Assessment of Environmental Impacts of an Aging and Stagnating Water Supply Pipeline Network

City of Oslo, 1991–2006

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Supporting information is available on the *JIE* Web site

Summary

Aging urban infrastructure is a common phenomenon in industrialized countries. The urban water supply pipeline network in the city of Oslo is an example. Even as it faces increasing operational, maintenance, and management challenges, it needs to better its environmental performance by reducing, for instance, the associated greenhouse gas emissions. In this article the authors examine the environmental life cycle performance of Oslo's water supply pipelines by analyzing annual resource consumption and emissions as well as life cycle assessment (LCA) impact potentials over a period of 16 years, taking into account the production/manufacture, installation, operation, maintenance, rehabilitation, and retirement of pipelines. It is seen that the water supply pipeline network of Oslo has already reached a state of saturation on a per capita basis, that is, it is not expanding any more relative to the population it serves, and the stock is now rapidly aging. This article is part of a total urban water cycle system analysis for Oslo, and analyzes more specifically the environmental impacts from the material flows in the water distribution network, examining six environmental impact categories using the SimaPro (version 7.1.8) software, Ecoinvent database, and the CML 2001 (version 2.04) methodology. The long-term management of stocks calls for a strong focus on cost optimization, energy efficiency, and environmental friendliness. Global warming and abiotic depletion emerge as the major impact categories from the water pipeline system, and the largest contribution is from the production and installation phases and the medium-size pipelines in the network.

Introduction and Literature Review

Knowledge of the annual material additions to pipeline stocks as well as the operation and maintenance schedules provides insight into life cycle energy consumption and life cycle emissions to the environment from a water supply pipeline network. This article presents a study of the life cycle environmental impacts from the water pipeline network in Oslo and identifies the relative contributions of the different phases of the life cycle using dynamic material flow analysis (MFA) and environmental life cycle assessment (LCA) methods. The work is part of a full urban water and wastewater system assessment for the city of Oslo (Ugarelli et al. 2010; Venkatesh and Brattebø 2011a, 2011b, 2011c, 2011d; Venkatesh et al. 2009, 2011; Venkatesh

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and Ugarelli 2010). In this article, only the pipeline network is considered, excluding pumping stations, water treatment plants, and components of the water distribution network other than pipelines. The relative importance of each phase over the lifetime of the water supply system changes as the network expands and gets older. This is a point to be considered especially when developing management strategies for aging infrastructure assets such as pipeline networks. According to the Association of Consultant Engineers (ACE 2009), the average leakage rate in water pipeline networks in Norway is approximately 30%, while the European average is much less. The rehabilitation/replacement rate for wastewater pipelines in Norway dropped from 0.56% in 2004 to approximately 0.45% in 2008. The ACE report argues for an increase in the rehabilitation rate, and the water and wastewater pipeline networks are characterized as being in a poor state vis-à-vis other infrastructures in Norway. The U.S. Environmental Protection Agency (U.S. EPA 2009), in a recent analysis, raised concerns about the limited investment in the United States for rehabilitation and replacement of water and wastewater pipelines and called for LCA, life cycle costing, asset management guidance, and tools for prioritization of sewer pipeline inspection, better condition assessment approaches, and new design and implementation methods for the management of aging pipeline networks.

In this article, the water pipeline network is described and the methodology adopted here is briefly outlined. Then, the results from the material and energy flow analyses are presented and the subsequent LCA is carried out. The results obtained for the water pipeline network in this article are compared with those for the wastewater pipeline network in Oslo, examined by Venkatesh and colleagues (2011).

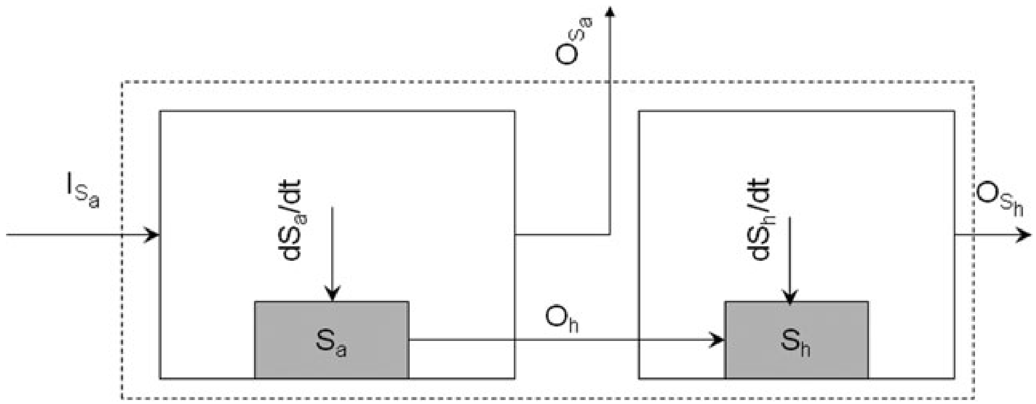
Studies have been published on the environmental performance of different subsystems of the urban water cycle system. In a study conducted in the United Kingdom, the Concrete Pipeline Systems Association (CPSA 2001) concluded that, among pipeline construction materials, concrete is the most environmentally friendly. Lassaux and colleagues (2007) carried out an LCA from the pumping stations to the wastewater treatment plants for the Walloon region in Belgium, and concluded that the construction phase of pipeline networks makes a significant contribution to the total environmental load. Eckard (2008) found that more than 50 million tonnes (t)[1] of carbon dioxide equivalent greenhouse gases were emitted from wastewater treatment (including sludge handling and methane degassing) alone in 2006 in the United States. Vince and colleagues (2008) used the CML 2001 methodology (CML 2002) and Gabi 4.2 software to conclude that energy consumption and chemicals production account for the greatest share of the environmental impacts due to potable water production. The same applies to wastewater treatment plants as well, as concluded by Nowak (2003).

