Estimation of CO_2 Emissions from the Life Cycle of a Potable Water Pipeline Project

Kalyan R. Piratla, S.M.ASCE[1]; Samuel T. Ariaratnam, M.ASCE[2]; and Aaron Cohen[3]

Abstract: The accumulation of CO_2 emissions in the atmosphere is considered a major contributor to climate change. Consequently, it is essential to control the emissions generated by human activities to protect the environment for future generations. Many countries have set their own emission control targets to achieve by the middle of the century. In this context, it is important to quantify emissions from human activity and consider alternatives in order to reduce these emissions. This paper demonstrates a model for estimating life-cycle emissions resulting from an underground potable water-line project that could be used as a managerial decision support tool. The life cycle of the water pipeline is divided into different phases for the analysis. Different methods are used to estimate the emissions in each phase of the life cycle. The results indicate the life-cycle emissions from a demonstration 152.4-m (500-ft), 200-mm (8-in.)-diameter water pipeline at a representative 1.22-m (4-ft) depth range between 1,463.23 t and 1,524.98 t depending on the pipe material chosen. Four different pipe materials have been considered as alternatives in this research. The results indicate that molecular-oriented PVC (PVC-O) provides the best environmental savings compared to PVC, high-density polyethylene pipe (HDPE), and ductile iron in the demonstration of the potable water project. **DOI:** **10.1061/(ASCE)ME.1943-5479.0000069.** *© 2012 American Society of Civil Engineers.*

CE Database subject headings: Emissions; Life cycles; Water distribution systems; Water pipelines.

Author keywords: CO_2 emissions; Life-cycle analysis; Water pipelines.

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Introduction

Environmental protection from pollutants resulting from combustion of fossil fuels has become a global priority and is seen as an important step toward sustainability. The combustion of fossil fuels releases greenhouse gases, which are believed to cause global warming. In the United States, fossil-fuel combustion accounted for 94.1% of CO_2 emissions in 2008 (U.S. EPA 2010). Globally, approximately 30,377 Tg (teragram; equivalent to one million metric tons; 1 t $\approx$ 2204.62 lb) of CO_2 were added to the atmosphere through the combustion of fossil fuels in 2008; the United States accounted for approximately 19% (U.S. EPA 2010). Table 1 presents the recent trends in U.S. greenhouse-gas emissions. Many countries have set their own targets for reducing greenhouse-gas emissions. In these times of restrictions and regulations on greenhouse-gas emissions that result from different activities in society, it is essential to quantify the environmental impacts of any proposed project during the design stage. Table 1 shows that the five major fuel-consuming sectors contributing to CO_2 emissions from fossil-fuel combustion are electricity generation, transportation, industrial, residential, and commercial. Every sector should try to think of ways to minimize energy consumption and reduce emissions, thus moving toward sustainable development. Four percent of the nation's electricity use goes toward moving and treating water and wastewater (EPRI 2002). The EPA estimated the capital needs for drinking-water infrastructure in the United States from 2000 to 2019 to be approximately \$274 billion (EPA 2002). With such a huge investment, it is essential to monitor the environmental impacts on all water infrastructure projects and minimize them whenever possible. This paper demonstrates a model for assessing, quantifying, and comparing life-cycle energy consumption and CO_2 emissions from a demonstration underground-pipeline project. The life-cycle activities include the extraction of raw materials, manufacturing the pipe used in the project, transporting the pipe to the construction site, laying the pipe, operating and maintaining the pipe, dismantling, and disposal or recycling. A methodology for conducting life-cycle environmental analysis (LCEA) for an underground water pipeline project is demonstrated. The CO_2 life-cycle emissions are quantified and compared for four different pipe materials. The results found that the molecular-oriented PVC (PVC-O) pipe type results in lesser emissions than PVC, high-density polyethylene (HDPE), and ductile iron pipe. This study made an effort to access quality data on all the life-cycle stages considered. However, there are number of assumptions made in this study because of the unavailability of adequate data. The environmental aspects of any project should be evaluated during the design phase itself to arrive at an environmentally sound design. It is observed that pumping water is the most dominant phase of the life cycle, resulting in large amounts of CO_2 emissions (approximately 98%). To achieve the predetermined emission-reduction targets set by different states and municipalities, it is important to quantify emissions from different projects. The LCEA tool presented in this paper will be helpful in this aspect. This decision support tool will aid managers in evaluating the environmental effects of a proposed project and in looking for alternatives to minimize these effects.

