Combined MFA-LCA for Analysis of Wastewater Pipeline Networks

Case Study of Oslo, Norway

G. Venkatesh, Johanne Hammervold, and Helge Brattebø

Keywords:

concrete
greenhouse gas (GHG) emissions
industrial ecology
life cycle assessment (LCA)
material flow analysis (MFA)
polyvinyl chloride (PVC)

:// Supplementary material is available on the *JIE* Web site

Summary

Oslo's wastewater pipeline network has an aging stock of concrete, steel, and polyvinyl chloride (PVC) pipelines, which calls for a good portion of expenditures to be directed toward maintenance and investments in rehabilitation. The stock, as it is in 2008, is a direct consequence of the influx of pipelines of different sizes, lengths, and materials of construction into the system over the years. A material flow analysis (MFA) facilitates an analysis of the environmental impacts associated with the manufacture, installation, operation, maintenance, rehabilitation, and retirement of the pipelines. The forecast of the future flows of materials—which, again, is highly interlinked with the historic flows—provides insight into the likely future environmental impacts. This will enable decision makers keen on alleviating such impacts to think along the lines of eco-friendlier processes and technologies or simply different ways of doing business. Needless to say, the operation and maintenance phase accounts for the major bulk of emissions and calls for energy-efficient approaches to this phase of the life cycle, even as manufacturers strive to make their processes energy-efficient and attempt to include captive renewable energy in their total energy consumption. This article focuses on the life cycle greenhouse gas emissions associated with the wastewater pipeline network in the city of Oslo.

Address correspondence to:
G. Venkatesh
Industrial Ecology Program
Department of Hydraulic and Environmental Engineering
Norwegian University of Science and Technology (NTNU)
SP Andresensv 5
Valgrinda, Trondheim NO-7491
Norway
venkatesh.govindarajan@ntnu.no

DOI: 10.1111/j.1530-9290.2009.00143.x

Volume 13, Number 4

Introduction

In this article, we study the greenhouse gas (GHG) emissions associated with the wastewater pipeline network in Oslo, Norway, and identify the contributions of the different phases in the life cycle to that network, by using dynamic material flow analysis (MFA) and environmental life cycle analysis (LCA) as tools. Oslo's wastewater pipeline network has evolved over the years. Knowledge of the flows into (and out of) the network—the additions of new pipelines to the network and rehabilitations done on old pipelines—as well as the operation and maintenance schedules followed provides insights into life cycle energy consumption and life cycle emissions to environmental media. In this article, only the pipelines per se are considered, and the network does not include the pumping stations that feed wastewater into it, the wastewater treatment plants to which the pipelines supply wastewater and from which they take effluent away, and other components of the wastewater network, such as manholes. We intend to discuss these components of the network in subsequent studies, however. The relative importance of each phase over the lifetime changes, and is a point to be considered, especially when one has to manage aging infrastructure assets such as pipelines.

In the following sections, the pipeline network is described in brief and the methodology adopted is sketched out. A detailed literature review pertaining to LCA and greenhouse gas emissions from water–wastewater systems is presented in the Methodology section. We interpret the flows into stock in terms of the metals and alloys of which the pipelines are composed and calculate forecasts of the future material flows into the system and the life cycle greenhouse gas emissions for the wastewater pipeline network (through 2027). Finally, we draw conclusions and interpret the findings in terms of sustainability and triple bottom line management.

Background

Ugarelli and colleagues (2008) report that at the end of 2006, the Oslo sewer network consisted of 52,960 pipelines, with a total length of 2,253 kilometers (km).[1] Sewage pipes accounted for 670 km, storm-water pipelines for 760 km, and combined flow pipes for 823 km. Of the 2,253 km of pipelines in the network, only about 1,940 km could be characterized comprehensively. (This is the equivalent of about 49,900 individual pipelines—about 94% of the total of 52,960 in the stock.)[2] Of this, there were about 76 km of ferrous pipes, about 250 km of polyvinyl chloride (PVC) pipes, and more than 1,600 km of concrete pipelines. Understanding the material flows into the network enables one to batch the pipelines in the stock at any point of time on the basis of their physical lifetimes. More detailed information on the physical data for the sewer network in Oslo can be obtained from work by Ugarelli and colleagues (2008), who also carried out a thorough analysis of the economics of asset management.

Pipelines are long-lived, and, after fabrication and installation *sub-terra* (which entails a series of operations), they are attended to regularly. The following operations may be performed on a pipeline during the operation and maintenance phase of its lifetime, at the end of which it is retired from service:

- Internal coating of pipes for corrosion resistance
- Replacement of smaller parts of a pipeline stretch
- General repair
- Visual inspection
- Cleaning and flushing
- Alterations in the direction or route along which the pipelines are laid, including exhumation (digging up) and replacement of pipes
- Rehabilitation methods that do not require digging, whereby a new pipe is laid within an existing pipe.

Note that we do not have data about the outflows of pipelines from the network—retired pipelines that are left buried underground and disconnected from the network. Besides, no "end-of-life handling" as such takes place in the case of these infrastructure assets, unless, of course, one considers them to be recyclable or reusable materials for the future, in the case of exigencies

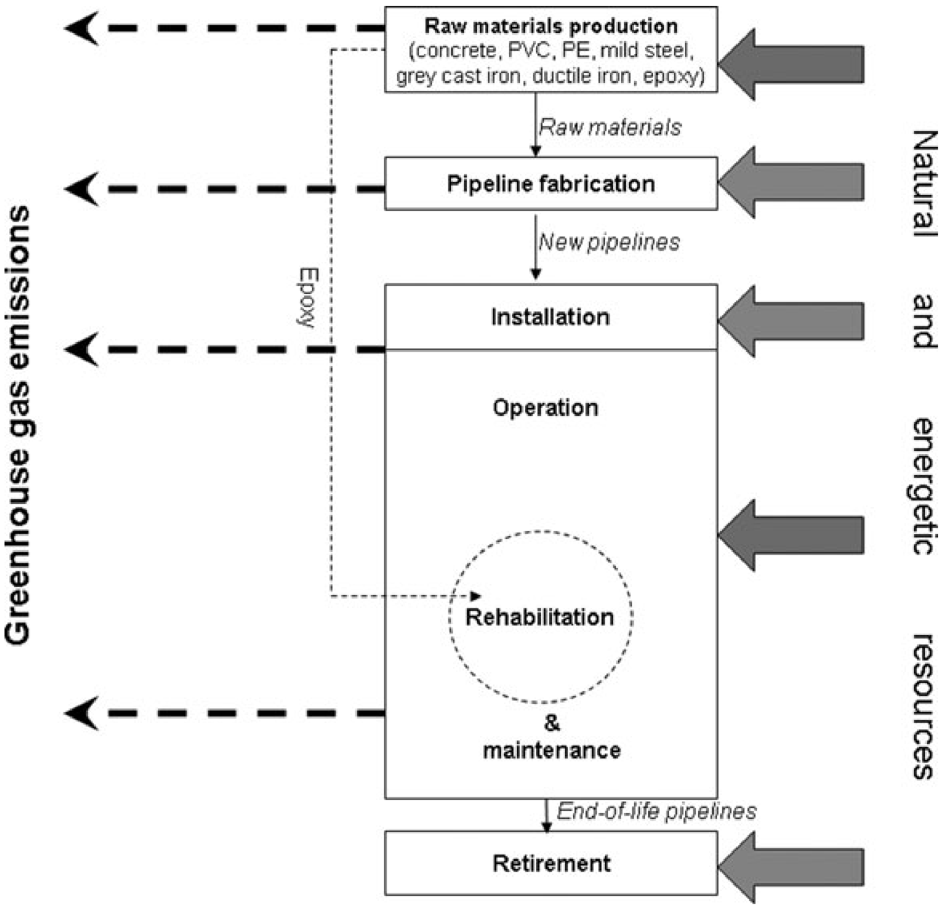

Figure 1 Life cycle of wastewater pipelines. PVC = polyvinyl chloride; PE = polyethylene.