Venkatesh and colleagues (2009) calculated the mass flows into the wastewater pipeline stock in Oslo for the period 1991 to 2006, including the global warming potential of the life cycle stages, and concluded that, in an expanding network, the production and installation stages account for the majority of greenhouse gas emissions, while in a saturated network global warming potential decreases substantially. Kawashima (2002) argues that infrastructure LCA is extremely important as a policy planning tool, while observing that a significant share (more than 80%) of life cycle carbon dioxide emissions for an activated sludge wastewater treatment plant occurs during the operation phase. More recently, Strutt and colleagues (2008) assessed the carbon footprint of water supply. Among other things, their article demonstrated that by resorting to the use of more recycled steel and cement-concrete aggregates when pipelines are added to networks, a reduction of 25% in greenhouse gas emissions is possible. Racoviceanu and colleagues (2007) have shown that the electricity use for water treatment, in general, is less than that for water distribution or wastewater treatment. Their article notes that in the water supply network of Toronto, more than 75% of the energy consumption in the water treatment plants is attributable to the pumping of raw water at the intake and pumping out of the treated supply water. One of the conclusions by Racoviceanu and colleagues (2007) is that by reducing water consumption, the energy demand, and thereby the operational expenses, can be reduced substantially. Ambrose and Burn (2005), in the calculation of embodied energy in pipelines of different materials in an Australian case study, have made a differentiation between, from least to greatest in terms of magnitude, embodied energy associated with just the upstream manufacturing and production processes, embodied energy that takes into account the energy expended during the installation, and embodied energy associated with the life cycle energy consumption.

While water and wastewater treatment, being the most significant contributors to the environmental impacts in an urban water and wastewater system, have been studied extensively by many researchers, the life cycle environmental impacts associated with water pipeline networks have not previously been studied in detail. This article presents a methodology to do this, and applies it to the city of Oslo. This, being a historical analysis, provides useful insights into how the pipeline network has evolved over time with respect to material and energy inputs, associated emissions, and the concomitant environmental impacts. It does not perform any kind of forecast for the future, apart from concluding that in an aging and saturated network like Oslo's, with a sharply declining need for new pipelines, rehabilitation and maintenance activities account for almost all of the environmental impacts.

Methodology

Pipelines are long-lived and, after fabrication and installation, subterra, they have to be inspected and maintained regularly. During the operation and maintenance phase of their lifetimes, a range of operations are performed: internal coating of the pipes to impart corrosion resistance, replacement of smaller parts of a pipeline, general repair, visual inspection, cleaning/flushing, alterations in the direction/route along which the pipelines are laid, exhumation (digging up) and replacement



I_{S_a}	Annual water pipeline material inflows	O_h	Disconnected water pipelines hibernating sub-terra
dS_a/dt	Additions to water pipeline stock	dS_h/dt	Rate of change of hibernating water pipeline stock
S_a	Active operating water pipeline stock at beginning of year	S_h	Hibernating stock of water pipelines
O_{S_a}	Outflows from active water pipeline stock for recycling	O_{S_h}	Outflow from hibernating stock

Figure 1 Understanding pipeline material flows from a dynamic material flows analysis (MFA) perspective (dotted lines in the figure indicate the system boundaries).

of pipes, as well as rehabilitation without digging, where a new pipe is laid within an existing pipe (Venkatesh et al. 2009).

This study aims to determine the life cycle environmental impacts of the pipeline stock. This necessitates the careful examination of stock characteristics and their development over time. The approach in this article has been to study the stock from a dynamic MFA and stock-composition perspective before proceeding with the LCA. The outline of the methodology adopted, based on discussions with partners in the Oslo Water and Wastewater Department (Oslo VAV in Norwegian), is given in brief in the following subsections.

Determining Material and Energy Flows

The starting point of the work was to study the development of the network in size and composition over time (pipeline types and material content) since 1900. A standard MFA procedure was used; see figure 1 where the pipeline stocks and the annual inflows and outflows are indicated. The fact that pipelines at the end of their lives are not actually removed as outflows to waste management (or material recycling) but are left inactive in the ground as hibernating stocks was taken into consideration.

The mass balance principles applied to this system give the following, considering the active and the hibernating stocks:

$$I_{S_a} = dS_a/dt + O_{S_a} + O_h$$
$$O_h = dS_h/dt + O_{S_h}$$

The intention at the outset was to examine the mathematical relationship between outflows and inflows by using a lifetime distribution function and carry out a mathematical dynamic MFA modeling of the system, as illustrated in figure 1, annually over time since 1900. However, this could not easily be done since Oslo VAV could not provide good quantitative data on the development of the size of the hibernating stock (S_h) and their annual inflow (O_h). Moreover, they confirmed that the annual outflow from the active wastewater pipeline stock for recycling (O_{Sa}) was negligible. On the other hand, what they could provide was a detailed accounting of all annual inputs to the system (I_{Sa}) since 1900 in terms of the types of pipelines and their locations, sizes, and material content. The rehabilitation (plus replacement) rate during 1991–2006 has been well under 1% per year on average (as calculated by the authors). Instances of replacements form a small subset of these. Thus the "outflow masses" (O_h), and thereby the replacement mass inflows (a very small component of I_{Sa}), can be assumed to be negligible. Thus it would not be inaccurate to assume that nearly 100% of I_{Sa} is merely an addition to the pipeline stock contribution to network expansion.

Venkatesh and colleagues (2009) investigated the change in size and composition of the wastewater pipeline stock in Oslo. In the present article, the same has been done for the active water pipeline stock (S_a in figure 1) for the period 1900–2006 (refer to figure 3). Outlined below are details on the procedures adopted to calculate the material and energy flows related to the water pipeline stock for the period 1991–2006.

The material additions to the stock of water pipelines are calculated by using the database obtained from Oslo VAV. Pipe thicknesses are obtained from standard charts and material densities from relevant sources (see the supporting information on the journal Web site). The inflows are categorized into three size classes: small size (diameter $\leq$ 199 millimeters [mm]),[2] medium size (diameter 200–399 mm) and large size (diameter $\geq$ 400 mm). In order to facilitate comparison with the wastewater pipeline network in Oslo (Venkatesh et al. 2011), the time period considered for this study is 1991–2006. The production of mild steel (i.e., low-carbon steel with manganese as the main alloying element) 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 mass flows of crushed gravel used as bedding material during pipe installation during the 1991–2006 period were appreciable: 580,000 t, calculated on the basis of information provided by Sægrov (2008). Small amounts of cement mortar, zinc, and bitumen entered the network as coating materials. Dissipative losses of coating materials, which can be considered as outflows from the network, always occur, but these are difficult to estimate.

