different color coded bins are exposed by inhabitants following the predefined daily schedule which are collected by means of specific vehicles selected on the basis of route characteristics (e.g. route width and population density). Routes are optimized in order to avoid the paradox where waste transportation for recycling impacts more than avoiding recycling at all (Salhofer et al., 2007). Although Treviso is one of the municipalities with higher pro-capita income in the Veneto region, its waste production is the lowest among those having similar pro-capita income in Italy. Municipality of Treviso has been subdivided into three zones: Zone 1: Old town (inside the historic walls), Zone 2: Treviso city center (outside the old city walls) and Zone 3: Suburban area outside Treviso, called urban belt. Zone 1 also embeds historical centers of other municipalities such as Castelfranco Veneto, Montebelluna ed Asolo where waste collection frequency is higher due to reduced bins’ size (Cuccu et al., 2015).

In order to establish the GHG emissions impact of door-to-door solid waste collection in the area of Treviso, CF assessment was performed. To keep track of all GHG elements, CF was assessed by applying the SimaPro 8.2 LCA software from Prè with the Ecoinvent v.3.2 database. The selected impact assessment method was the “Greenhouse Gas Protocol method” which has been developed by the World Resources Institute (WRI) and the World Business Council on Sustainable Development (WBCSD) and aims to test the usability of the draft GHG Protocol CF standards (WRI/WBCSD, 2004).

GHG Protocol’s characterization factors per substance are identical to the IPCC 2007 GWP (100a) method (Solomon, 2007) in SimaPro. The only difference is that carbon uptake and biogenic carbon emissions are included in this method and that a distinction is made between direct impacts: Fossil based carbon (carbon originating from fossil fuels and indirect impacts: i) Biogenic carbon (carbon originating from biogenic sources such as plants and trees); ii) Carbon from Land transformation; and iii)

Carbon uptake (CO_2 that is stored in plants and trees as they grow).

To evaluate the GHG emissions, the Ecoinvent processes developed for different transport lorries were used and adapted. For each lorry process, five different sources of GHG emissions are assessed: lorry construction & disposal, lorry maintenance, road construction & use, fuel extraction & transport and fuel combustion.

The default main unit of measure to estimate the emissions for lorry, used in Ecoinvent, is tons per kilometre, which is based on the average tons transported during operation multiplied by the mileage in the assessed period. The direct use of this default unit of measure was not suitable in our study because, even though information about total kilometres and total tonnage per year was available, the number of trips (or average kilometres per trip) was necessary to calculate average trip load from the total annual amount. Moreover, the variability in trips' distances is very large and would bring too uncertainty in the final estimation. To face this issue, the selected unit of measure was defined as the total amount of annual fuel consumption which was provided by Contarina for each lorry. GHG emissions are in fact directly related to fuel consumption allowing for a more precise estimation. The procedure used to perform the proposed fuel-based CF assessment is further explained in the next sections.

2.2. Data

The waste collection fleet of Contarina is wide and differentiated; vehicles utilized for door-to-door collection of solid waste are 290 subdivided into 6 typologies as reported in Table 1.

Table 1. Vehicles utilized for door-to-door collection of solid waste (CNG: Compressed Natural Gas; LPG: Liquid Propane Gas)

Type of vehicles	***Description***	***Type of fuel***	***Number of vehicles***
RU	Vehicle with a single tank	Diesel	250
ADV	Vehicle with double tank	CNG	8
ADV	Vehicle with double tank	Diesel	1
ACM	Mini rear compactor	Diesel	18
PM	Porter	LPG/Petrol	5
TR	Truck	Diesel	8
TOTAL			**290**

Each vehicle typology includes many categories of lorries characterized by fuel type (diesel, petrol, Liquid Propane Gas - LPG, Compressed Natural Gas - CNG), Euro emission class (spanning from Euro 2 to Euro 6) and mass category (metric tons' classes in: less than 3.5, 3.5 – 7.5, 7.5 – 16, 16 – 32, more than 32). These differentiating aspects are the same used by the Ecoinvent database under the transport category for lorries allowing to assign a specific Ecoinvent process to each assessed vehicle category.