that make recovery of metal, concrete, and plastics from retired pipelines economically feasible and practicable. We are therefore, in a way, talking about potential mine-sites in cities—of course, less exploitable, economically and practically, than other infrastructure components above ground in cities. CPSA (2001) considers the use of grout in the United Kingdom for stuffing decommissioned pipelines. This article, however, excludes this phase from the analysis. (Strutt and colleagues [2008], e.g., also assume decommissioning phase emissions to be zero.)

Figure 1 is a schematic representation of the life cycle of pipelines, in which the greenhouse gas emissions from each of the different stages of the life cycle are indicated.

Methodology

MFA

New Pipelines—From 1991 to 2006

The addition to stocks—the “component flow analysis”—is the premise on which this MFA is based. The assumptions we made to translate the pipeline-lengths data into weights of materials are listed in Appendix S1.1 in the Supplementary Material on the Web. It should be noted again at this juncture that only 49,900 of the 52,960 pipelines are considered for the analysis. The masses determined and the percentages thereof indicated are all with respect to these 49,900 pipelines. The material flows are determined on a decadal basis through 1990 and on an annual basis from 1991 to 2006.

Material Inputs due to Rehabilitation

We assume that all the rehabilitation involves the cast-in-place pipe (CIPP) approach, given that more than 90% of pipelines have been rehabilitated by this method during the past decade. In this process, the inner curved surface of the pipeline to be rehabilitated is coated with epoxy resin. Wastewater then flows within this "new" epoxy resin pipeline, and the older pipeline concentric to it on the outside no longer comes into contact with the flow. The inputs of epoxy polymers are also taken into consideration in the overall MFA. Data about rehabilitated pipelines are available on an annual basis for the period 1991 to 2006. Assumptions regarding thickness and density of the epoxy resin coating are noted in Appendix S1.1 in the Supplementary Material on the Web.

Material Inputs during Installation and the Operation and Maintenance Phase

The bedding materials that find their way into the network when new pipelines are installed are naturally sourced (or even recycled) and generally require minimal processing; hence, their contributions to emissions to the environmental media are insignificant. These material flows thereby are not dealt with in this article. Likewise, the consumption of chemicals and cleaning agents during the operation and maintenance phase is relatively negligible and hence not probed further in the article.

Forecast of Material Flows

Ugarelli and colleagues (2008) use knowledge of the pipeline stock changes over time to compare two approaches to rehabilitation over the next 2 decades—the economic lifetime approach and the physical lifetime approach. This article borrows the results of the economic analysis carried out by Ugarelli and colleagues and, on the basis of those results, estimates the likely material flows and associated emissions for the said time period. The optimum rehabilitation rates for the two approaches determined by Ugarelli and colleagues are assumed to be constant for the 20-year study period and are used to calculate the material flows and emissions associated with rehabilitation. The authors determined optimum rehabilitation rates of 1.2% for the physical lifetime approach and 1.4% for the economic lifetime approach. The shares of small-, medium-, and large-diameter pipelines in the rehabilitated stock every year are assumed to be the same as in the overall stock of pipelines at the end of 2006—approximately 5:3:2. For each of the classes, a mean diameter is calculated from the rehabilitated stock of 1991–2006. These mean diameters are 211, 315, and 614 millimeters (mm), respectively.

As far as the addition of new pipelines to the network between 2008 and 2027 is concerned, we assume that about 3 km of pipeline is added every year (on the basis of information from the Oslo Water and Wastewater Agency [Oslo VAV]) (Kristiansen 2008). We further assume an equal split in terms of length between small and medium-size pipelines. A mean diameter of 125 mm for small pipelines (less than 249 mm in diameter) and 375 mm for medium-size ones (between 250 mm and 499 mm in diameter) is considered. Even though the proclivity is greatly toward PVC pipelines, seven scenarios are considered for this analysis. These are shown in table 1, and the results are presented in table 2. As we do not have comprehensive data for 2007 at the time of writing, such data do not figure in the analysis of the past. Also, because 2007 is the past with respect to the time of writing, it is not considered as the start of the forecast period.

Energy Flow Analysis

The installation, operation, and maintenance activities of the use phase of pipelines are also associated with energy (fuel) consumption and thereby environmental emissions. The present article concerns itself only with the fuel consumed in the installation, repair, inspection, and rehabilitation of pipelines (diesel consumption in machinery and vehicles deployed for these purposes), not with the emissions associated with the treated effluent wastewater that flows through the pipelines during the use phase or the energy consumed at the pumping stations during the use phase to pump the wastewater through the pipelines. Fuel consumption by Oslo VAV's vehicles deployed "on the field," as well as diesel consumed in the installation of new pipelines and rehabilitation of older ones, is taken into account.

Table 1 Scenarios considered for forecast of material flows into the network

Scenario	*PVC (km)*	*Mild steel (km)*	*Concrete (km)*
A	0	0	1.5(s) + 1.5(med)
B	0	1.5(s) + 1.5(med)	0
C	1.5(s) + 1.5(med)	0	0
D	0.5(s) + 0.5(med)	0.5(s) + 0.5(med)	0.5(s) + 0.5(med)
E	0.75(s) + 0.75(med)	0.75(s) + 0.75(med)	0
F	0.75(s) + 0.75(med)	0	0.75(s) + 0.75(med)
G	0	0.75(s) + 0.75(med)	0.75(s) + 0.75(med)

Note: s = small-diameter pipelines; med = medium-diameter pipelines.

Although the former data are provided for the period 2001–2006, the latter are determined from the unit values (liters per meter of pipeline) furnished by Oslo VAV, provided in Appendix S1.2 in the Supplementary Material on the Web. The unit values are assumed to be the same for the entire period of study. Likewise, the average of the known values of vehicular fuel consumption for the period 2001–2006 is determined and considered as a constant for the period 1991 – 2000 as well as for 2008 and beyond. Diesel consumption in the operation phase is given as totals for the entire network. We assume equal shares for small, medium, and large pipes each year between 1991 and 2008. Note, however, that data for the energy consumed for the regular maintenance operations, such as flushing, are not available.

Most of the pipelines are fabricated in Norway, and the transport distance from manufacture to the site in Oslo is assumed to be an average of 250 km. Ductile iron pipes are imported mainly from Germany. The transport distances for these are assumed to be 600 km by road (truck) and, thereafter, 650 km by cargo ship (the distance from Kiel, Germany, to Oslo). The diesel consumption is calculated accordingly. As far as the transport of bedding materials is concerned, we assume that the ballpark figures for diesel consumption in installation provided by Oslo VAV (Kristiansen 2008, personal communication) include the diesel consumed for transporting the bedding materials.