Data on rehabilitation were obtained upon request from Oslo VAV. The foremost rehabilitation method, as in the case of wastewater pipelines (Venkatesh et al. 2009), has been the cast-in-place-pipe (CIPP) method, where a thin polymeric coating is applied to the inner circumference of the pipeline, effectively isolating it from the flow and subjecting only the surface of the polymeric coating to the direct radial stresses imposed by the flowing water. Of course, the pipe material surrounding the coating serves as an envelope to this "new pipe" cast in place inside it. In effect, it is passive, but it forms a part of the network as it encases the load-bearing polymeric sheath on its inner surface area. We had some problems in quantifying these inputs due to a lack of data comprehensiveness. Of the 81 kilometers (km)[3] of pipelines that were rehabilitated, complete information was available for only 35 km, while for the remaining, the year of rehabilitation was not recorded. A thickness of 7 mm of epoxy resin was assumed to be applied to every pipeline that was rehabilitated by the CIPP method between the years 1991 and 2006. Polyurethane has also been introduced in pipeline rehabilitation, but to a much lesser extent, and we therefore assume all rehabilitation material in our analysis of this period to be epoxy resin.

As far as energy flows are concerned, estimates for the consumption of diesel in the installation and rehabilitation of pipelines (in terms of unit length of pipeline) were obtained by interaction with Oslo VAV (Kristiansen 2008). The diesel consumed by vehicles deployed during the operation and maintenance phase accounts for almost all the energy consumption in this phase. This consumption was calculated assuming proportionality to the average length of pipelines in the network during the period. Section II of the appendix (in the supporting information on the journal Web site) lists the values thus obtained. Most of the pipelines were fabricated in Norway, and the transport distance from manufacture to the site in Oslo is assumed to be 250 km, on average. Ductile iron pipes are imported mainly from Germany. The transport distances for these are assumed to be 600 km by road (truck) and then 650 km by cargo ship (the distance from Kiel, Germany, to Oslo). The diesel consumption is calculated accordingly. As regards the transport of bedding materials, it is assumed that the estimate for diesel consumption in pipeline installation referred to earlier includes the diesel consumed for transporting the bedding materials (Venkatesh et al. 2009).

Determining Environmental (Life Cycle Assessment) Impacts

Environmental impacts are determined by the use of a suitable LCA method on the basis of examination of cradle-to-grave activities for water pipelines in the system. Figure 2 gives a schematic representation of the life cycle of water pipelines, where we indicate material flows, energy flows, and emissions from each phase of the life cycle.

Accurate data about the outflows of pipelines from the network, that is, the retirement of pipelines whereby they are disconnected from the network and completely replaced by new pipe lengths, were not available for our analysis. The rehabilitation (plus replacement) rate during 1991–2006 has been well under 1% per year on average (as calculated by the authors, and also referred to earlier in this article). Instances of replacements form a small subset of these. Thus the "outflow masses," and thereby the replacement mass inflows, can be assumed to be negligible. It therefore follows that the energy consumed in the decommissioning process can be neglected as insignificant in this analysis. Hence annual pipeline additions to the material stock, accounting for the network expansion, are almost the same as the total pipeline material mass inflows.

The LCA is based on the MFA results for the water pipeline network. The software SimaPro 7.1 was used (PRé Consultants 2008). Emission data were obtained from the Ecoinvent database (Swiss Centre for Life Cycle Inventories 2008), using generic processes based on average European technologies instead of case-specific data (details are provided in section V in the appendix available as supporting information on the journal Web site). The processes were modified slightly to adapt to the case considered for this study. The CML 2001 v2.04 impact assessment method (CML 2002) is applied. Abiotic depletion potential (ADP), acidification potential (AP), eutrophication potential (EP), global warming potential (GWP), ozone layer depletion potential (ODP), and photochemical oxidation potential (PCOP) were the impact categories assessed. The toxicity categories were not considered in this article, owing to the relatively higher uncertainties associated with fate modeling in the impact assessment. However, the authors maintain that if these uncertainties can be overcome and more impact categories could be included in the analysis, a more comprehensive LCA can be done. Recent developments in the USEtox model seem to open up the possibility for more scientifically accurate estimates of toxicity in the future, since USEtox is claimed to provide a harmonized approach to assessing and evaluating

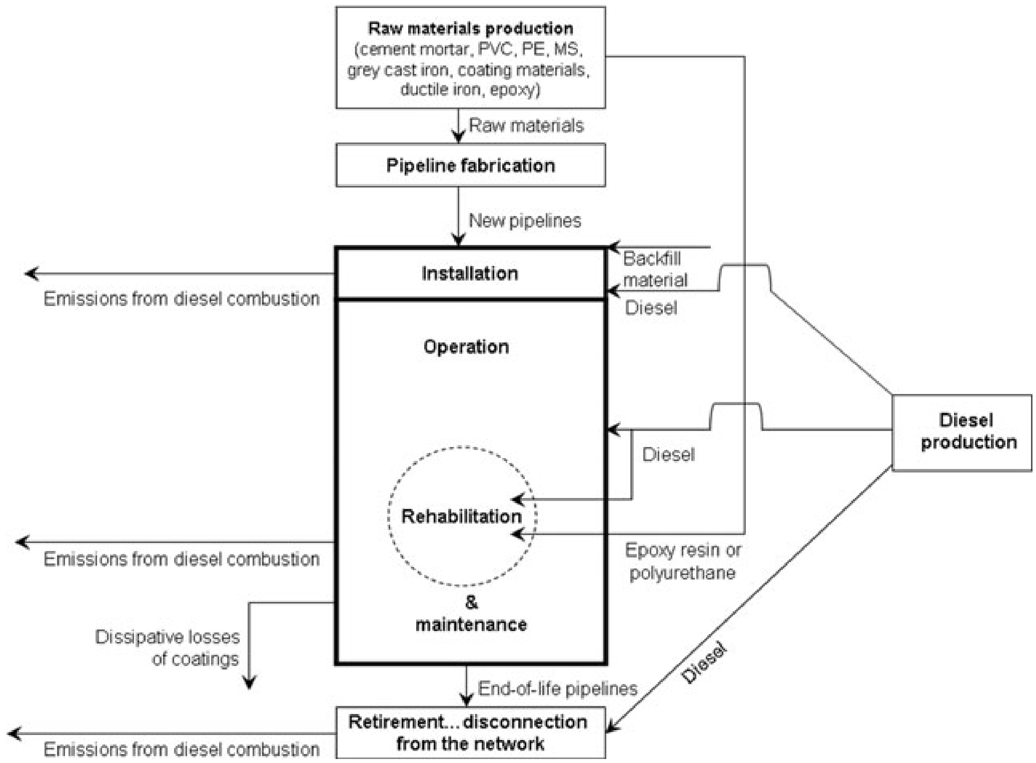


Figure 2 Material and energy flows in the water pipeline network. PVC = polyvinyl chloride; PE = polyethylene; MS = mild steel.

risks from chemicals embedded within products (Hauschild et al. 2009). The impacts were determined on an annual basis from 1991 to 2006. Technological developments would definitely have made manufacturing more efficient over time with respect to energy consumption and emissions. However, in the absence of reliable information about how technology has contributed to a decrease in emissions per unit mass of production, the same technology is assumed to have been applicable through the entire 16-year period.

