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Technical Note

Estimation and Evaluation of Greenhouse Gas Emissions during the Life-Cycle of Wastewater Pipelines: Case Study of Tehran, Iran

Roghani, B.[1], Tabesh, M.[2*], Amrollahi, M.S.[3] and Venkatesh, G.[4]

[1] Ph.D. Candidate, School of Civil Engineering, College of Engineering, University of Tehran, Tehran, Iran.
[2] Professor, Centre of Excellence for Engineering and Management of Civil Infrastructures, School of Civil Engineering, College of Engineering, University of Tehran, Tehran, Iran.
[3] M.Sc. Graduate Student, School of Civil Engineering, College of Engineering, University of Tehran, Tehran, Iran.
[4] Senior Lecturer, Department of Engineering and Chemical Sciences, Faculty of Health, Science and Technology, Karlstad University, Karlstad, Sweden.

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ABSTRACT: Climate change occasioned by the accumulation of greenhouse gases (GHGs) is now widely accepted as an issue which mankind needs to address. The starting point is necessarily the determination of all the sources of emissions during the life-cycles of the studied components. Post-calculation, the results ought to be presented to decision-makers in a clear manner so as to provide the basis on which corrective actions could be considered. This paper calculates the GHGs emissions during the life-cycle of wastewater pipelines and introduces a different approach to communicate information about GHGs released, to decision-makers. Different diameters of concrete and high-density polyethylene (HDPE) wastewater pipes are compared in a case study. Results show that the total CO_2-equivalent (CO_2-eq) emissions attributed to concrete pipes are greater than HDPE pipes. Hence, the equivalent bio-productive area of forest required to sequester the CO_2 (the major GHG) and its corresponding costs will be greater for the former.

Keywords: CO_2-eq Emissions, Concrete Pipes, Ecological Footprint, HDPE Pipes, LCA, Wastewater Collection Networks.

INTRODUCTION

Greenhouse gas (GHG) emissions attributed to the combustion of fossil fuels have been instrumental in bringing the world to the juncture it finds itself in, with regard to climate change and associated challenges. Of late, the environmental aspect of sustainability has been factored into decision-making in the infrastructure sector, in Tehran (Iran) (RPCT, 2012). According to a World Bank report, the air pollution index was equal to 282 'unhealthy' days in year-2000 in Tehran (World Bank, 2005). Every country is expected to formulate its own strategies and targets for the mitigation of global warming.

* Corresponding author E-mail: mtabesh@ut.ac.ir

Cities which are highly populated and polluted bear a greater share of the responsibility in this regard. In the USA, capital investment for sewage and stormwater transport systems is estimated at USD 298 billion over the next two decades, with pipelines accounting for nearly 75% of this (ASCE, 2013). If such investments are to be committed, a strict monitoring of environmental impacts is warranted. Hereon, pipe materials, in addition to their influence on purchase, maintenance and operation costs, have key effect on environmental burdens such as resource depletion, energy usage, and GHG emissions. Therefore, a comprehensive study about ecological footprint of various pipe materials is necessary along with pipe network design and cost estimation in water and wastewater projects to find out suitable material types. As regards, the Life Cycle Assessment (LCA) as a useful and effective method to quantify environmental footprints throughout the life cycle of a product or service could be implemented. The Life Cycle Assessment (LCA) has been primarily used to compare the impacts caused by different products (disposable versus reusable for instance).

By implementing LCA technique, environmental impacts of products can be evaluated based on their materials and energy inputs and outputs. In literature, one finds many studies focusing on the life cycle environmental impacts of key civil infrastructure systems (Salem et al., 2003). One of the very first LCA studies in the area of water and wastewater pipeline industry was conducted by Dennison et al. (1999). They compared the life cycle environmental impacts of two different potable water pipe materials and identified the hotspots in the life cycle. However, they did not compare the two materials holistically.

Filion et al. (2004) developed a Life Cycle Energy Analysis model and applied it to the New York City water supply tunnels in order to compare the life cycle energy utilization of different pipe replacement schedules. While the GHG emissions were being calculated, transportation of pipelines from fabrication units to construction sites and their installation were excluded from the analysis. This model is more applicable to the entire water distribution network; than pipe segments.

Occasionally in water industry, a section of pipeline is installed either to replace an older pipe or for a new utility. Therefore, the energy requirements and GHG emissions resulting from that section have to be considered. Recio et al. (2005), in a case study, estimated the life cycle CO_2 emissions of different types of pipes in Spain. Dandy et al. (2006) presented a water distribution system optimization program that interconnects the sustainability objectives of whole life cycle costs, energy use, GHG emissions, and resource consumption. In another study, Venkatesh et al. (2009) calculated the GHG emissions in different stages of the life cycle of wastewater pipelines in the city of Oslo (Norway). They concluded that the operation, maintenance, and rehabilitation phases in an ageing and saturated wastewater pipeline network like Oslo's will be the prime contributors to GHG emissions in the future. However, they noted that a considerable amount of the total emissions occurred in the past, during the fabrication of the pipelines. Wu et al. (2010) adopted a multi-criteria single and multi-objective optimization approaches to optimally reduce costs and GHG emissions, in the design of water distribution systems. They applied their method to two hypothetical water distribution systems and concluded that as a multi-objective approach provides more insight for decision makers into the trade-offs between the objectives, it is recommended for the optimization of WDSs accounting for GHG emissions when considering carbon pricing. Du et al. (2012)

analysed the global warming potential in the life cycles of six in-vogue types of water and wastewater pipe materials. The results showed that for pipe diameters less than or equal to 61 cm, ductile iron pipe contributes the most to global warming, and for diameters greater than or equal to 76 cm, PVC dominates the emissions. In Du et al. (2012), only the upstream manufacturing, transportation and installation phases were included. In another study, Kim et al. (2012) investigated the environmental impact of four sewer pipe materials by focusing on GHGs emission. They applied their method to Deajeon city (South Korea) and concluded that the concrete pipe can be the first option than other pipe materials in the environmental aspect.