In this study, we compare the physical lifetime approach and the economic lifetime approach. The fuel consumed for the installation of new pipelines remains the same for all the scenarios. The difference arises in the fuel consumption for the rehabilitation of old pipelines. The average annual vehicular fuel consumption is assumed to be the same for all scenarios in both the approaches. The fuel consumption data for 1991–2006 and for the forecast period 2008–2027 are tabulated in table 3.

Life Cycle Assessment

Goal and Scope

The life cycle assessment (LCA) is based on the MFA results for the wastewater pipeline network. Greenhouse gas emissions related to production, transport, installation, operation, maintenance, and rehabilitation of pipelines are included in the study. Emissions data were obtained from SimaPro (PRé Consultants 2008), the Ecoinvent database (Swiss Centre for Life Cycle Inventories 2008), and the CML2002 impact assessment method (CML 2001), with a time horizon of the impacts of 100 years. Generic processes based on average European technologies available in the Ecoinvent database were applied, instead of case-specific data. We modified the processes slightly to adapt to the case considered for this study. Emissions were determined on an annual basis for the period 1991 – 2006 and also for the 14 scenarios (7 × 2 approaches) for the forecast period. If one considers a time series, technological developments would definitely have made manufacturing more efficient over time, with respect to energy consumption and emissions. In the absence of reliable information about how technology has contributed to a drop in emissions per unit mass of production, however, we avoided speculation did not calculate impacts for the period prior to 1991.

The goal of this LCA is both to test the methodology of combining LCA and MFA and

Table 2 Forecast of annual mass flows into the network in the form of additional pipelines (kilograms of materials from 2008 to 2027)

Year	*Material*	A	B	C	D	E	F	G
2008	Concrete	131,079	0	0	43,693	0	65,540	65,540
	Mild steel	0	65,026	0	21,675	32,513	0	32,513
	PVC	0	0	22,754	7,585	11,377	11,377	0
2009	Concrete	131,079	0	0	43,693	0	65,540	65,540
	Mild steel	0	65,026	0	21,675	32,513	0	32,513
	PVC	0	0	22,754	7,585	11,377	11,377	0
2010	Concrete	131,079	0	0	43,693	0	65,540	65,540
	Mild steel	0	65,026	0	21,675	32,513	0	32,513
	PVC	0	0	22,754	7,585	11,377	11,377	0
2011	Concrete	131,079	0	0	43,693	0	65,540	65,540
	Mild steel	0	65,026	0	21,675	32,513	0	32,513
	PVC	0	0	22,754	7,585	11,377	11,377	0
2012	Concrete	131,079	0	0	43,693	0	65,540	65,540
	Mild steel	0	65,026	0	21,675	32,513	0	32,513
	PVC	0	0	22,754	7,585	11,377	11,377	0
2013	Concrete	131,079	0	0	43,693	0	65,540	65,540
	Mild steel	0	65,026	0	21,675	32,513	0	32,513
	PVC	0	0	22,754	7,585	11,377	11,377	0
2014	Concrete	131,079	0	0	43,693	0	65,540	65,540
	Mild steel	0	65,026	0	21,675	32,513	0	32,513
	PVC	0	0	22,754	7,585	11,377	11,377	0
2015	Concrete	131,079	0	0	43,693	0	65,540	65,540
	Mild steel	0	65,026	0	21,675	32,513	0	32,513
	PVC	0	0	22,754	7,585	11,377	11,377	0
2016	Concrete	131,079	0	0	43,693	0	65,540	65,540
	Mild steel	0	65,026	0	21,675	32,513	0	32,513
	PVC	0	0	22,754	7,585	11,377	11,377	0
2017	Concrete	131,079	0	0	43,693	0	65,540	65,540
	Mild steel	0	65,026	0	21,675	32,513	0	32,513
	PVC	0	0	22,754	7,585	11,377	11,377	0
2018	Concrete	131,079	0	0	43,693	0	65,540	65,540
	Mild steel	0	65,026	0	21,675	32,513	0	32,513
	PVC	0	0	22,754	7,585	11,377	11,377	0
2019	Concrete	131,079	0	0	43,693	0	65,540	65,540
	Mild steel	0	65,026	0	21,675	32,513	0	32,513
	PVC	0	0	22,754	7,585	11,377	11,377	0
2020	Concrete	131,079	0	0	43,693	0	65,540	65,540
	Mild steel	0	65,026	0	21,675	32,513	0	32,513
	PVC	0	0	22,754	7,585	11,377	11,377	0
2021	Concrete	131,079	0	0	43,693	0	65,540	65,540
	Mild steel	0	65,026	0	21,675	32,513	0	32,513
	PVC	0	0	22,754	7,585	11,377	11,377	0
2022	Concrete	131,079	0	0	43,693	0	65,540	65,540
	Mild steel	0	65,026	0	21,675	32,513	0	32,513
	PVC	0	0	22,754	7,585	11,377	11,377	0
2023	Concrete	131,079	0	0	43,693	0	65,540	65,540
	Mild steel	0	65,026	0	21,675	32,513	0	32,513
	PVC	0	0	22,754	7,585	11,377	11,377	0

Continued.

Table 2 Continued

Year	*Material*	A	B	C	D	E	F	G
2024	Concrete	131,079	0	0	43,693	0	65,540	65,540
	Mild steel	0	65,026	0	21,675	32,513	0	32,513
	PVC	0	0	22,754	7,585	11,377	11,377	0
2025	Concrete	131,079	0	0	43,693	0	65,540	65,540
	Mild steel	0	65,026	0	21,675	32,513	0	32,513
	PVC	0	0	22,754	7,585	11,377	11,377	0
2026	Concrete	131,079	0	0	43,693	0	65,540	65,540
	Mild steel	0	65,026	0	21,675	32,513	0	32,513
	PVC	0	0	22,754	7,585	11,377	11,377	0
2027	Concrete	131,079	0	0	43,693	0	65,540	65,540
	Mild steel	0	65,026	0	21,675	32,513	0	32,513
	PVC	0	0	22,754	7,585	11,377	11,377	0

Note: PVC = polyvinyl chloride.

to obtain results for greenhouse gas emissions related to the material flows in the network. An LCA should ideally encompass all environmental impacts, as a system may perform well in some respects but not in others. In this article, however, as mentioned earlier, only greenhouse gas emissions are considered, and they are expressed as carbon dioxide (CO_2) equivalents. A wide range of greenhouse gases are accounted for: carbon dioxide, methane, nitrous oxide, carbon monoxide, sulfur hexafluoride, chlorofluorocarbons (CFCs), hydrofluorocarbons (HFCs), and so forth.