The goal of the LCA is both to test the methodology developed and published by Venkatesh and colleagues (2011) on water pipeline systems and Venkatesh and colleagues (2009) on wastewater pipeline systems, and to obtain results for the environmental impact related to the flows that are mobilized by the pipeline network stock over time. The function of the water pipeline network is to distribute potable water from its sources, via treatment plants, to the users in Oslo. This should be done at a specified demand profile of quality, quantity, regularity, and pressure throughout the year, also taking into consideration leakages in the water distribution network and the fact that the demand profile is not constant from year to year, since the city population is growing. Further, new water pipelines are added to the system from year to year and some of the existing pipelines have to be rehabilitated each year. The functional unit for our analysis is defined as follows: one year's operation and maintenance of the water supply network in the city of Oslo, meeting a specified demand profile of quality, quantity, regularity, and pressure, including the needed installation of new and the rehabilitation of existing pipes. Materials and components included in the study are polyvinyl chloride (PVC), polyethylene (PE), mild steel, grey cast iron, and ductile iron pipes; epoxy resin used for rehabilitation; diesel fuel (used in all the phases); and crushed gravel, which is used as bedding material. Coating materials, which are used in relatively smaller amounts, were excluded from the analysis. For all materials, environmental impacts occurring in all life cycle phases from cradle to gate (from raw material extraction to finished product at the site) were included. For diesel, however, transportation from the storage site to the point of use was not taken into consideration. The disconnection of retiring pipes may consume some energy, however, this was excluded from the LCA, as we assume it to be negligible. This exclusion is supported by the work of Strutt and colleagues (2008), in which emissions from the decommissioning phase were neglected. Crushed gravel, though not insignificant in terms of mass additions, has a very meager contribution to the environmental impacts (less than 2%, as per a preliminary calculation by the authors) and can be neglected. Section IX in the appendix (available as supporting information on the journal Web site) lists the unit emissions for the different environmental impacts as respective equivalents (including transportation to the site, except for diesel).

The normalization factors applied in this study are the total emissions per impact category in Western Europe for the year 1995, estimated by Huijbregts and colleagues (2003).

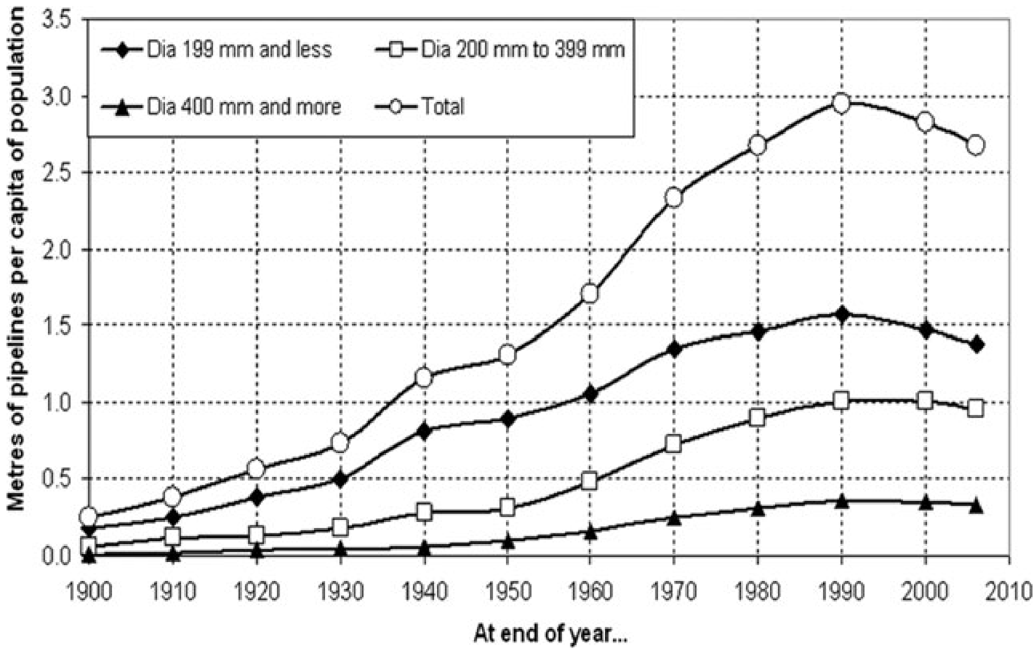


Figure 3 Meters per capita over time of functioning water pipelines in Oslo.

Weighting is, of course, very subjective, and is often a political issue. Here, the authors had the option to refrain from weighting and report only the normalized values, but decided to go a step further and obtain the weighted averages as well. Section IV in the appendix (available as supporting information on the journal Web site) lists the normalization and weighting factors we used in this study. The weighting factors applied have been sourced from the U.S. National Institute of Standards and Technology (BFRL 2008).

The contributions of the pipelines to each of the impacts over time and the shares of the three different size categories and the three life cycle phases to the overall impacts are determined. The authors studied the impact of replacing epoxy resin with polyurethane as a CIPP rehabilitation material. In a stagnating and aging pipeline network, it is the rehabilitation and operation and maintenance phases that dominate as far as the environmental impacts are concerned (Venkatesh et al. 2009; Venkatesh and Ugarelli 2010).

Results and Discussions

Material Flows

Figure 3 shows the evolution in the water pipeline stocks in Oslo, on a meters-of-pipeline-per-capita basis. Only those pipelines that were functional in the network at the time of the study were considered. In other words, this is, in a way, an age–size matrix of the presently functioning network. Data about pipelines that may have been disconnected from the network and left beneath the ground were not available. The classification was done on the basis of the three size categories—small, medium, and large—and the diameter ranges are indicated in the legend of the figure. At the end of year 2006, there were 2.6 meters (m)[4] of water pipeline per capita in the network, of which small-diameter pipelines accounted for about 1.4 m, medium-diameter ones for nearly 0.9 m, and large-diameter ones for 0.3 m. The per capita length peaked in 1990, to nearly 3 m per capita, before decreasing to its 2006 value.