In a recent study, Vahidi et al. (2015) compared four different types of wastewater pipe materials named composite fiber reinforced polymer (FRP), PVC, ductile iron, and concrete. They had an attempt to quantify environmental impacts such as ozone layer depletion, eco toxicity, and energy consumption, but not Global Warming Potential (GWP). They considered a small to medium sized city with 200,000 populations as their study area and the results showed that the pipe production phase had the main environmental impacts among the different phases of studied pipelines. Also, ductile iron had the maximum impact and PVC had the minimum impact on most of the considered areas.

In most of the previous studies environmental impact categories are expressed in their conventional units, for example Global warming metrics expressed in kg-CO_2-eq. However, providing the environmental impacts of development projects in the aforementioned format may not be really helpful for decision makers. As decision makers should compare alternative options to select the most beneficiary one, they should be able to predict the benefits and costs in a consistent manner. The common unit of measurement is usually money (TECHNEAU, 2008). Thereby, conversions of the absolute GHG emission values to carbon taxes or carbon credits can be very helpful to consider them in decision-making processes and as a result, monitor and reduce GHG emissions. These are tradable certificates; each representing the right to emit one ton of greenhouse gases (measured in carbon dioxide equivalents). The credits-scheme has been operated by the European Union Emission Trading Scheme (EU-ETS) to control the amount of GHGs produced in the EU countries. The major drawback of this credit is its high liquidity risk which results in over-allocation, windfall allocation, and price volatility in the global economy (Kim et al., 2013).

Carbon tax is an environmental tax levied on the carbon content of fuels. It is closely related to the domestic Social Cost of Carbon (SCC), which is the marginal cost of emitting one extra ton of carbon at any point in time (Yohe et al., 2007). By levying such a tax, emitters are provided with an incentive to try to reduce their emissions and thereby tax payments. Although, carbon taxes are less affected by market conditions and pose less liquidity risks, they cannot regulate the upper limit of emissions. The drawbacks of carbon taxes are as follows:

1. Difficulty in determining the level of externality and thereby the amount of tax to be levied;
2. Possibility of tax evasion;
3. Dissatisfaction of consumers with the new taxes;
4. Relocation of the production units to countries with no or lower carbon taxes.

Kim et al. (2013) proposed an eco-friendly decision making procedure which enables designers to select the most economical and environment-friendly option through the planning phase of the construction project. They integrated the results of the life cycle cost (LCC) method and the carbon tax approach (as the environmental impact indicator) in a case study comparing two types of girder bridges – steel box and pre-stressed concrete box. They concluded that application of the 'CO_2-eq converted cost' may change the best alternative. Additionally, the optimal alternative could be changed with continuous fluctuations in the carbon tax.

The present paper focuses on wastewater pipelines. The pipes are assumed to have a 50-year operational lifetime, and are made of either concrete or HDPE (as representatives for rigid and flexible pipe materials).

As it is now becoming increasingly common for carbon related emissions to be priced under an emission trading scheme (Wu et al., 2010), in this paper, aside from the CO_2 estimation which is released during the life cycle of Concrete and HDPE sewer pipelines, the results were systematically monetized. By this way, they will be fully understandable for decision makers. Moreover, the environmental outputs could be easily considered in the Cost-Benefit analysis.

METHODOLOGY

The previous LCA studies in wastewater industry mainly focused on Wastewater Treatment Plant (WWTP), while the information about the sewer system is limited (Vahidi et al., 2015). Therefore, the present paper focuses on wastewater pipelines. The pipes are assumed to have a 50-year operational lifetime, and are made of either concrete or HDPE. The life cycle activities and the considered system boundary in this study are illustrated in Figure 1. Determining the boundary is an important step in LCA studies which is directly affected from data inventory and effects on the results.

In addition, as it is essential to present results in a decision maker friendly way, a new methodology has been introduced in the current paper to evaluate the total estimated GHG emissions by accessing real data on the life cycle stages. However, assumptions are inevitable owing to the non-availability of adequate amounts of data. The specific steps to achieve this goal are presented in Figure 2.

The life cycle typically begins with raw material extraction which is usually energy-intensive. Raw materials are transported to pipe fabrication units, and both transportation and fabrication are contributors to GHGs. The environmental input-output life cycle assessment (EIO-LCA) technique can be used to quantify GHG emissions related to the fabrication phase of the life cycle of pipelines. This technique tracks monetary and material flows among industry sectors involved in the manufacturing of a given item or service. The Carnegie Mellon online EIO-LCA model, developed by the Carnegie Mellon University Green Design Institute, was selected to estimate the GHG emissions because of its widespread use and accessibility (Carnegie, 2016). This model, on date, has versions other than the American one; however, an Iranian version is yet to be developed. The 1997 US National Purchaser Price Model has been used in this paper (as a proxy; again, as mentioned earlier, an assumption without which it would have been difficult to proceed as per the methodology outlined in the paper). Since the price data from Iran are for year 2016, they have to be converted to 1997 USD so that the aforementioned model can be used.