Three waste collection management scenarios were assessed, characterized by the covered area and used vehicles: *Scenario 1* - Annual CF of the whole door-to-door collection service; *Scenario 2* - Annual CF of the door-to-door collection in historical centers only and; *Scenario 1bis* - Annual CF of the whole door-to-door collection service under ameliorative sustainability conditions.

Scenario 1 considers the whole Contarina fleet and door-to-door solid waste collection in the whole managed area for year 2015 by assessing emissions generated by all vehicle typologies and categories.

Scenario 2 considers only the small lorries used for the door-to-door solid waste collection in Zone 1 (i.e. the historical centers) for year 2015.

Scenario 1bis is a hypothetical scenario, based on Scenario 1, which considers the whole Contarina fleet and door-to-door solid waste collection in the whole managed area and where all diesel powered RU vehicles have been substitutes with CNG powered vehicles with the same load performance characteristics.

2.3. Converting unit of measure

As stated before, the selected unit of measure for the presented CF assessment is fuel consumption. Information about fuel consumption of the different vehicles was provided by Contarina in different units of measure according to fuel type: diesel, LPG and petrol were supplied in Liters, while CNG in kilograms. None of these units of measure has a correspondence in Ecoinvent which uses kilograms for diesel, LPG and petrol and cubic meters for CNG. Conversion of the different units of measure were performed by using conversion factors provided by the Department for Environment Food & Rural Affairs (DEFRA) U.K. (DEFRA, 2016; Ronco et al., 2014) as reported in Table 2.

Table 2. Units of measure conversion factors divided according to fuel typology

Fuel type	***Unit***	***To***	***Factor***
Diesel	lt	kg	0.851
CNG	kg	m^3	0.008
LPG	lt	kg	0.510
Petrol	lt	kg	0.749

2.4. Defining lorry categories

While most lorry categories used by Contarina for door-to-door solid waste collection were directly associated with the related Ecoinvent transport process by finding the correspondent lorry on the basis of the three aspects already mentioned in this section (i.e. fuel type, Euro emission class and mass category), this was not possible for some specific categories such as the Euro 2 emission class lorries and lorries with non-diesel powered engines. The Euro 2 issue was resolved by approximating the five Euro 2 vehicles present in Contarina's fleet with the corresponding Euro 3 processes in Ecoinvent. Non-diesel powered engines are not included in Ecoinvent transport processes while Ecoinvent's processes are available for passengers' cars large size powered by petrol, LPG and CNG. The latest were adapted to simulate equivalent lorry emissions. To this end, first a conversion factor *k* was calculated starting from a lorry diesel and a passenger car diesel by dividing car's fuel consumption by lorry fuel consumption. Because fuel consumption for all cars is based on one kilometre movements regardless of fuel type, this means that *k* can be used for all cars. Given the assumption that all sources of emissions being part of the lorry process (lorry construction & disposal, lorry maintenance and road construction & use) are linearly related to fuel consumption, *k* was then used to calculate the amount of the three processes to be set in the new equivalent lorry processes by multiplying original lorry diesel sources of emissions by *k*. Since fuels consumption was used as unit of measure, the frequent start and stop of vehicles has been implicitly taken into account.

2.5. Creation of hypothetical CNG powered lorries for scenario 1bis

Scenario 1bis is based on the hypothetical substitution of all diesel powered RU vehicles with CNG powered vehicles having the same load performance characteristics. Assuming that CNG powered lorries will be used as the current diesel powered lorries are, the information on annual total amount of mileage and collected tonnage of the current diesel powered lorries can be used to formulate a hypothesis on the amount of CNG which will be necessary to perform the same work. To this end a statistical model was developed to correlate mileage and tonnage to CNG consumption by generating a linear correlation model starting from the known CNG lorries already present in Contarina's fleet. Linear models were created for correlation between CNG consumption and mileage only, tonnage only and both, to find which of the three options better fits the data according to their coefficient of determination (i.e. R^2). The best fit resulted for the model where both predictors were used. The obtained linear predictor was applied against all diesel powered RU vehicles from Scenario 1 to finally obtain the hypothetical Scenario 1bis which simulates ameliorative sustainability conditions.