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[1] Doctoral Research Assistant, Del E. Webb School of Construction, Ira A. Fulton School of Engineering, Arizona State Univ., Tempe, AZ 85287. E-mail: Kalyan.Piratla@asu.edu

[2] Professor, Del E. Webb School of Construction, Ira A. Fulton School of Engineering, Arizona State Univ., Tempe, AZ 85287 (corresponding author). E-mail: samuel.ariaratnam@asu.edu

[3] Lecturer, Del E. Webb School of Construction, Ira A. Fulton School of Engineering, Arizona State Univ., Tempe, AZ 85287. E-mail: aaron.cohen@asu.edu

Note. This manuscript was submitted on November 29, 2010; approved on April 20, 2011; published online on April 25, 2011. Discussion period open until June 1, 2012; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Management in Engineering***, Vol. 28, No. 1, January 1, 2012. ©ASCE, ISSN 0742-597X/2012/1-22–30/\$25.00.

Table 1. Recent Trends in U.S. CO_2 Emissions in Tg CO_2 or Million Metric Tons CO_2 (U.S. EPA 2010)

Source	1990	1995	2000	2005	2006	2007	2008
Fossil-fuel combustion	4,735.7	5,029.5	5,593.4	5,753.3	5,652.8	5,757.0	5,572.8
Electricity generation	1,820.8	1,947.9	2,296.9	2,402.1	2,346.4	2,412.8	2,363.5
Transportation	1,485.8	1,608.0	1,809.5	1,895.3	1,876.7	1,893.7	1,785.3
Industrial	845.4	862.6	852.2	825.6	850.7	842.2	819.3
Residential	339.1	353.3	371.2	358.4	322.1	341.7	342.7
Commercial	216.7	223.2	227.7	221.3	206.0	217.4	219.5
U.S. territories	27.9	34.5	35.9	50.6	50.9	49.1	42.5
Other	365.1	397.8	383.8	355.1	364.4	363.2	348.4
Total CO_2 emissions	5,100.8	5,427.3	5,977.2	6,108.4	6,017.2	6,120.2	5,921.2

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Previous Research

Life-cycle assessments (LCAs) have been primarily used for products to assess environmental performance. Life-cycle approaches for water and wastewater systems are receiving great attention because the entire life-cycle approach entertains different design alternatives by understanding the processes/activities with huge environmental effects (Racoviceanu and Karney 2010). The literature provides numerous examples of studies that have explored the life-cycle aspects of key civil infrastructure systems (Salem et al. 2003). There have been several LCA studies in the wastewater and drinking-water infrastructure area. Emmerson et al. (1995) performed one of the first LCA studies in the water industry and used the LCA tool to evaluate the environmental effects of small-scale sewage-treatment works. The study concluded that energy use is an important contribution to the total environmental impact associated with small-scale sewage plants. Savic and Walters (1997) explored the combination of conventional optimization techniques and sustainability aspects to minimize resource consumption. In similar studies, Dennison et al. (1998, 1999) and Lundin et al. (2000) have presented the environmental effects of wastewater and water infrastructure. Zhang and Wilson (2000) performed an LCA for a large sewage-treatment plant in southeast Asia and reinforced the results of Emmerson et al. (1995), pointing to energy as the primary contributor to the environmental burdens. Skipworth et al. (2002) investigated the entire life-cycle costs of water-distribution systems in the United Kingdom. Vidal et al. (2002) also used LCA for understanding the environmental consequences of wastewater treatment. Colombo and Karney (2002) considered the relationships between pipe leakage and energy expenditure in the operations and management of water-distribution systems. Raluy et al. (2006) used LCA to compare three commercial desalination technologies used to supply potable water: reverse osmosis (RO), multieffect desalination (MED), and multistage flash (MSF). Their research revealed that the energy used is the primary contributor to environmental burdens, and that the operational stage of the technologies has the highest share of environmental effects. Filion (2004) developed a LCEA to quantify the energy consumption of a water-distribution system. The LCEA model was applied to New York tunnels problem to compare the life-cycle energy use for different pipe-replacement schedules. A limitation is that the study did not consider the installation phase and transportation phase when estimating CO_2 emissions. Filion (2004) demonstrates an approach that is more applicable to an entire water-distribution system rather than for a segment of pipe. Recently, Venkatesh and Brattebo (2011) studied at a system level the direct energy, cost, and environmental effects resulting from the operation and maintenance phases of water and wastewater systems in Oslo. More often in the water industry, a section of pipeline needs to be installed either to replace an old pipe or for a new utility. In this context, it is important to understand the energy requirements and CO_2 emissions resulting from a particular section. The model presented in this paper is applicable to a single section of pipeline buried underground rather than for an entire system. Similar to the current study, Recio et al. (2005) also quantified the CO_2 life-cycle emissions of a pipeline project in Spain through a case study. However, the metrics used to quantify emissions in the current research are different. Additionally, the installation and break-repair phases of the pipeline life cycle were not addressed. Dandy et al. (2006) developed a water-distribution-system optimization program that incorporates the sustainability objectives of whole-of-life-cycle costs, energy use, greenhouse-gas emissions, and resource consumption. Stokes and Horvath (2005) used a hybrid LCA (i.e., a process LCA combined with an environmental input-output model) to evaluate and compare water importation, water recycling, and desalination alternatives in Northern and Southern California. Ghimire and Barkdoll (2007) introduced ecoefficiency analysis as a tool to help municipalities determine the ecological effect of a project. Wu et al. (2010) developed a multiobjective optimization procedure to design water-distribution systems that minimize costs and greenhouse-gas emissions. Venkatesh et al. (2009) studied the contribution of different stages in the life cycle of wastewater pipelines to greenhouse-gas emissions, and reported the domination of the installation phase. The operational stage of a wastewater pipeline does not include any pumping energy because wastewater pipelines are typically gravity driven, unlike the water pipelines.