The corresponding material flows are shown since before 1900 in figure 4 and in more detail annually since 1991 in figure 5. At the end of 2006 there were 22,240 t of ductile iron, 59,000 t of grey cast iron, 10,160 t of mild steel, 45 t of PVC, and 180 t of PE in the water pipeline network of Oslo. There were also smaller quantities of other metals and materials, such as zinc, copper, aluminum, bitumen, etc., but they were left out of this study. (Refer to sections I and II in the appendix in the supplementary material on the journal Web site for the assumptions made in the calculations of the masses.)

In addition to the material flows due to additions of pipelines, as shown above, rehabilitation also introduces epoxy into the network (see section VI in the appendix in the supplementary material on the journal Web site). In the period 1991–2006, more than half of the total epoxy mass of 220 t was used to rehabilitate medium-size pipelines. The small-size pipelines accounted for 15% of the total and the large-size category accounted for the remainder.

Energy Flows

Detailed information on annual diesel fuel consumption as a result of pipeline installation, rehabilitation, and vehicular traction during the operation and maintenance phase is given in

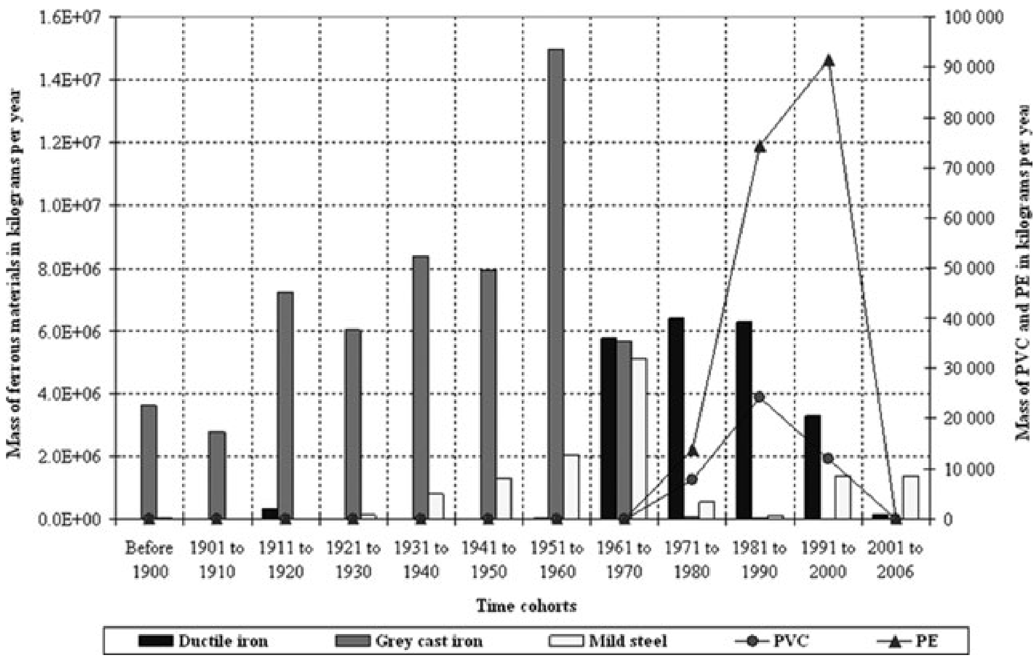


Figure 4 Historic pipeline material inflows to Oslo's water supply network.

section III in the appendix (available as supporting information on the journal Web site), and the results are graphically shown in figure 6.

It is evident that the diesel consumption for installation of new pipelines accounted for the main share (more than 80%) of the total consumption in 1991–2002. From 2003, owing to the fact that no new pipelines were added, the operation and maintenance phase dominated, while the rehabilitation phase accounted for a very small portion of the annual energy consumption for installation, rehabilitation, and operation and maintenance activities.

The total diesel consumed directly on-site by the utility in the installation, rehabilitation, and operation and maintenance phases was more than 4.7 million liters (L)[5] during the period under study, in comparison to 11 million L consumed in the wastewater pipeline network (Venkatesh et al. 2009). In 2004 the consumption plummeted to less than one-sixth of what it was in 2003, and then decreased steadily to about 55,000 L in

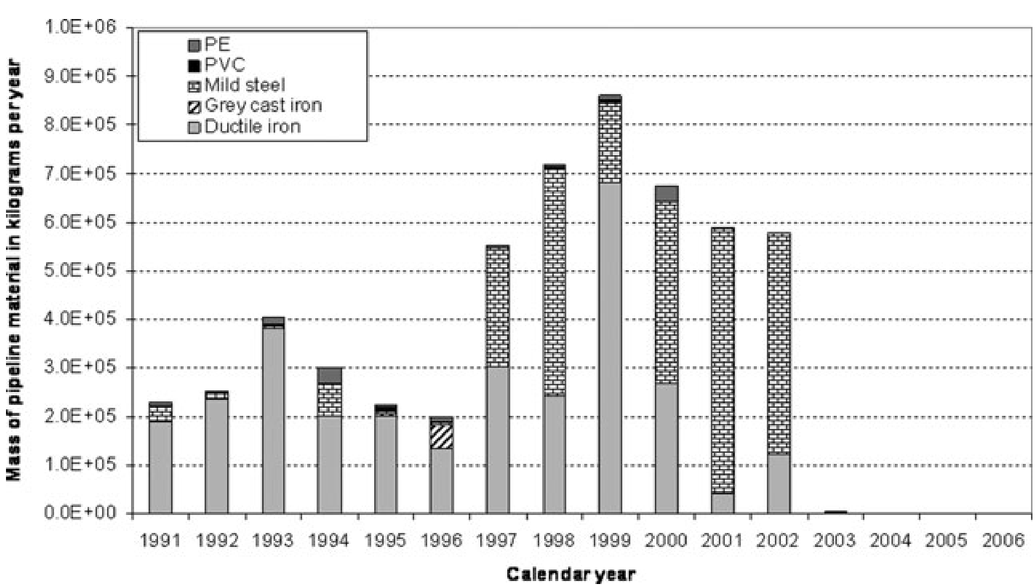


Figure 5 Annual pipeline material inflows to the water pipeline network, 1991–2006.