LCA studies have been published on environmental performance of sewer pipes. One such is the study by CPSA (2001), which concludes that concrete is the most environmentally sound material for sewer networks. Lassaux and colleagues (2007) performed an LCA from pumping stations to wastewater treatment plants for the Walloon region in Belgium and conclude, inter alia, that the “before-the-tap” building of the pipeline network had a significant contribution to the total environmental load, although the after-the-tap water discharges and wastewater treatment accounted for the lion’s share of the load. Remy and colleagues (2007) present an LCA of selected sanitation concepts that focuses on the downstream—urine separation, feces compositing, and treatment of gray wastewater. Gouda and colleagues (2003) conducted an LCA to compare different ways of handling sludge solids. Kawashima (2002), although he avers that infrastructure LCA is extremely important as a tool for policy planning, observes that 86% of the life cycle carbon dioxide emissions for an activated sludge wastewater treatment plant treating 33,450 cubic meters of wastewater daily occur during the operation phase. More recently, Strutt and colleagues (2008) assessed the carbon footprint of water supply. Eckard (2008) states that more than 50 million tonnes of CO_2-equivalent greenhouse gases from wastewater treatment (including sludge handling and methane degassing)[3] were emitted in 2006 alone in the United States. This figure, incidentally, accounts for just 1% of the total greenhouse gas (GHG) emissions in the country. In this article, we focus on just one component of the water–wastewater network and, within that component, consider just a single environmental measure—emission of greenhouse gases, in carbon dioxide equivalents. The analysis is thus narrowed down both in width and depth.

Materials or components included in the study are concrete, PVC, polyethylene (PE), mild steel, gray cast iron and ductile iron pipes, epoxy resin used for rehabilitation, and diesel fuel (refer to Appendix S1.3 in the Supplementary Material on the Web). For all materials, impacts that occur in all life cycle stages from cradle to gate (from raw material extraction to finished product at the factory) are included, as shown for concrete pipelines as an example in figure 2. The

Table 3 Diesel fuel consumption (in liters) from 1991 to 2006 and forecasts for 2008 to 2027

	Installation of pipelines				*Rehabilitation of pipelines*					
Phase	*Small*	*Medium*	*Large*	**Total**	*Small*	*Medium*	*Large*	**Total**	*O&M vehicular fuel*	**Grand total**
1991	545,370	324,800	100,215	**970,385**	13,982	8,639	2,111	**24,732**	66,973	**1,062,090**
1992	499,380	339,680	47,880	**886,940**	11,705	9,238	1,107	**22,050**	66,973	**975,963**
1993	306,950	151,480	44,235	**502,665**	5,642	1,973	216	**7,831**	66,973	**577,469**
1994	261,100	289,200	16,470	**566,770**	5,424	4,460	0	**9,884**	66,973	**643,627**
1995	167,265	137,280	50,985	**355,530**	2,034	2,510	954	**5,498**	66,973	**428,001**
1996	159,390	146,760	11,970	**318,120**	3,950	1,188	710	**5,848**	66,973	**390,941**
1997	238,105	165,640	21,330	**425,075**	4,183	1,137	512	**5,832**	66,973	**497,800**
1998	178,360	151,600	34,560	**364,520**	2,334	1,707	1,682	**5,723**	66,973	**437,216**
1999	232,715	161,760	19,350	**413,825**	2,649	1,470	686	**4,805**	66,973	**485,603**
2000	138,530	184,560	11,835	**334,925**	2,107	2,297	208	**4,612**	66,973	**406,510**
2001	100,555	135,760	40,095	**276,410**	1,854	1,625	722	**4,201**	68,608	**349,219**
2002	102,970	183,120	42,840	**328,930**	2,050	1,028	50	**3,128**	64,362	**396,420**
2003	56,000	183,120	11,565	**250,685**	206	1,448	300	**1,954**	69,911	**322,550**
2004	50,715	56,080	54,585	**161,380**	494	300	466	**1,260**	63,689	**226,329**
2005	58,520	149,360	46,125	**254,005**	92	2,357	0	**2,449**	63,579	**320,033**
2006	12,495	105,400	0	**117,895**	6	0	0	**6**	65,936	**182,837**

	Economic lifetime approach				*Physical lifetime approach*			
Phase	*Installation*	*Rehabilitation*	*O&M vehicular fuel*	**Total**	*Installation*	*Rehabilitation*	*O&M vehicular fuel*	**Total**
2008	112,500	36,345	66,973	**215,818**	112,500	31,153	66,973	**210,626**
2009	112,500	36,401	66,973	**215,874**	112,500	31,201	66,973	**210,674**
2010	112,500	36,458	66,973	**215,931**	112,500	31,250	66,973	**210,723**
2011	112,500	36,515	66,973	**215,988**	112,500	31,298	66,973	**210,771**
2012	112,500	36,572	66,973	**216,045**	112,500	31,347	66,973	**210,820**
2013	112,500	36,628	66,973	**216,101**	112,500	31,396	66,973	**210,869**
2014	112,500	36,685	66,973	**216,158**	112,500	31,444	66,973	**210,917**

Continued.

Table 3 Continued

	Economic lifetime approach				Physical lifetime approach			
Phase	*Installation*	*Rehabilitation*	*O&M vehicular fuel*	***Total***	*Installation*	*Rehabilitation*	*O&M vehicular fuel*	***Total***
2015	112,500	36,742	66,973	**216,215**	112,500	31,493	66,973	**210,966**
2016	112,500	36,798	66,973	**216,271**	112,500	31,541	66,973	**211,014**
2017	112,500	36,855	66,973	**216,328**	112,500	31,590	66,973	**211,063**
2018	112,500	36,912	66,973	**216,385**	112,500	31,639	66,973	**211,112**
2019	112,500	36,968	66,973	**216,441**	112,500	31,687	66,973	**211,160**
2020	112,500	37,025	66,973	**216,498**	112,500	31,736	66,973	**211,209**
2021	112,500	37,082	66,973	**216,555**	112,500	31,784	66,973	**211,257**
2022	112,500	37,139	66,973	**216,612**	112,500	31,833	66,973	**211,306**
2023	112,500	37,195	66,973	**216,668**	112,500	31,882	66,973	**211,355**
2024	112,500	37,252	66973	**216,725**	112,500	31,930	66,973	**211,403**
2025	112,500	37,309	66,973	**216,782**	112,500	31,979	66,973	**211,452**
2026	112,500	37,365	66,973	**216,838**	112,500	32,027	66,973	**211,500**
2027	112,500	37,422	66,973	**216,895**	112,500	32,076	66,973	**211,549**

Note: O&M = operation and maintenance. One liter (L) = 0.001 cubic meters (SI) ≈ 0.264 gal.

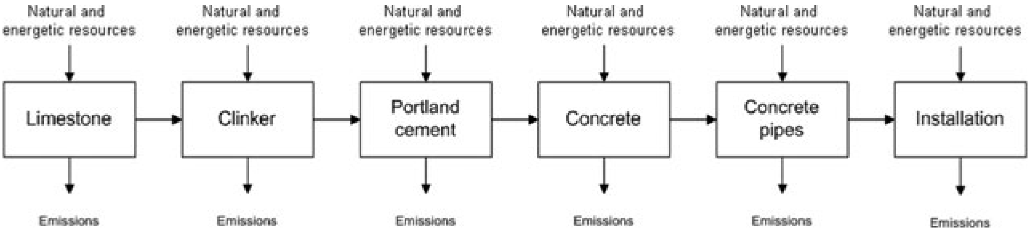

Figure 2 Life cycle stages of concrete pipelines (operation, maintenance, and retirement not shown; horizontal arrows indicate interstage transport).

operation, maintenance, rehabilitation, and retirement stages—which would figure in a cradle-to-grave diagram—have not been indicated.