2.6. Calculating impacts in Simapro for the different lorry categories

Once all scenarios data were elaborated according to the previous sections, they were ready to be input for application in SimaPro. Total fuel consumption data for each lorry category in the correct unit of measure was input in the correspondent process in the software. As stated before, the unit of measure for lorry transport in SimaPro is tonnes per kilometre (tkm) while the selected unit of measure for our application was fuel consumption. In order to convert between the two, the fuel quantity per tkm reported in each transport process was used to calculate the tkm to be input in the process, according to Eq. (1):

$$y = \frac{x}{k} \tag{1}$$

where: *y* is the amount of tkm to input in SimaPro, *x* is the overall fuel consumption and *k* is the amount of fuel consumed for each tkm.

Processes related to all lorry categories were grouped into the three scenarios and each scenario was assessed with the GHG Protocol method in order to evaluate the overall emissions as well as the contributions of each of the four transport sub-processes and four method's results.

3. Results and discussion

The application of the previously described methodology led to the following results for the three considered scenarios. Total CF emissions were assessed by analysing direct and indirect emissions (i.e. emission related to direct and indirect impacts as mentioned in Section 2). As direct emissions represent the main contribution in the results their five constituting emission sources (i.e. lorry construction & disposal, lorry maintenance, road construction & use, fuel extraction & transport and fuel combustion) were also further analysed.

Results of Scenario 1 and Scenario 1bis were compared and CF results are reported in Table 3, where contributions of direct and indirect emissions are displayed alongside with contributions of the five direct emissions sources.

Table 3. CF for scenario 1 and 1bis divided by emission sources typology

Source of emissions	*Scenario 1 (kg CO_2eq)*	*Scenario 1bis (kg CO_2eq)*
Indirect emissions	**1.41E+05**	**2.62E+04**
Direct emissions	**7.73E+06**	**1.53E+06**
lorry construction & disposal	5.84E+05	7.74E+04
lorry maintenance	4.28E+05	5.69E+04
road construction & use	4.13E+05	1.13E+03
fuel extraction & transport	9.83E+05	1.99E+05
fuel combustion	5.32E+06	1.08E+06
Total	**7.87E+06**	**1.55E+06**

The comparison between the current scenario 1 and the ameliorative scenario 1bis (Fig. 1), clearly pointed out that CF would be remarkably reduced by converting part of the fleet to CNG (scenario 1bis). Specifically, CF due to direct and indirect emissions could be reduced by 80% and 81%, respectively, compared to 2015's situation. An additional comparison of 1 and 1bis scenarios' CF caused by direct emissions (Fig. 2) showed a clear decrease in the contribution of each of the five sources of emissions as the use of CNG increases. Specifically, emissions due to lorry construction & disposal, lorry maintenance, road construction & use, fuel extraction & transport and fuel combustion are reduced by 87%, 87%, 73%, 80% and 80%, respectively.

As far as Scenario 2 is concerned, CF results are reported in Fig. 3, in which contributions of direct and indirect emissions are also specified for each investigated historical centre. As reported in Fig. 3, the historical centre of Treviso has the lowest CF, although it has the most numerous fleet (9 vehicles) for the door-to-door collection service, serving the highest number of users (6.888). For Asolo, Montebelluna and Castelfranco, 1, 2 and 3 vehicles are employed respectively, serving 379, 2.198 and 2.547 users. This result can be explained considering that 8 out of 9 vehicles used in the historical centre of Treviso are CNG powered and only one is petrol / LPG powered, while the vehicles employed in the other historical centres are all diesel powered.

The same conclusions are further confirmed by the analysis of the CF due to direct emissions estimated for the four historical city centres (Fig. 4).

In fact, for the historical centre of Treviso not only the emissions related to fuel combustion and fuel extraction & transport decrease significantly compared to the other historical city centers, but also the emissions resulting from the other three sources of emissions (lorry construction & disposal, lorry maintenance and road construction & use). This is perfectly normal as CF (and LCA in general) directly relates emissions to the selected unit of measure, which is fuel consumption in the proposed methodology. This justifies the fact that all sources of emissions are always directly proportional to the amount of fuel used and to the different emissions generated by the combustion of different fuel types (CNG and petrol / LPG). Similar studies were conducted in other municipalities such as Rome, Bologna and other southern Italy cities (De Feo et al., 2016; Ripa et al., 2017; Tunesi et al., 2016; Vitale et al., 2017). In all cases similar results were obtained where fuel consumption accounts for the highest contribution in CO_2eq emissions.