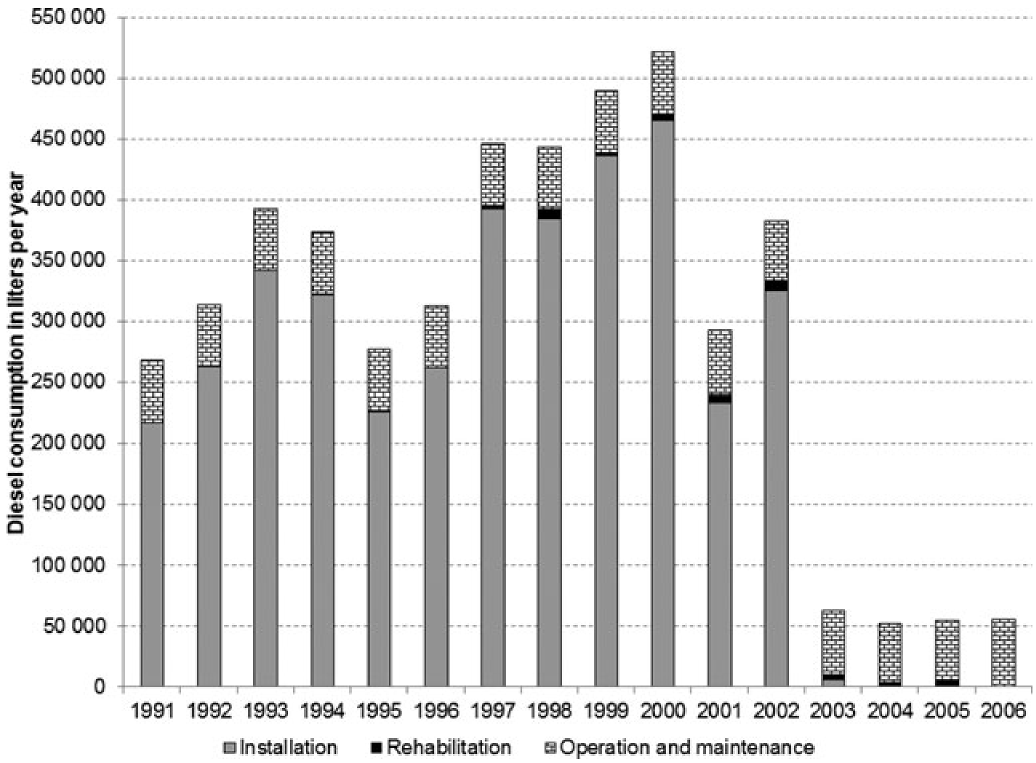


Figure 6 Diesel fuel consumption in different life cycle phases of the water pipeline network, 1991–2006.

2006. The domination of the operation and maintenance phase, accompanied by a reduction in the overall diesel consumption, is quite typical of saturating pipeline networks.

Environmental Impacts—Results of the Life Cycle Assessment

In this section, the results obtained and the interpretations thereof for each of the six impact categories are summarized, while section IV of the appendix (available as supporting information on the journal Web site) lists the normalized impact values for all six categories.

From figure 7, it is evident that it is the production and installation phases in the life cycle of water pipelines that dominate the environmental impacts—more than 85% from 1991 to 2002. Environmental impact is given here as the aggregated total score values, after normalization to per capita impacts and weighting, as explained in the appendix (available as supporting information on the journal Web site). It should be mentioned that although the mass of crushed gravel that enters the pipeline network as bedding material is significant, its contribution to the life cycle environmental impacts, as determined by the authors, is less than 1.5% on average. The aggregated normalized and weighted value was at its highest in 1999. Thereafter, in 2003, owing to no additions made to the pipeline network, the environmental impacts decreased substantially, to about one-tenth of the previous level. From an environmental point of view, in a saturated network, the impacts are much lower vis-à-vis an expanding one. However, if utilities are keen on achieving further reductions, focus could be directed toward using vehicles powered by electricity or biofuels for the operation and maintenance schedules, and biodiesel instead of 100% fossil diesel during the rehabilitation operations. The effect of replacing epoxy resin with polyurethane as a rehabilitation material is discussed below.

Figure 8 verifies that global warming is the most significant environmental impact from the pipeline network, and this is primarily due to the use of diesel fuel during the installation phase and the energy consumption and coke usage in the upstream production processes of epoxy resin and ductile iron. Abiotic depletion comes second, and the sources are traceable to petroleum being the primary raw material for epoxy and diesel production. Acidification is the third most significant impact, and this is due to sulfur dioxide and nitrogen oxide emissions from the combustion of diesel during the installation phase and upstream emissions in power plants supplying electricity to the production units.

The ratio of masses of small-, medium-, and large-diameter pipelines inducted into the network in 1991–2006 was 1:3.6:3.2. The corresponding ratio of lengths was 1:1.72:0.33. The masses of epoxy resins used to rehabilitate pipelines (small, medium, and large) were in the ratio 1:3.3:2.3, while their corresponding lengths were in the ratio 1:2.9:0.57. Hence medium-size pipes dominate the network in terms of both length and mass. (The

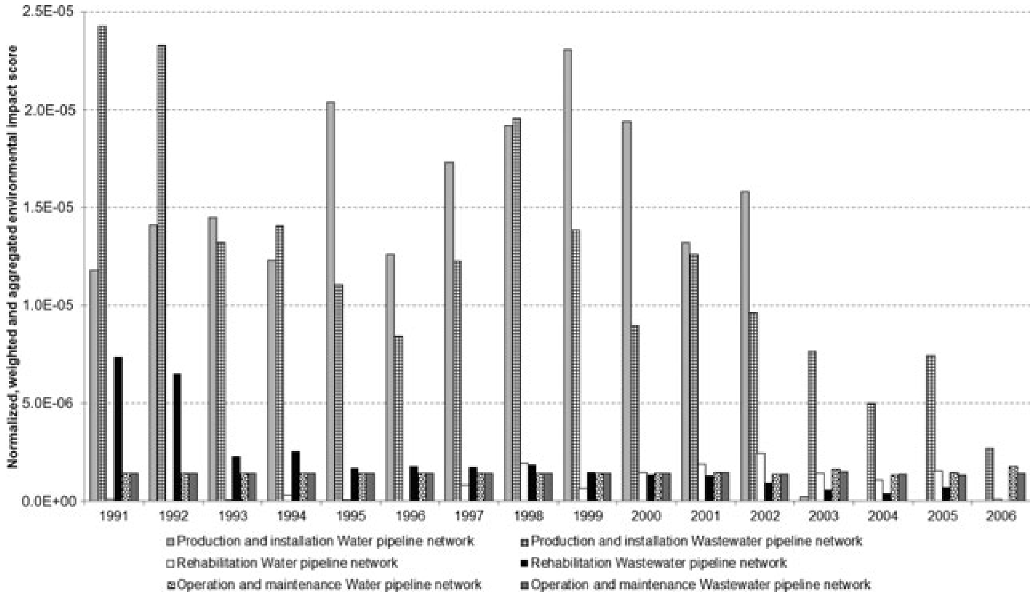


Figure 7 Annual environmental impact from Oslo's water and wastewater pipeline networks—contribution of each phase of the life cycle.