It should be noted that the retirement of pipes, whereby they are disconnected from the network and left beneath the ground, also consumes energy. Given the paucity of data on this front, however, this stage has been excluded from the LCA. The next subsection briefly describes the production and transport processes for the different materials and components. All inputs to the processes have life cycle inventory (LCI) data in the Ecoinvent database; thus, the system border of each material or component becomes very wide.

Material Consumption and Production

The data for the consumption of pipeline materials and epoxy resin for rehabilitation were obtained from the MFA. The emissions associated with this transport were calculated and added to the cradle-to-gate emissions. The production of mild steel and gray cast/ductile iron pipes is assumed to be based on 39% scrap and 61% pig iron, which was the average production mix for Europe in 2005 (Eurofer 2008). The concrete pipes are assumed to contain 5% steel reinforcement (weight fraction). The ferrous pipes are treated with various materials for corrosion protection. Ductile and gray cast iron pipes are treated with cement mortar (internal), zinc/galvalume, and bitumen (external).[4] Mild steel is treated with cement mortar (internal) and bitumen (external). To determine whether the coatings contribute significantly to the emissions, we chose 1992, as the influx of ferrous pipelines into the network was high in this year. Greenhouse gas emissions in 1992 associated with bitumen were below 4,000 kg carbon dioxide equivalents (kg CO_2-equivalent).[5] This accounts for less than 0.1% of the total greenhouse gas emissions this year (and about 8% of the emissions related to the coated ferrous pipelines). Cement mortar and zinc account for 1,000 kg and 4,200 kg CO_2-equivalents of emissions in 1992, respectively. Hence, the emissions due to coating materials are excluded from the LCA. The quantities of galvalume (used after 2000) and the emissions thereby are negligible as well. Table 4 lists the unit greenhouse gas emissions in kg CO_2-equivalents for the pipes, the epoxy resin, and the diesel fuel.

Results and Discussion

Material Flows—to 2006

The ferrous pipelines in the network are coated with cement mortar, bitumen, zinc, or galvalume to resist corrosion. Given that in 2006, ferrous pipelines accounted for a mere 3% of the total stock in kilometers and less than 0.9% of the total in weight, however, these flows are

Table 4 Unit greenhouse gas emissions in kilograms of carbon dioxide equivalents (kg CO_2-eq)

Material	*Unit*	*kg CO_2-eq*
PVC pipe	kg	2.36
PE pipe	kg	2.33
Mild steel pipe	kg	1.51
Ductile iron pipe	kg	3.41
Gray cast iron pipe	kg	3.34
Concrete pipe	kg	0.23
Epoxy resin	kg	6.70
Diesel fuel	liter	3.19

Note: PVC = polyvinyl chloride; PE = polyethylene.

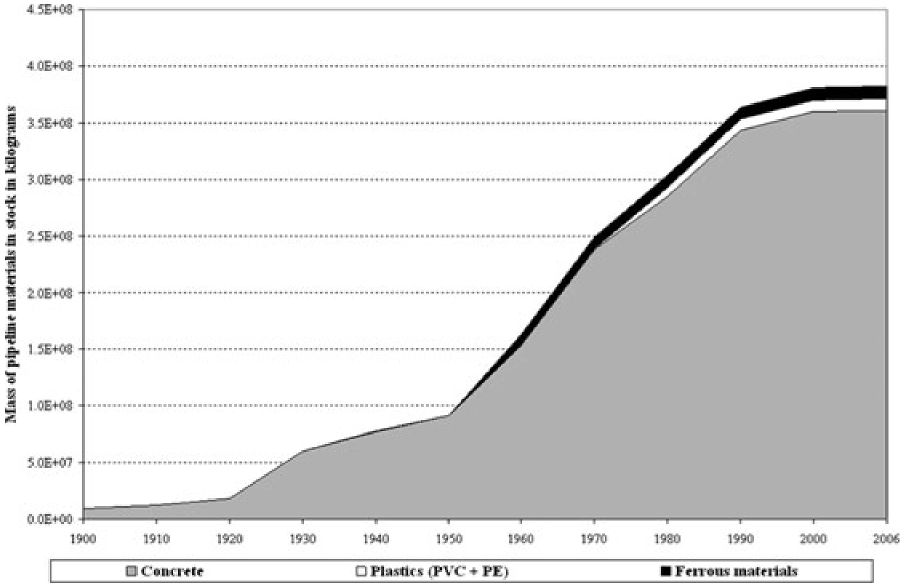

Figure 3 Growth of the pipeline stock, in terms of influx of masses of pipeline materials. PVC = polyvinyl chloride; PE = polyethylene.

considered to have relatively little impact as far as emissions are concerned and hence are ignored. Stones and bricks accounted for a small percentage of the total weight of pipelines and a very small fraction of the total length. They have been excluded from the analysis. At the end of 2006, the pipeline network contained 11.6 million kg ferrous materials (gray cast iron, ductile iron, and mild steel taken together), 10.98 million kg plastics (PVC and PE taken together), and 362 million kg concrete.

The pipeline also contained smaller quantities of other metals and materials, such as zinc, copper, aluminum, and bitumen, which, as mentioned earlier, have been excluded. Figure 3 depicts the material additions to stocks in different time segments. The pipelines are segmented on the basis of their sizes into small, medium, and large. Concrete masses at the end of 2006 can be categorized into small, medium, and large pipelines approximately according to the ratio 1:2:7. For plastics (PVC and PE), this ratio was approximately 1:2:10. For ferrous materials, it was 1:1:8. Table 5 provides data regarding additions of masses of concrete, ductile iron, mild steel, PVC, and PE into the network between 1991 and 2006. No gray cast iron pipelines were installed during this period.

Figure 4 shows the mass flows of epoxy resins into the network by way of rehabilitation of pipelines between 1991 and 2006 (and also forecasted flows for the future). The figure shows an almost hyperbolic reduction in the meters of pipelines rehabilitated and thereby the epoxy resins introduced into the network after 1992. Epoxy resins introduced to rehabilitate small pipelines accounted for a little more than 50% of the total epoxy inflows of 575,493 kg in 1991–2006.

Material Flow Forecasts

As far as additions of new pipelines are concerned, for both the approaches taken in this study, the seven scenarios detailed in table 1 are considered. Using the same assumptions for calculations listed in Appendix S1.1 in the Supplementary Material on the Web, we calculated the likely inflows of materials (concrete, ferrous materials, and plastics) due to additional pipelines between 2008 and 2027. The results are presented in table 2.