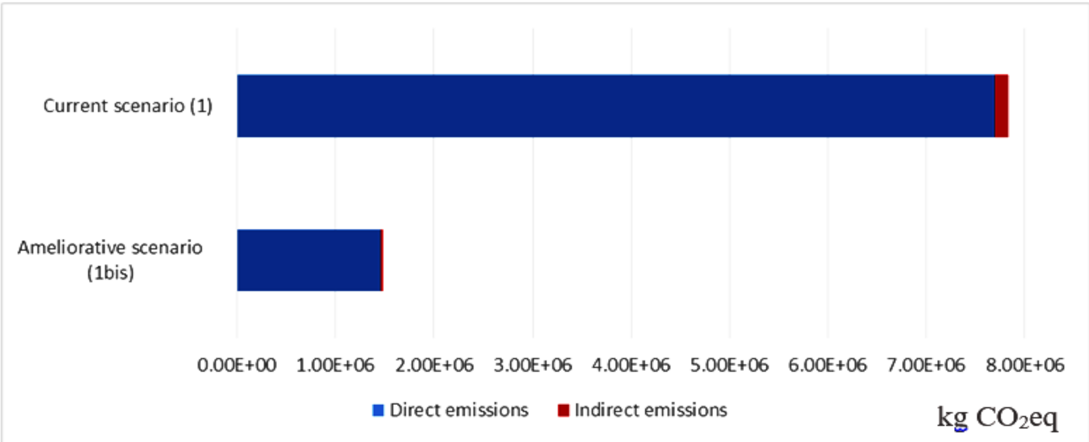

Fig. 1. Comparison of the CF for the current (1) and the ameliorative (1bis) scenarios

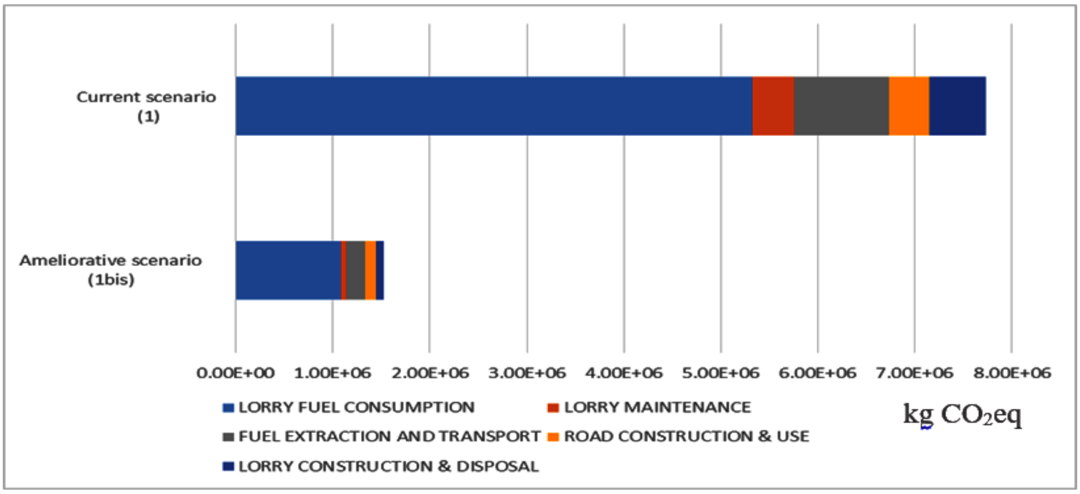

Fig. 2. Comparison of direct emission sources between current (1) and ameliorative scenarios (1bis)