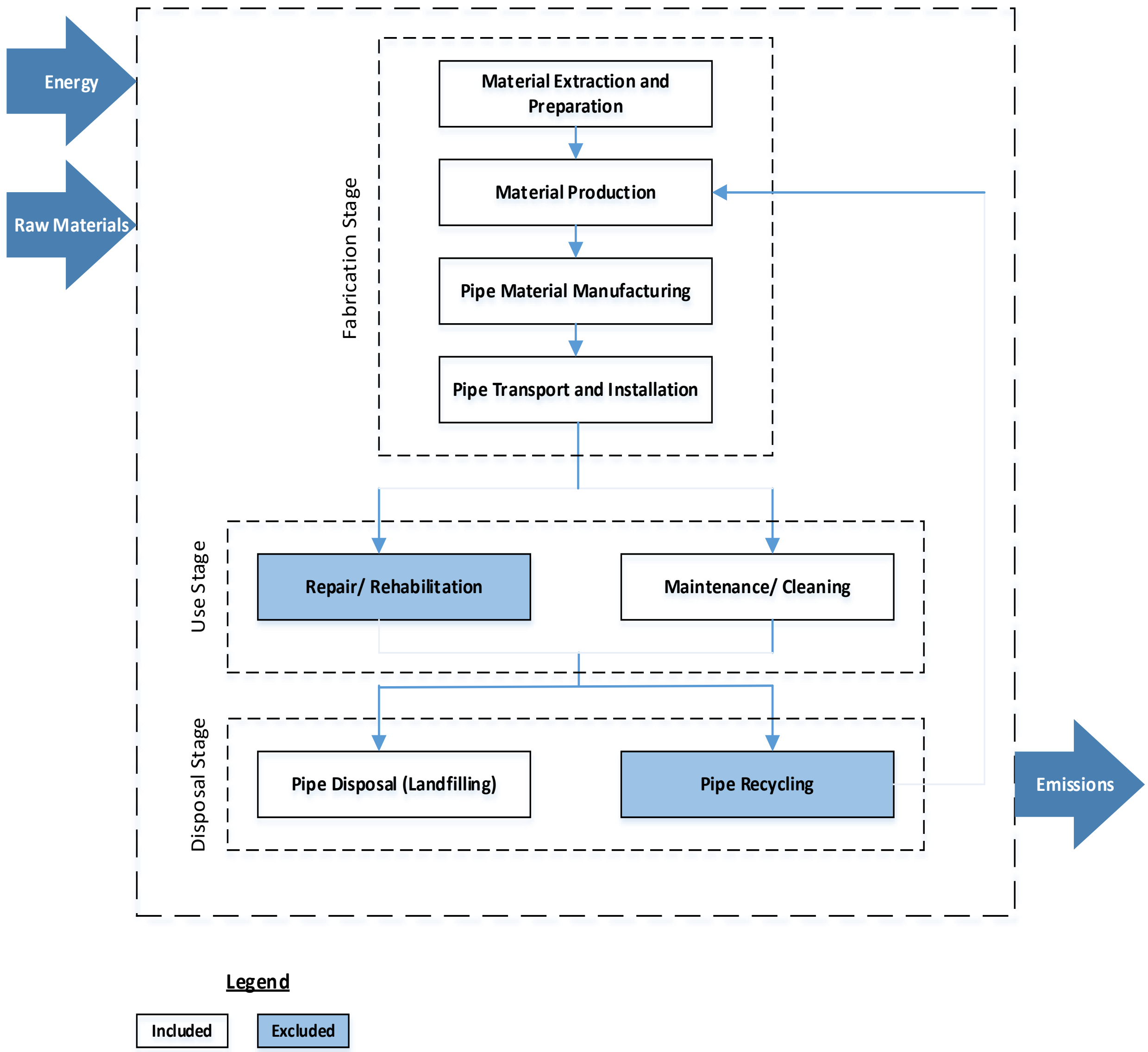

Fig. 1. Life-cycle of a wastewater pipeline project

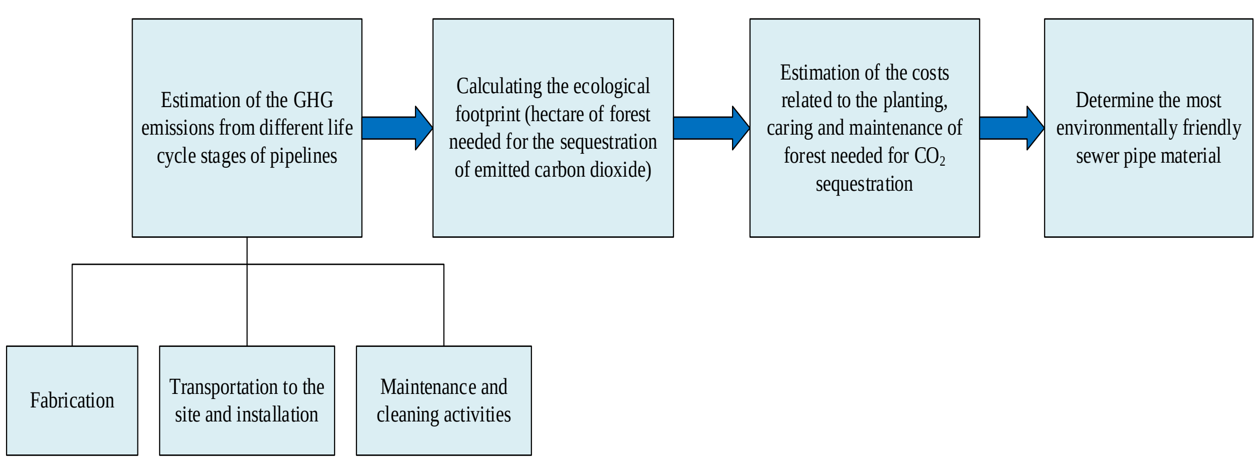

Fig. 2. Flowchart of the proposed methodology

This can be achieved by using Eq. (1) and the assumptions that 1 USD is equal to 35000 IRR and the average US discount rate is 0.50% (Trading Economics, 2016).

$$P_n = P_0 \times (1 + r)^n \qquad (1)$$

where P_n is the value at the end of the n^{th} year, P_0 is the value in the base year, r is the interest rate and n is the number of years.

The functional unit (measurable unit to represent a function) in the present study is defined as the unit length of pipelines (1 km). The converted costs for 1 km of HDPE and concrete pipelines are inserted into the EIO-LCA online model under the industry sectors #326122 (Plastic pipes and pipe fitting manufacturing) and #327332 (Concrete pipe manufacturing), respectively. As Table 1 shows, production of pipes with larger diameters emits more GHGs. Additionally, it is observed that the GHG emissions during the fabrication of HDPE pipes are lower than or almost equal to those for concrete pipes of the same size. By considering the 350 mm concrete and HDPE pipes as an example, cement manufacturing is the major source of greenhouse gas emissions in the production stage of concrete pipes followed by truck transportation and power generation and supply (Figure 3a). On the other side, power generation and supply followed by truck transportation and plastics material and resin manufacturing are the main contributors to the total amount of GHGs emission during the production stage of HDPE pipes (Figure 3b).