Economic Lifetime Approach

In addition to the material flows due to additions of pipelines, the rehabilitation rate of 1.4% also introduces epoxy resins into the network

Table 5 Annual mass flows into the network in the form of additional pipelines (kilograms of materials from 1991 to 2006)

Year	*Category*	*Concrete*	*Ductile iron*	*Mild steel*	*PE*	*PVC*
1991	Small	702,452	839	0	449	3,827
	Medium	567,622	1,594	0	4,222	24,031
	Large	418,557	0	0	4,313	32,072
1992	Small	548,479	15,222	0	182	11,223
	Medium	578,243	14,155	0	3,737	44,579
	Large	475,920	0	0	2,673	20,461
1993	Small	272,498	396	1,296	898	15,729
	Medium	113,695	1,083	0	3,571	40,058
	Large	253,967	0	0	13,555	12,357
1994	Small	249,660	0	0	457	9,629
	Medium	381,547	0	0	6,623	55,977
	Large	423,682	0	0	37,965	92,213
1995	Small	131,761	0	0	117	15,028
	Medium	238,123	0	0	3,940	38,692
	Large	770,094	24,220	0	22,636	3,845
1996	Small	202,426	0	0	265	2,288
	Medium	96,480	0	0	60	37,868
	Large	287,882	0	0	0	6,580
1997	Small	208,329	0	0	208	16,191
	Medium	122,942	0	0	1,349	43,221
	Large	848,736	0	0	12,391	13,221
1998	Small	127,912	0	0	1,978	16,423
	Medium	143,749	0	0	4,170	36,919
	Large	6,925,373	0	0	1,223	49,795
1999	Small	1,412,784	0	0	2,151	20,841
	Medium	178,243	0	0	978	33,212
	Large	445,937	0	89,497	12,481	186
2000	Small	114,466	0	0	3,874	10,207
	Medium	189,584	0	0	2,678	50,903
	Large	24,596	0	0	0	7,523
2001	Small	65,738	0	0	0	9,711
	Medium	94,859	0	0	2,876	39,307
	Large	775,320	0	0	201,354	302
2002	Small	53,641	0	0	550	11,233
	Medium	81,488	0	0	1,579	69,735
	Large	268,825	0	0	6,391	22,994
2003	Small	3,246	0	0	1,178	9,054
	Medium	0	0	0	5,544	66,127
	Large	446,854	0	0	8,161	1,418
2004	Small	7,852	0	0	428	6,639
	Medium	3,006	0	0	559	33,341
	Large	364,926	0	0	11,517	3,698
2005	Small	28,635	0	0	2,595	4,255
	Medium	89,421	0	0	1,868	60,349
	Large	333,153	0	0	7,348	0
2006	Small	0	0	0	0	2,496
	Medium	0	0	0	237	8,253
	Large	0	0	0	0	0

Note: PVC = polyvinyl chloride; PE = polyethylene.

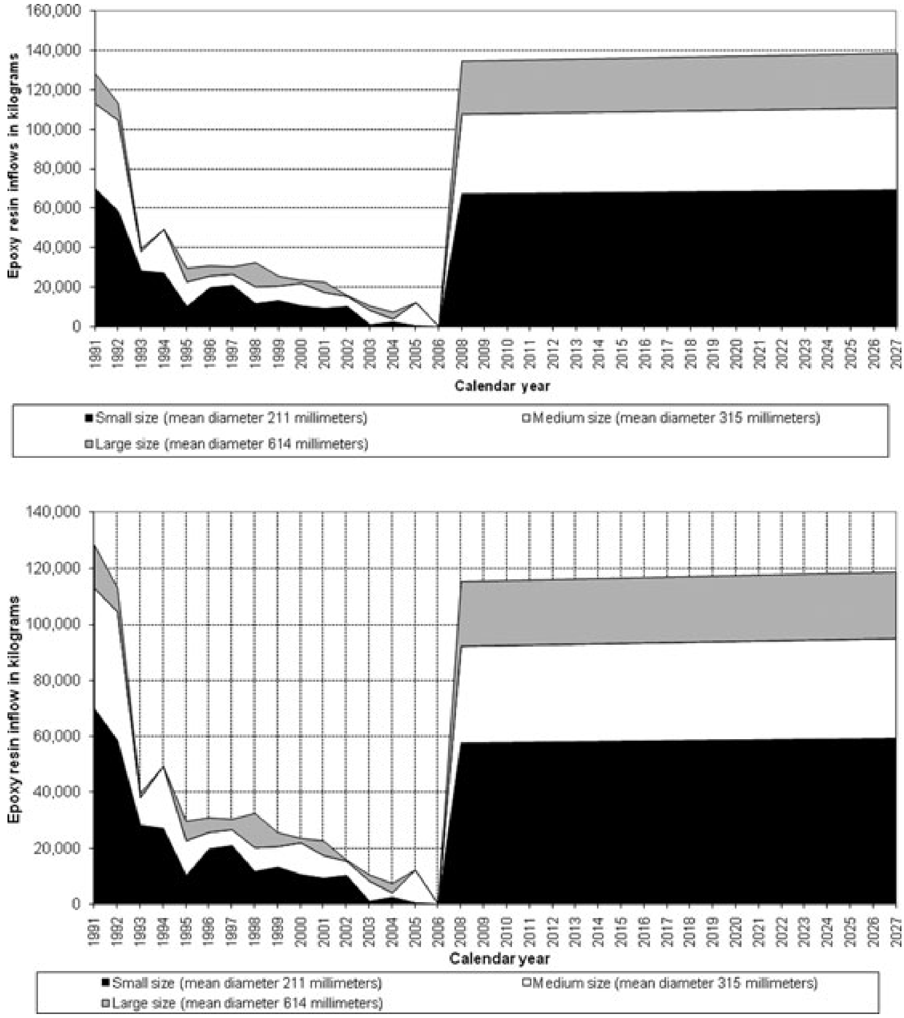

Figure 4 Annual mass flows of epoxy resins through rehabilitation from 1991 to 2006 and forecasts for 2008 to 2027, according to the physical lifetime approach (above) and the economic lifetime approach (below).

when the economic lifetime approach is adopted. Figure 4 depicts the mass flows of epoxy resins into the network between 2008 and 2027. While the annual rehabilitated lengths increased gradually from 26.9 km to 27.7 km in 20 years, the annual mass flows of epoxy resins into the network increased from around 134 tonnes to 138 tonnes. The total addition of epoxy resins during this 2-decade period was about 2,736 tonnes, with small pipelines accounting for half the addition (1,368 tonnes), medium-size pipes for 30% (820 tonnes), and the large-diameter pipelines for the remaining amount.

Physical Lifetime Approach

The rehabilitation rate of 1.2% introduces epoxy resins into the network when the physical lifetime approach is adopted. With this approach, the intensity of rehabilitation is relatively less; 468 km was rehabilitated in 20 years vis-à-vis 546 km with the economic lifetime approach. The total mass of epoxy resins inducted into the network thereby also decreased by about 390 tonnes with respect to the economic lifetime approach (see figure 4).

In both approaches, figure 4 shows the striking fact that Oslo VAV now needs to invest in

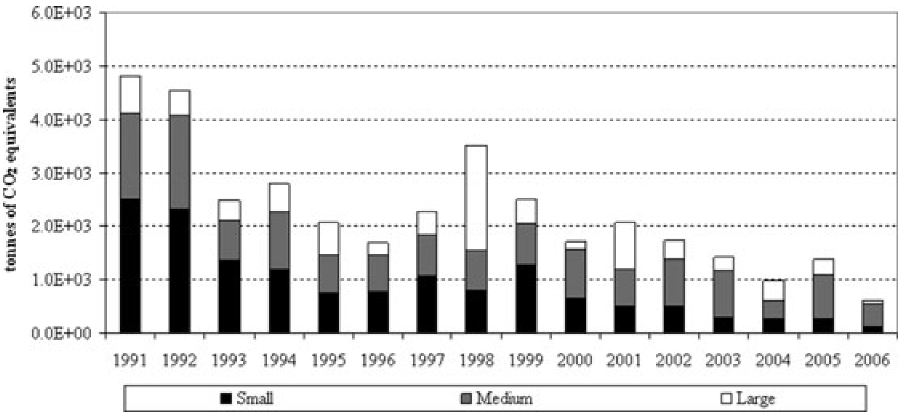

Figure 5 Greenhouse gas emissions in 1991–2006, categorized on the basis of sizes of pipelines. Small diameter ≤ 249 millimeters (mm); medium diameter ≥ 250 mm and ≤ 499 mm; large diameter ≥ 500 mm.

more rehabilitation than it did during the 1991–2006 period. Although the influx of epoxy resins into the network decreased rapidly from 1991 to 2006 because of diminishing expenditure on rehabilitation, a consistent rehabilitation schedule is called for in the future. Rehabilitation must be done sooner rather than later, lest the backlog pile up and exert greater pressure on the administration's financial capacity. For example, the average rehabilitation rate in 1991–2006 was a measly 0.4%. It now needs to be a minimum of 1.2%.