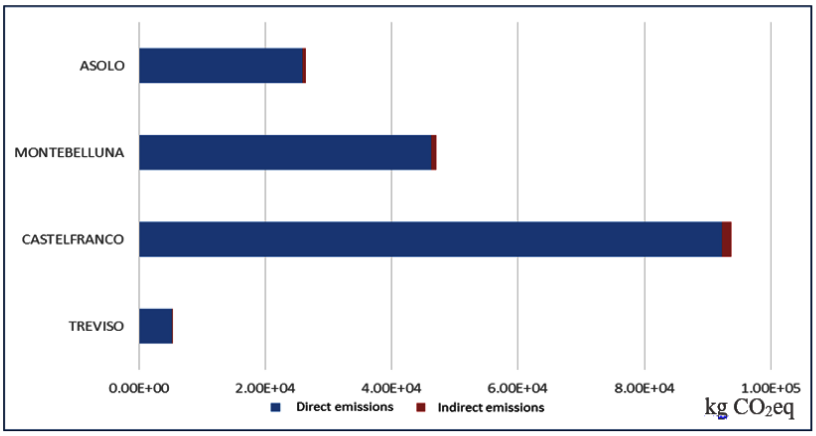

Fig. 3. Comparison between direct and indirect emissions in the four historical centres, Scenario 2

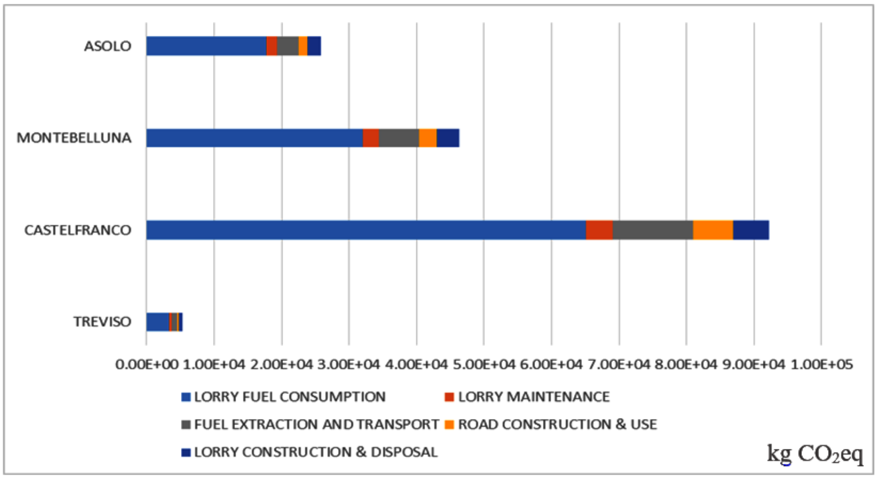

Fig. 4. Comparison of the four historical city centres for the direct emissions resulting from the five elements

4. Conclusions

This study applied the CF approach to evaluate the environmental impacts of the door-to-door waste collection service operated by the company Contarina S.p.A. (Italy).

The assessment was performed for both the currently employed fleet (with figures for 2015), with a specific focus on the service performance for the four historical city centres, and for a hypothetical fleet where all 250 diesel powered RU vehicles are replaced with CNG powered vehicles with the same load performance characteristics.

The results of this study clearly showed that the use of CNG, compared to the use of diesel, would be an environmentally sustainable alternative. In fact, by applying the ameliorative scenario Contarina could reduce the CF of its door-to-door collection service by 80%.

The choice to replace only the RU vehicles is dictated by the different power of CNG engines compared to diesel ones. Only the RU vehicles, in fact, can guarantee similar efficiency and safety of operation conditions, even if fully loaded, when CNG powered.

The conversion to CNG of vehicles with higher capacity such as ACM or road tractors (which handle up to 20 tons of waste), would not be as efficient. Finally, a simple economic analysis (results not shown) allowed to highlight that CNG is responsible for a lower amount of emissions of CO_{2eq}, at a lower cost.

However, this reduced cost would not be sufficient to amortize, by the life time of the new vehicles, the costs Contarina should initially invest for converting the 250 diesel trucks to CNG. The company is therefore investigating the possibility of producing in-house bio-methane by processing the wet waste collected in the area of Treviso province. This solution would allow to further reduce its overall CF and improve the outcome of the economic analysis.

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