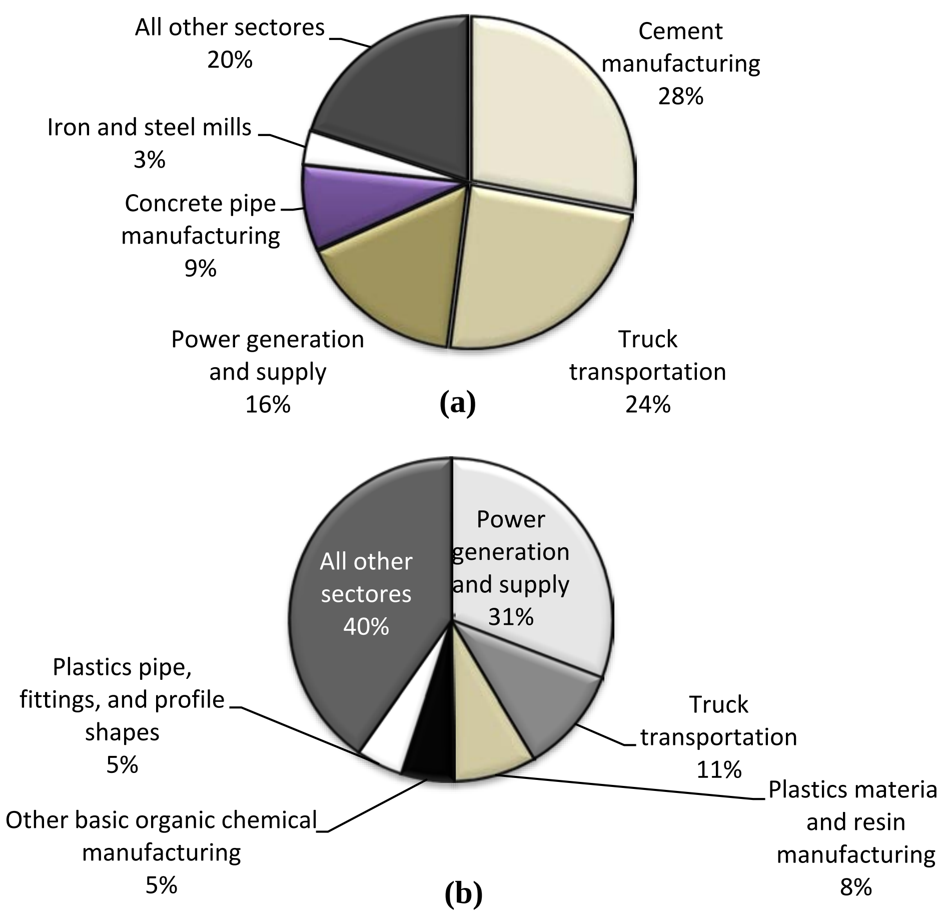

Fig. 3. Sectorial GHG emissions during the production of 350 mm; a) Concrete; b) HDPE pipes (Carnegie Mellon online model outputs)

Table 1. Present and converted prices and the model outputs

Pipe Material	Diameter	Present Price for 1 km of Pipe in Iran (2016 IRR)	Present Price for 1 km of Pipe in Iran (2016 USD)	Discounted Price for 1 km of Pipe (1997 USD)	CO_{2e} Emissions (Output of the Model) (kg/km)
HDPE	200	115,000,000	33,090	29,949	26,500
	250	135,850,000	39,090	35,379	31,300
	300	264,124,000	76,000	68,785	60,800
	350	369,000,000	106,180	96,100	85,000
Concrete	200	78,540,000	22,600	20,454	25,600
	250	101,824,000	29,300	26,518	33,200
	300	259,599,000	74,700	67,608	84,700
	350	320,415,000	92,200	83,447	105,000

Each US dollar was approximately equal to 35000 IRR when this paper was prepared.

Based on previous research results, like CPSA Report (2011), increase in the diameter of pipes - greater than 450 mm - leads to an increase in the GHG emissions for HDPE vis-à-vis concrete. Although, as it is presented in Table 1, the costs of the HDPE pipes are almost higher than concrete pipes, by using the inter – industrial – sectors – monetary – transaction Carnegie Mellon Model, the GHG emissions of concrete pipes were observed to be greater than those of HDPE pipes. It should be noted that because of the paucity of data, and by virtue of the fact that wastewater collection networks have a majority of small diameter pipes (WERF, 2004), pipe diameters less than 450 mm are considered in this analysis.

After fabrication, pipes are transported to the installation-sites. The amount of GHG emissions in this stage is the function of the distance travelled, vehicle types and fuel consumption. Either the trench excavation technique or trenchless methods can be deployed for the installation. In a study conducted by Ariaratnam and Sihabuddin (2009), GHG emissions during the installation phase of a wastewater pipeline, by the conventional trench excavation and pipe bursting methods were compared. The results show that the emissions related to the latter are 80% less than the former.

Results from Zhang et al. (2012) showed that the GHG emissions during the transportation and installation phases by using conventional trench excavation method, account for 13% of the life cycle emissions.

In the present study it is assumed that pipelines are transported to the installation site by Volvo FH trucks which have the allowable load capacity equal to 40 tonnes. The corresponding amount of GHG emissions are estimated for a unit distance length (one km) of pipe transportation. Besides, by considering the Komatsu S4D102LE-2 as an excavator vehicle with the grab capacity of 0.96 m^3 and average diesel consumption value equal to 30 Lh^{-1}, the GHG emissions related to installation phase could be calculated (with the presumption that 180 buckets of earth could be excavated per hour and the $CO_{2\text{-eq}}$ of diesel combustion is 2.73 kg L^{-1} diesel burned (Qi and Chang, 2013). The estimated amounts of GHG emissions in this phase are presented in Table 3. According to this table, the transportation and earthwork of larger size pipes are more fuel consuming activities and as a result, more GHG emissions are produced. It is worth mentioning that the earthwork of same-sized HDPE and concrete pipes are assumed to be identical. In accordance with Vahidi et al. (2015) fuel consumption for trench excavation is the main source of GHG emissions in this stage.