Energy Flows: Past and Forecast

Table 3 presents the data pertaining to diesel consumption in installation, rehabilitation, and vehicular traction during the operation and maintenance phase. This table clearly illustrates an advantage of adopting the physical lifetime approach to rehabilitation over the economic lifetime approach. It is also evident that diesel consumption for installation of new pipelines accounted for the lion's share of the total consumption every year in 1991–2006 (more than 90% each year). The total diesel consumption decreased from 1991 to 2006, and in the forecast period it remains almost stable. The installation process in the forecast period accounts for slightly more than 50% of the total consumption, in sharp contrast to what it was in the 1991–2006 period. The total diesel consumed in installation, rehabilitation, and operation and maintenance activities was around 1 million liters in 1991 and it decreased to a little less than 183,000 liters in 2006. In the forecast period, for the economic lifetime approach, the total diesel consumed increased from 215,818 liters in 2008 to 216,895 liters in 2027. The corresponding figures for the physical lifetime approach were 210,626 liters and 211,549 liters, respectively. Vehicular fuel consumption for the period 2008–2027 has been assumed to be constant at 66,973 liters per year—the average of the values for 2001–2006.

Greenhouse Gas Emissions: Past and Forecast

The greenhouse gas emissions for the period 1991–2006 are depicted in figures 5 and 6. The small-diameter pipelines dominated in the initial years, before the medium- and the large-diameter pipelines surpassed them. In 1998, there was an influx of large-diameter, long concrete pipelines into the network, which explains the significant contribution by large-diameter pipelines in that year and the increase in emissions by 1,050 tonnes of CO_2-equivalent from the previous year (see figure 5). In terms of mass inputs, large-diameter pipelines accounted for three times as much as the small pipelines. Most of the small pipelines installed during this period were either PVC or PE, whereas the larger ones were primarily concrete. A look at table 4, however, reveals that the greenhouse gas emissions associated with PVC and PE pipelines were almost 10 times greater than

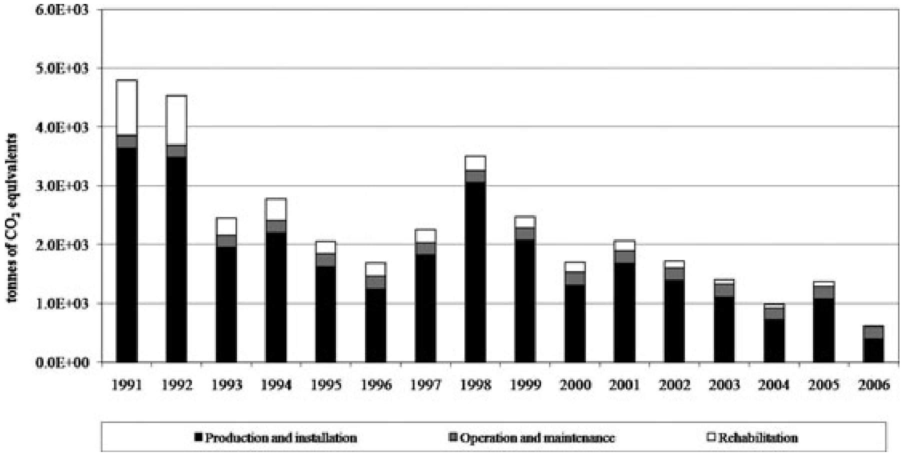

Figure 6 Greenhouse gas emissions in 1991–2006, categorized on the basis of pipelines' life cycle stages.

those associated with concrete pipelines on a unit mass basis. This leads to the conclusion that the small pipelines contributed to about three times as much of the total emissions in 1991–2006 vis-à-vis the large-diameter ones. From figure 6, it is also clear that installation of pipelines (production, transport, and the installation process per se) contributed the lion's share of the greenhouse gas emissions in 1991–2006. Epoxy resin used for rehabilitation emitted more greenhouse gases than the other materials and components in the production stage (see table 4), but the diesel consumption for installation of pipelines was much greater than that for rehabilitating them with the high-emitting epoxy resin, on a unit length basis. This more than offsets the difference. The per-capita greenhouse gas emissions are not depicted in the article. Suffice it to say that the population of Oslo has been increasing gradually from 1991 to 2006, whereas the emissions as depicted in figures 5 and 6 have fluctuated, even as they have decreased from 4,750 tonnes of CO_2-equivalent in 1991 to a little more than 500 tonnes of CO_2-equivalent in 2006. One can thereby safely aver that the per capita greenhouse gas emissions from the wastewater pipeline network have been decreasing.

It is noteworthy that, although the network was nearing saturation, the greenhouse gas emissions associated with production, fabrication, and installation were higher than those due to operation and maintenance activities and rehabilitation taken together. Additions were certainly less in 1991–2006 vis-à-vis the 1950–1990 period, but they had not stopped altogether. The network was growing, although at a very slow pace. Furthermore, the diesel consumption for installation per meter of pipeline was about 20 times greater than that for rehabilitation. Also, as shown in figure 4, the rehabilitation rate dwindled during the said 16-year period.

At this juncture, it is also worthwhile to contemplate how the greenhouse gas emissions were shared among these three life cycle stages before 1991. The network swelled in the 1950–1990 period, with 1,250 km of pipelines added—at an average of more than 30 km every year. Figure 3 substantiates this fact when one translates it into mass influxes. Much information is not available about rehabilitation during this period, but one can safely surmise that a younger network does not call for as much rehabilitation as an older network does. The share of upstream production and installation of pipelines to the life cycle greenhouse gas emissions would have been much higher than what it has been in 1991–2006.

Emission Forecasts

As far as the future scenarios are concerned, in general, one notes a monotonously increasing linear trend. Table 6 shows the results for the installation phase and the use phase (operation, maintenance, and rehabilitation taken together) for 2008 and 2027. In sharp contrast to the emissions in 1991–2006, when the network

Table 6 Greenhouse gas emissions for 2008 and 2027

Physical lifetime approach	*Production and installation (tonnes of CO_2-eq)*		*Operation and maintenance + rehabilitation (tonnes of CO_2-eq)*	
Scenario	*2008*	*2027*	*2008*	*2027*
A	388	388	1,088	1,114
B	457	457	1,088	1,114
C	412	412	1,088	1,114
D	419	419	1,088	1,114
E	434	434	1,088	1,114
F	400	400	1,088	1,114
G	422	422	1,088	1,114
Economic lifetime approach	*Production and installation (tonnes of CO_2-eq)*		*Operation and maintenance + rehabilitation (tonnes of CO_2-eq)*	
Scenario	*2008*	*2027*	*2008*	*2027*
A	388	388	1,233	1,264
B	457	457	1,233	1,264
C	412	412	1,233	1,264
D	419	419	1,233	1,264
E	434	434	1,233	1,264
F	400	400	1,233	1,264
G	422	422	1,233	1,264

Note: CO_2-eq = carbon dioxide equivalents.

was still growing, the emissions due to installation account for less than one-third of the total during the forecast period. Scenario A (only concrete pipelines added) turns out to be the best, and Scenario B (only mild steel pipelines added) is the worst. The difference between the two extremes, however, is marginal.