specific environmental impact scores [on a per capita basis] have been plotted and are available in section VII of the appendix, available as supporting information on the journal Web site.) The population statistics for Oslo were obtained from Statistics Norway (www.ssb.no). If the per capita environmental impact scores are visualized on the basis of the pipeline size categories, the medium-size pipes dominate in terms of environmental impact, except in 2001 due to more pronounced rehabilitation of large-size pipelines that year. The reasons can be traced back to the mass and length proportions given at the beginning of this paragraph. In the time period considered for this analysis, it turned out that the lengths and masses of medium-diameter pipelines installed and rehabilitated were larger than their small-size and large-size counterparts in the network. More kilometers of medium-size pipelines installed and rehabilitated also implies a correspondingly greater attribution of diesel and epoxy resin to the pipelines of this category. This is in sharp contrast to the network of wastewater pipelines, where smaller

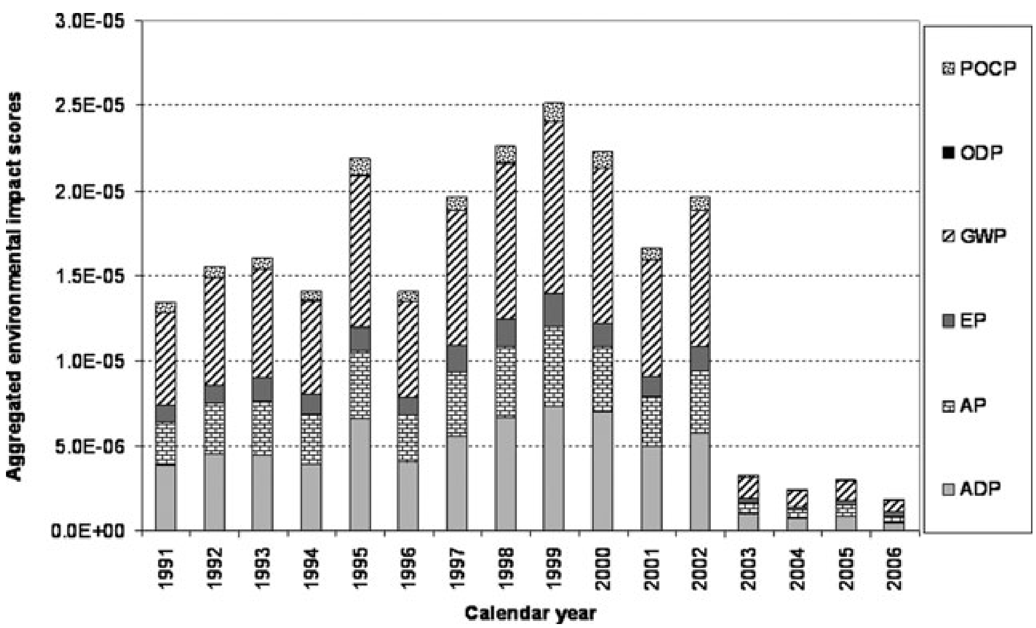


Figure 8 Annual environmental impact from Oslo's water pipeline network—contribution of different types of environmental impact (refer to the subsection "Determining environmental (LCA) impacts" for the expansions of the acronyms in the legend).

pipelines dominated in the initial years before yielding to the medium-size ones toward the end of this 16-year time period (Venkatesh et al. 2009).

Using Polyurethane as a Pipeline Rehabilitation Material

According to the practice in Oslo, polyurethane is slowly becoming the material of choice for rehabilitation of pipelines, and it may soon totally replace the use of epoxy resin. For a given length and diameter of pipe, if epoxy resin were to be replaced by polyurethane as a rehabilitation material, the mass ratio of epoxy to polyurethane would be 2.4. In other words, for every kilogram of polyurethane used, 2.4 kg of epoxy would have been avoided (compare the typical data on thicknesses and specific gravities of the two materials as listed in section I in the appendix, available as supporting information on the journal Web site). However, we have calculated that the aggregated environmental impact is reduced by a much greater factor (3.36). Of course, if the price and functional quality of polyurethane is superior to that of epoxy resin, it would be a much-called-for substitution. For a more complete analysis, these issues will have to be investigated more in detail.

Water Pipeline Network Versus Wastewater Pipeline Network

The authors previously performed a similar LCA for wastewater pipelines (Venkatesh et al. 2011). For comparative purposes, figure 7 shows the environmental impact scores of both water and wastewater pipeline networks in Oslo.

There was an influx of more than 21,725 t of pipeline materials and 572 t of epoxy resin into the wastewater pipeline network from 1991 to 2006, compared to 5,581 t and 220 t, respectively, in the water pipeline network. Epoxy resin has the highest global warming potential among the materials considered. The materials for the wastewater pipeline network were concrete, PVC, and PE, while ferrous materials dominated in the case of the water pipeline network. For instance, more than 400 t of PE found its way into the wastewater pipeline network, and PE has the highest abiotic depletion potential (in per unit mass terms) among all the relevant pipeline materials, and it also has a global warming potential greater than mild steel and concrete. Conversely, only 117 t of PE were used in the water pipeline network. While about 105 km of water pipelines (mostly ductile iron and PE) were added, 176 km of wastewater pipelines (mostly concrete) were introduced between 1991 and 2006. There are significant offsets arising from the vast bulk of concrete wastewater pipelines: concrete, in comparison with PVC, PE, mild steel, ductile iron, and gray cast iron, has very low impacts. Also, acidification impacts in the case of water pipelines are greater than that due to wastewater pipelines, owing to the greater proportions of ductile iron pipes in the former. The result of all these issues is that the annual aggregated (normalized and weighted) environmental impacts from the water supply pipeline network and the wastewater pipeline network in Oslo during the same period is more or less of the same order of magnitude, despite the fact that much more pipeline mass was used in the wastewater network.