In the operation and maintenance (O & M) phase of the life cycle, energy consumed for pumping, pipeline inspection and maintenance, contribute to the GHG emissions. As the sewer mains are mostly installed at a gradient and avail of gravity to transport the sewage, the pumping energy consumption is negligible (Petit-Boix et al., 2015). Further, GHG emissions during inspection can also be overlooked (Piratla et al., 2012). Therefore, most of the GHG emissions during this phase is related to the maintenance activities like cleaning and pipe breakage repairs.

In order to estimate the GHG emissions during the cleaning and pipe-break repair activities, the blockage rate and the number of incidences of pipe collapse are to be considered (assumed or approximated). Hafskjold et al. (2004) recommends Eq. (2) for the calculation of the blockage rate.

$$B.R = B.R_{Ave} \times TRF \tag{2}$$

where *B.R* is the number of annual blockage events per metre of pipe, $B.R_{Ave}$ is the average number of blockage events for one kilometre of all types of pipes in the area being studied, and *TRF* is the total risk factor which can be obtained by multiplying some factors related to physical and operational circumstances of each pipe (e.g. diameter, age, material of construction, wastewater characteristics, etc.).

Since the wastewater collection network's blockage events are recorded only for the last few years in Tehran, TRF is calculated according to the coefficients presented in Ugarelli et al. (2010). These factors are summarized in Appendix 1. Based on the blockage events information recorded in Tehran during 2010-2013, $B.R_{Ave}$ is equal to 8.5×10^{-2} blockage/km/yr.

Different methods can be used in order to remove the blockages of wastewater pipes. Water jetting with high pressure is the main method for cleaning different types of sewers and drains (CPSA, 2008). The efficency of this method depends on many factors such as diameter of the pipe, characteristics of pump curve and type of the nozzle (Calomino et al., 2007). Several equipment are available to carry out the de-blocking operations. In the current study, features of Truck Jet 100 (a Mercedes-Benz product), are considered. Some of these specifications are listed in Appendix 2.

Based on the metadata about the blockage events, such as the mean distance between the office of the maintenance personnel and the site of the blockage event, the average time required by the maintenance personnel to reach the location, and the total number of annual operations, the GHG emissions related to the pipe-blockage-removals can be estimated. Based on interviews with the maintenance-and-repair personnel in Tehran, the mean time for commuting to the location of the blockage event is considered to be 2 hours. By assuming that the average speed of the car used for the commuting is 60 kilometres per hour, the GHG emissions per trip can be calculated as 26.64 kg. The cleaning operation performed by water jet machines takes nearly 2 hours; and based on spreadsheets developed by the Department for Environment, Food and Rural Affairs (DEFRA, 2010), the GHG emissions during the cleaning operation amount to 80 kg of $CO_{2\text{-eq}}$.

According to the US Army Corps of Engineers, a concrete pipe has a service life of 70-100 years. Moreover, designers should not expect a material service life greater than 50 years for any plastic pipe (ACPA, 2012). Thereby, the operation phase is assumed to be 50 years long to have comparable results (refer to Table 2 for the total GHG emissions per km of pipelines in this stage).

Table 2. GHG emissions in the cleaning operation period for 1 km wastewater pipe

Pipe Material	Diameter (mm)	0-19 TRF	0-19 Blockage Rate (Blockage/year)	0-19 GHG Emissions (Kg CO_2-eq)	20-39 TRF	20-39 Blockage Rate (Blockage/year)	20-39 GHG Emissions (Kg CO_2-eq)	40-50 TRF	40-50 Blockage Rate (Blockage/year)	40-50 GHG Emissions (Kg CO_2-eq)	Total Blockage	Total GHG Emissions (Kg CO_2-eq)
HDPE	200	0.335	2.85 E-2	60.73	0.897	7.62 E-2	162.54	2.128	1.81 E-1	192.91	3.9	416.19
	250	0.149	1.26 E-2	26.94	0.398	3.38 E-2	72.10	0.944	8.02 E-2	85.57	1.73	184.60
	300	0.159	1.35 E-2	28.90	0.427	3.63 E-2	77.34	1.013	8.61 E-2	91.80	1.9	198.03
	350	0.083	7.1 E-3	15.13	0.223	1.9 E-2	40.51	0.530	4.51 E-2	48.07	1	103.71
Concrete	200	1.028	8.74 E-2	186.38	2.752	2.34 E-1	498.85	6.532	5.55 E-1	592.05	12	1277.28
	250	0.456	3.88 E-2	82.67	1.221	1.04 E-1	221.27	2.897	2.46 E-1	262.60	5.3	566.53
	300	0.489	4.16 E-2	88.68	1.309	1.11 E-1	237.35	3.108	2.64 E-1	281.70	5.7	607.74
	350	0.256	2.18 E-2	46.45	0.686	5.83 E-2	124.31	1.628	1.38 E-2	147.53	3	318.29

Table 3. GHG emission through different stages of HDPE and Concrete pipes life cycle

Stages	Pipe Material	200 Kg $CO_{2\text{-eq}}$ per km	200 %	250 Kg $CO_{2\text{-eq}}$ per km	250 %	300 Kg $CO_{2\text{-eq}}$ per km	300 %	350 Kg $CO_{2\text{-eq}}$ per km	350 %
Pipe Production	HDPE	26,500	92	31,300	93.1	60,800	95.9	85,000	96.7
	Concrete	25,600	89	33,200	92.5	84,700	96.5	105,000	97.1
Pipe Transportation and Installation	HDPE	1,879	6.5	2,140	6.4	2,429	3.8	2,834	3.2
	Concrete	1,881	6.5	2,142	6	2,432	2.8	2,838	2.6
Operation	HDPE	416.19	1.5	184.60	0.5	198.03	0.3	103.71	0.1
	Concrete	1277.28	4.5	566.53	1.5	607.74	0.7	318	0.3
Total	HDPE	28,795	100	33,625	100	63,427	100	87,938	100
	Concrete	28,758		35,909		87,740		108,156	

The number of blockage accidents and as a result, the amount of GHG emissions related to the cleaning operations of HDPE pipes are approximately one third of that of the corresponding concrete pipes (refer to Appendix 1). Also, it is evident that as the pipes get older, the incidence of blockage events, and thereby the GHG emissions will increase.