In the physical lifetime approach, the annual greenhouse gas emissions rise by 26 tonnes of CO_2-equivalent in 20 years, whereas in the economic lifetime approach, the rise is 31 tonnes of CO_2-equivalent in the same period of time. The reduction in emissions from adopting the physical lifetime approach is around 150 tonnes of CO_2-equivalent annually, which goes down very well in the context of concerns about global warming. Of course, although this alone might seem to be a drop in the ocean, reductions in emissions all over the world would make a very big positive difference.

Nonetheless, this difference in greenhouse gas emissions is certainly not a strong driver by itself when it comes to deciding on suitable rehabilitation approaches for the future. It does, however, serve to reinforce the superiority of the physical lifetime approach to rehabilitation, given that it is one of the many secondary beneficial outcomes of adoption of that approach—economic gains being the primary one.

Discussion

We set out to determine the contributions of the different stages in the life cycle of wastewater pipelines in the Oslo wastewater network to greenhouse gas emissions (carbon dioxide, methane, nitrous oxide, and carbon monoxide). Because of the lack of comprehensive data for the years before 1991, we restricted the study of the past to the period 1991–2006 and chose 2008–2027 as the forecast period. The findings point to the domination of the installation phase (and the PVC and PE pipelines within it) in 1991–2006. The network is now 52 years old (Venkatesh et al. 2008) and is almost saturated with respect to the number of pipelines at the time of writing. Material inputs will continue in the years to come, however—epoxy resins for rehabilitating the aging pipelines, and possible additions of 2–3 km of pipelines every year. Nonetheless, the operation, maintenance, and rehabilitation phases will be the prime contributors to greenhouse gas emissions in the future. This is true of any aging, saturated wastewater pipeline network in the world, the rate of additions to which dwindles over time. Administrations that take over the management of aging and saturated networks clearly need to adopt a different set of strategies than did earlier administrations when the network was growing. Note that the construction and embodied emissions of the materials used to fabricate an individual pipeline account for more than 80% of its life cycle emissions of greenhouse gases (Strutt et al. 2008). Therefore, in a saturating or saturated network, a significant bulk of the total emissions associated with the entire network occurred in the past.

In addition to adopting the physical lifetime approach to rehabilitation, which would aid in cutting down emissions, one could look at deploying fuel-efficient vehicles in the fleet and improving the energy efficiency of epoxy resin manufacture. (May [2008] writes about the Fleet-Green fleet management solution implemented by Garland Water Utilities in Texas, which has enabled a 65% improvement in fuel conservation in 2006 vis-à-vis 2005 and a subsequent reduction of 88 metric tonnes in vehicle emissions in 2007 with respect to 2005.) Some alternative materials may emit less than epoxy resin, but reduction of greenhouse gas emissions alone is not a strong driver for replacement in this case. Also, if additions are made to the network, some reductions in greenhouse gas emissions could be accomplished by the use of more of recycled and secondary steel and cement and concrete aggregates (if ferrous and concrete pipelines are added). Strutt and colleagues (2008) demonstrate that a reduction of 25% in greenhouse gas emissions is possible with this strategy.

The environmental aspect of management of infrastructure systems languished for years, while the social and economic aspects took center stage. Pipelines are required to fulfill the water and sanitation needs of the society. The maintenance and operation (and growth) of networks depend on the finances at the disposal of the administrative body. These finances are sourced from the consumers whose needs are being fulfilled. An entity such as Oslo VAV would like to optimize its expenditure and at the same time improve or maintain its level of service to the inhabitants of the city (Ugarelli et al. 2008; Venkatesh et al. 2008). If it wants to graduate from the double bottom line approach to management to the triple bottom line approach, it needs to always keep a watch over its environmental footprint. As Strutt and colleagues (2008) write, quantifying the greenhouse gas environmental impact in terms of carbon dioxide equivalents allows utilities to make choices that foster continued, sustainable operation in the future and complements efforts to evaluate environmental, financial, and social metrics. Strutt and colleagues add that strategies to estimate, analyze, and reduce greenhouse gas emissions from operations offer consumers solid evidence that their utilities are committed to positive stewardship of the environment. The present study, as stated earlier, has been narrowed down in depth and width. Only one environmental measure—greenhouse gas emissions—has been analyzed, and the rehabilitation stage in the life cycle of pipelines emerges in this case as the biggest contributor in the future. Other environmental impacts (CPSA 2001) need to be studied for the sewer network in Oslo.

Conclusions and Further Research

We had to work within limitations of availability of data. Hence, some exclusions were unavoidable. The study could not have been carried out without some reasonable assumptions. These, however, can be eliminated if access to more comprehensive data can be made possible. In this article, the focus was only on greenhouse gas emissions, which are by far the most discussed environmental concern in the 21st century. We plan to extend the analysis to the other key environmental impacts in a subsequent article. A similar analysis can be attempted for the water pipeline network of Oslo, and the results can be aggregated with the findings in this article to represent the entire pipeline network in the water–wastewater system in the city. Of course, pipeline networks in different cities can also be compared through the combined MFA-LCA methodology.

Acknowledgements

We are grateful to Per Kristiansen, chief of the sewage department at Oslo VAV, and the personnel of that department for their total support.

Notes

1. One kilometer (km, SI) ≈ 0.621 miles (mi).
2. A pipeline is a length of extruded pipe and is the simplest unit of the network. Each individual pipeline can be defined by its length, diameter, material of construction, and age.
3. One tonne (t) = 10^3 kilograms (kg, SI) ≈ 1.102 short tons.
4. Galvalume is an alloy of zinc and aluminium that has replaced pure zinc as a galvanizing agent for ferrous

materials. Derived from petroleum, bitumen is applied as a protective coating on the outside of pipes. Its composition is quite diverse, and among metals, the vanadium content in particular is important.

5. One kilogram (kg, SI) ≈ 2.204 pounds (lb). Carbon dioxide equivalency describes the quantity of a gas that would have the same greenhouse warming potential as a given amount of carbon dioxide.

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About the Authors

G. Venkatesh and **Johanne Hammervold** are PhD researchers and **Helge Brattebø** is a professor and head of department, all at the Department of Hydraulic and Environmental Engineering at the Norwegian University of Science and Technology (NTNU), Trondheim, Norway.

Supplementary Material

Additional Supplementary Material may be found in the online version of this article:

Supplement S1. This supplement contains key assumptions and background data for this study, including the following: assumptions about the physical characteristics of the pipelines studied in the MFA (Appendix S1.1), assumptions regarding energy consumption during pipeline installation and rehabilitation (Appendix S1.2), and background data regarding the SimaPro processes applied in this study (Appendix S1.3).