Conclusions, Limitations, and Scope for Further Work

The authors set out to determine the contributions of the different phases in the life cycle of water pipelines in Oslo's water and wastewater network to the environmental impact potential of abiotic depletion, acidification, eutrophication, global warming, ozone depletion, and photochemical oxidation. Owing to nonavailability of comprehensive data for the years before 1991, the authors restricted the study of the past to the period 1991–2006. An MFA was conducted to determine the annual influx of pipeline materials, coating materials, crushed gravel, and epoxy resin to the active stock, and the consumption of diesel fuel for installation, operation and maintenance, and rehabilitation.

The LCA findings point to the domination of the production and installation phases during the period 1991–2002, and the operation and maintenance phase thereafter. The medium-size pipelines emerged as the chief contributors to almost all the adverse environmental impacts. Global warming, abiotic depletion, and acidification are the most significant among all impacts considered. The acidification impact is greater in the case of water pipelines vis-à-vis wastewater pipelines, owing to the predominance of ferrous pipelines in the active water pipeline stock. Ferrous materials have a greater acidification potential as compared to concrete, which dominates the masses in the active wastewater pipeline stock. As pointed out by Kawashima (2002), LCA is certainly a useful tool for historical analysis as well as for strategic decision making to enable sustainable development in the future. As a water pipeline network evolves toward saturation, its contribution to the annual life cycle environmental impacts of the urban water and wastewater system decreases sharply, and as pointed out by Lassaux and colleagues (2007), the after-the-tap water discharges and wastewater treatment account for a very sizable portion of the life cycle environmental load of the urban water and wastewater system taken as a whole. The rehabilitation and operation and maintenance phases provide some opportunities for improvement in the system's environmental performance.

Material inputs to a stagnating water supply pipeline network will continue in the years to come, chiefly in the form of epoxy resins or polyurethane used for rehabilitation. Environmentally speaking, polyurethane is a better choice. However, price and availability need to be factored in as well. Diesel consumption will continue, and the incorporation of alternate fuels may further reduce environmental impacts such as global warming.

In a saturated pipeline network like the one analyzed in this article, the environmental impacts are very low, as depicted in figures 7 and 8. It is probably the eutrophication potential of the treated wastewater that is the most significant impact of an urban water and sanitation network (Lassaux et al. 2007).

It thus follows that the utility should focus its attention and investments on mitigating the impacts arising from wastewater treatment (greater nutrient removal) and storm water management, including overflow reductions, with the contributions of the pipeline networks (both water and wastewater) likely to be less significant in comparison.

The authors had to work within the limited availability of data. Hence some exclusions were unavoidable, and the study could not have been carried out without some assumptions. However, these need not have been made if access to more comprehensive data can be made possible.

As far as the production of pipes within Norway is concerned, the impacts related to this phase are sensitive to the choice of the electricity mix assumed for the analysis. There is an ongoing debate about the choice of a suitable electricity mix for LCA studies in Norway. While the Nordic mix overestimates impacts, the Norwegian electricity mix underestimates them. In a recent study, Graabak and Feilberg (2011) concluded that the marginal electricity in Europe today (as for Norwegian imports) emits about 655 grams of carbon dioxide per kilowatt-hour (g CO_2/kWh),[6] which is much more than the emissions from Norwegian (hydropower-based) electricity and also more than the emissions from the current Nordic electricity mix. However, it is not very likely that new water and wastewater pipeline design options will significantly influence the overall production capacity and technology mix in the European electricity generation market. Hence, according to the ILCD Handbook: General Guide for Life Cycle Assessment (European Commission 2010), we should apply the attributional LCA principle and assume average technologies in the electricity generation sector. Therefore, while the Nordic mix would probably overestimate environmental impacts, the Norwegian electricity mix would certainly underestimate them. Section VIII in the appendix (available as supporting information on the journal Web site) compares the Norwegian electricity mix with the Nordic mix (Swiss Centre for Life Cycle Inventories [2008]. Likewise, in the production process, there is also an uncertainty associated with the percentage of steel scrap used to produce the steel for pipe fabrication.

Some of the estimates of the data used for the LCA were actually ranges of values. The average of the extremities of the said ranges (or midpoints) was used in these cases, instead of performing a sensitivity analysis by considering different values within the ranges. If there is a forecasting component in the analysis (as in Venkatesh et al. 2009), sensitivity analysis becomes all the more important owing to the inevitable uncertainties of the future. Rehabilitation data are also not comprehensive, as referred to earlier. However, in retrospect, it can be seen from figure 7 that rehabilitation accounted for a very small share of the total environmental impacts from 1991 to 2002. Even if the missing data had been included, assuming that these were spread almost uniformly over the time period studied, the shares would not have changed appreciably. Of course, if a significant percentage of this uncounted rehabilitation happened after 2002, the percentage increase in the environmental impacts during the last four years of the time period would be more noticeable.

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Notes

1. One tonne (t) = 10^3 kilograms (kg, SI) $\approx$ 1.102 short tons.
2. One millimeter (mm) = 10^{-3} meters (m, SI) $\approx$ 0.039 inches.
3. One kilometer (km, SI) $\approx$ 0.621 miles (mi).
4. One meter (m, SI) $\approx$ 39.37 inches.
5. One liter (L) = 0.001 cubic meters (m^3, SI) $\approx$ 0.264 gallons (gal).
6. One gram (g) $\approx$ 0.035 oz; one kilowatt-hour (kWh) $\approx$ 3.6×10^6 joules (J, SI) $\approx$ 3.412×10^3 British thermal units (Btu).

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Supporting Information

Additional supporting information may be found in the online version of this article:

Supporting Information S1: This supporting information provides an appendix with details on the assumptions regarding the material flow analysis; energy consumption in installation and rehabilitation; diesel fuel consumption; normalization and weighting; processes used in SimaPro 7.1.5 LCA software; epoxy introduced into the network per year; per-capita environmental impacts by life cycle phase; Norwegian and Nordic energy mixes; and life cycle impact potentials for the results reported in the main text.