End-of-life handling of pipes is the last stage in their respective life cycles. The exhuming, transportation and recycling of the old pipes also contribute to life cycle GHG emissions. Alternately, the old pipes could also be left sub-terra. As stated in previous studies of this type, the demolition/recycling plans are the most uncertain in the life cycle of a civil structure (Kim et al., 2013). Thereby, as recommended by Piratla et al. (2012), this phase is ignored due to lack of information about energy consumption during the end-of-life handling activities.

After calculating the GHG emissions during the life cycle stages, a suitable indicator has to be adopted in order to communicate the environmental performance information to decision makers. The proposed indicators in literature – carbon credit and carbon tax – vary from country to country and may even be unrealistic at times. Eq. (3) can be looked upon as a solution to this problem (Herstein et al., 2009).

$$EF = \frac{GWP(1 - FABO) \times (10{,}000)}{(Period) \times (SR)} \tag{3}$$

where *EF* stands for the ecological footprint of fossil-fuel emissions expressed as the area of bio-productive forests required for CO_2 sequestration (m^2), *GWP* is global warming potential (tCO_2); *FABO* (fraction absorbed by ocean) is equal to 0.27 (base on the global average measured over the last decade, 2002-2011) (Quéré et al., 2013), *Period* is the period of time used for analysis of GWP (year) and *SR* (sequestration rate) is the forest CO_2 sequestration (3.738 *t* CO_2 per global hectares per year (Environmental Protection Authority (EPA) Victoria, 2005)).

As far as the EF factor is concerned, its presentation in the common form to managers and operators can bring some difficulties as the concept may not at once be clear and obvious to them. So, in order to facilitate the consideration of GHG emissions in the decision making process, this factor can be converted to tangible expenses. In this study, the expenditures related to the planting, caring and maintenance of bio-productive forest for CO_2 sequestration were used.

Hoff (2009) has stated that the cost of planting one hectare of forest is equal to € 8141 (approximately USD 10,176). It should be mentioned at this juncture that this cost also includes the maintenance expenses for 15 years. The equivalent bio-productive forest area can be expressed in terms of the equivalent costs of planting and nurturing (refer to Table 4 and Figure 4).

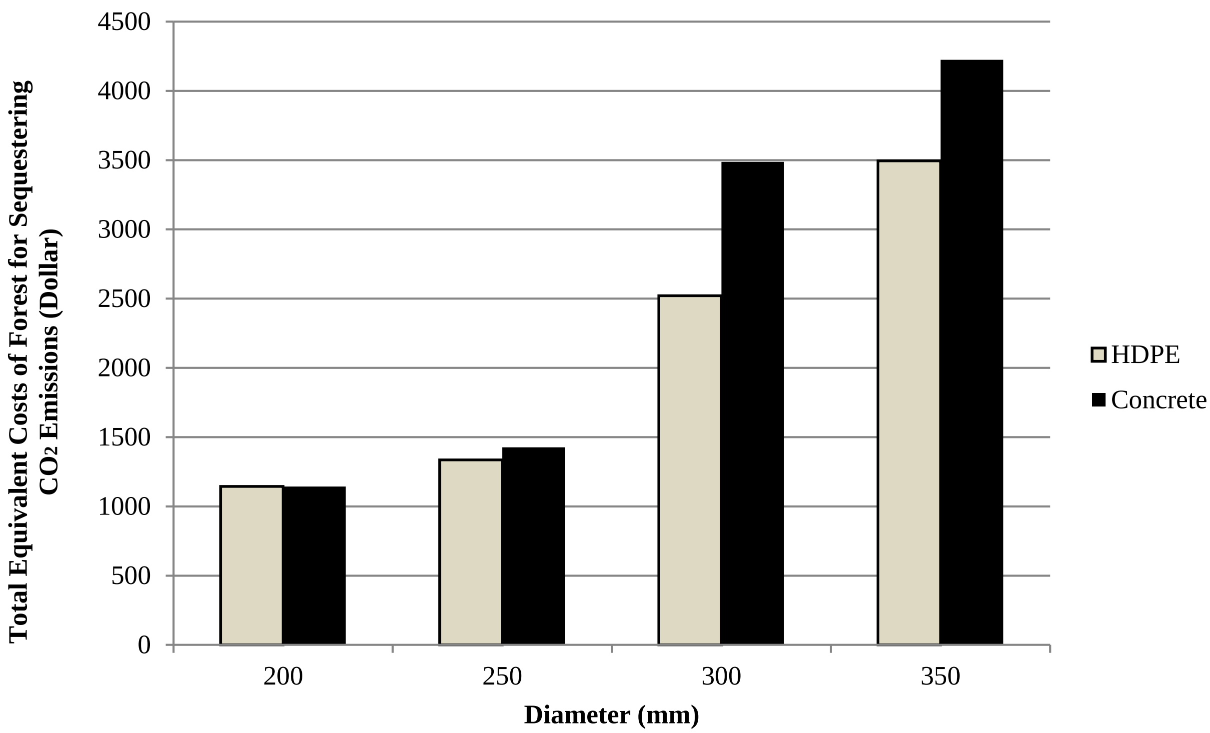

Fig. 4. Total equivalent cost of forest for sequestering CO_2 emissions* through the life cycle of all studied pipes

* Note that GHGs other than carbon dioxide are emitted in relatively very small amounts during the life cycle of wastewater pipelines, and hence, the approximation of all GHGs to carbon dioxide, in this paper, for the sake of the conversion made in the figure, is justified to some extent)

Table 4. The equivalent bio-productive area and its expenses related to each pipe segment

Pipe Material	Diameter (mm)	Total CO_{2e} Emissions ($kg \times 10^3/km$)	Equivalent Bio-Productive Forest (m^2)	Equivalent Costs of Forest (USD)
HDPE	200	28.8	1,125	1,144
	250	33.6	1,313	1,336
	300	63.4	2,477	2,521
	350	87.9	3,435	3,495
Concrete	200	28.8	1,123	1,143
	250	35.9	1,403	1,427
	300	87.7	3,427	3,487
	350	108.2	4224	4,299

RESULTS AND DISCUSSION

In this paper, life cycle GHG emissions of small-diameter HDPE and concrete pipes in Tehran were calculated. For the raw material extraction and pipe fabrication phase of the life cycle, the Carnegie Mellon online model (Carnegie, 2016) was used. While HDPE pipes are costlier than concrete ones, relatively greater GHGs are emitted through the life cycle stages of the concrete pipes. The equivalent 'forest costs' for the sequestration of carbon dioxide emitted during the pipeline production and installation phases, are shown in Figure 5 (on the basis of different pipe diameters). Based on the processes which were implemented in the production and installation phases of the pipes, it is clear that for diameters of 200 and 250 mm, the costs of creating a green space are approximately the same for both concrete and HDPE pipes. Nevertheless, the costs related to nurturing an equivalent forest for concrete pipes of diameters 300 and 350 mm, are approximately USD 800 higher than for the corresponding HDPE pipes. In addition, as Figure 6 illustrates for both pipe materials, as pipe diameters increase, the equivalent operational expenses (per unit length) decrease. In general though, the specific costs rise, as pipes get older.

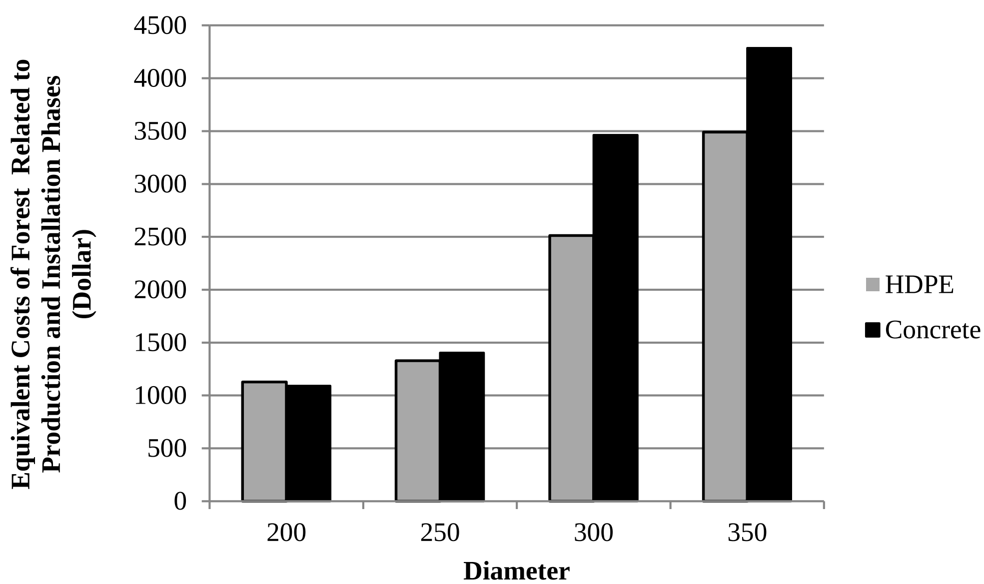

Fig. 5. The equivalent costs of forest for sequestering CO_2 emissions related to the production and installation phases for assumed Concrete and HDPE wastewater pipes

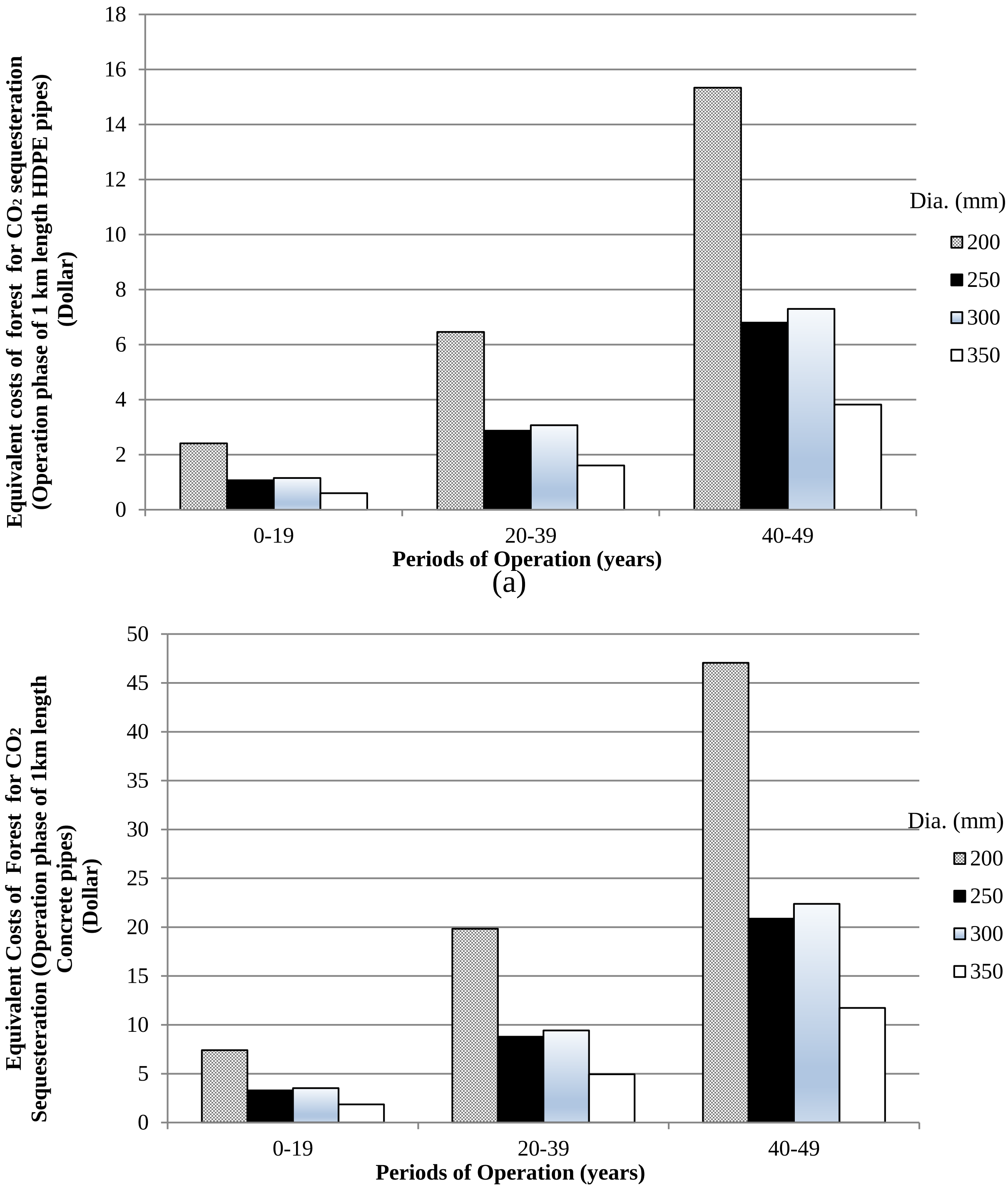

Fig. 6. The equivalent costs of forest for sequestering CO_2 emissions related to the operation phase for assumed; a) HDPE; b) Concrete pipes

It is also noteworthy to mention that the GHG emissions during the raw material extraction and pipe production stages, contribute to the lion's share of the emissions-pie (refer to Table 3). These results are in agreement with the observation made by Strutt et al. (2008), in which the authors stated that when pumping energy is excluded from the life cycle analysis, the GHG emissions from the production and installation phases account for 98% of the total impacts. Du et al. (2012) have put this percentage in the range of 92-97%. Therefore, the importance and imperativeness of the reduction of GHG emissions in this phase of the life cycle is obvious.

The aggregated equivalent life cycle forest costs for sequestration for both the materials of pipe construction are considerable. For instance, the total length of gravity wastewater collection network in the USA is approximately 1,190,914 km (EPA, 2009). Water Environment Research Foundation (2004) claimed that pipes of 300 mm diameter or smaller, form about 77 percent of the aforesaid gravity wastewater collection network. Based on Figure 4, it can be concluded that by utilizing concrete pipes in the assumed diameter classes in the wastewater collection network, the life cycle emissions will be about 80,457,673 Tons of CO_2-eq (or 314,254 ha as equivalent bio-productive forest or USD 3198 million as equivalent forest costs). If HDPE pipes are used, instead of concrete, the corresponding numbers are 58,162,826 Tons of CO_2-eq, 227,174 ha as equivalent bio-productive forest and USD 2312 million as equivalent forest-costs. According to the Tehran water and wastewater utility the total length of pipes in the gravity wastewater collection network would reach 9000 km. Considering the same ratio for pipe sizes smaller than 350 mm in diameter, the equivalent bio-productive forest and its related costs for concrete pipes will be 2,375 ha, and USD 24 million, respectively. By comparing with the forest area in the city of Tehran which is approximately 2700 hectares (Tehran Municipality ICT Organization, 2012), its considerable amount is revealed. Interestingly, it is just one small element of the common civil infrastructures in urban settings. If all infrastructures are included, the forest area needed and the associated costs would be substantial.

In the European Union, a penalty of USD 22 is considered to be reasonable per Ton of GHG emissions. By considering the case study of Tehran's wastewater collection network and based on the aforementioned conversion factor, the emission credit is roughly estimated as USD 13 million which is about half of the calculated amount in the present study.

CONCLUSIONS

In this paper, the life cycle GHG emissions attributed to the wastewater pipelines (made of concrete and HDPE) in Tehran (Iran) were calculated. The presented approach can be applied to a pipeline network project to gain a better understanding of the life cycle environmental impacts, before commencing work on the project. Results showed that concrete emerged as the lesser favourable of the two similar sizes of pipe. In order to make the outputs more comprehensible to the managers and operators, ecological footprint to approximate the required area of forests for sequestering the carbon dioxide was calculated. Then, in order to facilitate the consideration of GHG emissions in the decision making process, the related costs for planting, caring and maintenance of forests for 15 years were estimated. The presented index would assist to select the most suitable pipe based on environmental and economic issues. Also, the aforementioned estimated cost could be used in Life Cycle Cost (LCC) studies as a logical monetary representative of GHG emissions environmental impacts.

In some countries like European Union countries, a penalty is considered for each kg of CO_2 emissions (22 USD). But, this paper showed that how the proposed penalty could be far from the real costs which are imposed on the environment. As a result, the equivalent cost of forest surface area for sequestration CO_2 is suggested to be considered as a sensible estimation of environmental burdens' costs.

It is worth mentioning that bio-productive forests sequester carbon dioxide, which is the major greenhouse gas, for their photosynthetic process. However, in this paper, by converting the total GHG amount to equivalent forest surface area for sequestration, an approximation has been made. It must be noted that methane, nitrous oxide etc., which are much more potent than carbon dioxide, are emitted in relatively very small amounts during the life cycle of the wastewater pipelines, and on this premise, the approximation is justified.

For the future works, it is suggested that a precise thresholds for the total emissions allowed within different industries (e.g. water and wastewater industry) to be set and try to establish a mechanism for carbon trading. Therefore, companies are required to measure and report their carbon emissions and can trade their allowances, providing an incentive for them to reduce their emissions.

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APPENDICES

Appendix 1. Individual factors for calculating the TRF (Ugarelli et al., 2010)

Property	Criterion	Factor
Type	Storm water	0.03
	Sewage	1.37
	Combined flow	1.14
Diameter	200-230 mm	1.24
	250-280 mm	0.55
	300-335 mm	0.59
	350-380 mm	0.31
Material	Concrete	1.78
	Plastics	0.58
Age	0-19 year	0.34
	20-39 year	0.91
	40-59 year	2.16

Appendix 2. Characteristics of Truck Jet 100 (HFM Cleaning, 2013)

Pressure range (bar)	500 - 2500
Fuel consumption at 60% operating load (lit/h)	12.5
Power of pumps (kW)	100
Fuel consumption (lit/100km)	8.4
CO_2 emissions (g/km)	222