The methodology presented in this paper addresses all the phases of a pipe's life cycle with the objective of quantifying CO_2 emissions for a typical water pipeline project. The approach can be applied to any type of pipeline project to gain a better understanding of the resulting CO_2 emissions before starting a project.

Environmental Life-Cycle Analysis

The life-cycle environmental analysis of an underground potable water pipeline project was studied to demonstrate the methodology used in this research. For a given set of project parameters, four different pipe material options are considered. The CO_2 emissions from all the life-cycle phases, as shown in Fig. 1, have been quantified and compared for these four pipe materials: (1) PVC-O, (2) PVC, (3) HDPE, and (4) ductile iron. The energy consumption and emissions from different life-cycle phases depend on the properties of the pipe material, the type of technologies used (i.e., during the manufacturing of the pipe, installing the equipment, and the pump technologies), and the type of fluid flowing. The life-cycle period considered in this research is 50 years. Fig. 1 illustrates different life-cycle phases of a pipeline, showing energy consumption and emissions for relevant phases. The life cycle starts with the raw

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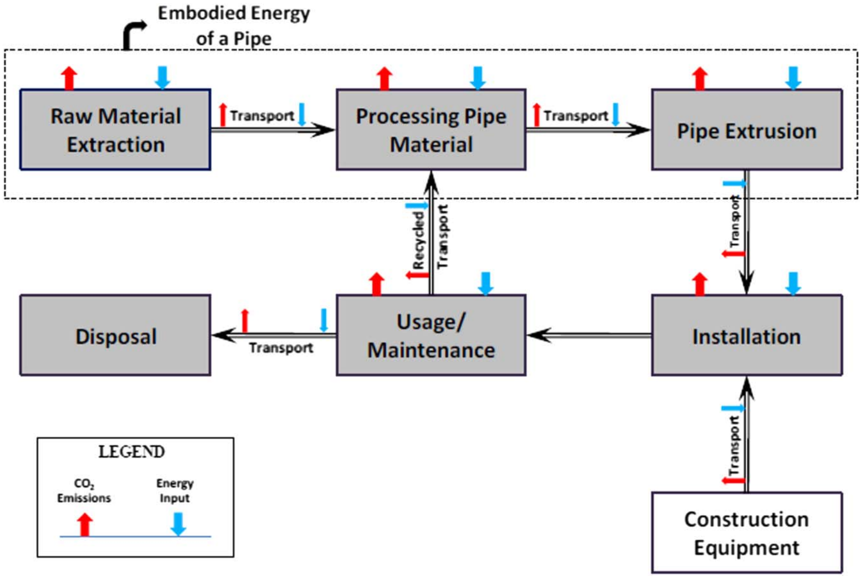

Fig. 1. Life cycle of a water pipeline project

material extraction phase, in which energy is required to extract the required raw materials from different sources. The extracted raw materials are transported to the manufacturing plant, where they are processed and the pipe material is produced. This step may involve large equipment and subsequently, large amounts of energy intake. Most of the equipment in the manufacturing plants is electricity driven, and thus will contribute to CO_2 emissions; more than 45% of the electricity in the United States is generated from fossil fuels [U.S. Energy Information Administration (EIA) 2009]. The manufactured product pipe needs to be extruded or casted in the form of a pipe according to the desired dimension. The extrusion process also consumes energy, because the material is pushed through a die of the desired cross section (in the case of plastic pipes) or casted centrifugally (in the case of ductile iron pipes). The pipes are then stored until they are transported to the construction site.

The installation process involves laying the pipe underground with the help of a set of construction equipment. The installation equipment needs to be transported to the site along with the pipe. Most of the construction equipment uses diesel as fuel, producing CO_2 emissions. Energy is required throughout the life period of a pipeline to pump water at a predetermined pressure and flow rate. Centrifugal pumps are typically used to pump water in distribution systems and are electricity driven, thereby contributing to CO_2 emissions. After the pipe is laid underground, it needs to be properly maintained and repaired when necessary. Maintenance activities involve cleaning, inspection, and repairing any pipe breaks or leaks. All these activities consume energy and release emissions. At the end of the life cycle (i.e., when the pipe is no longer suitable for meeting its intended function), the pipe is either removed and disposed/recycled or abandoned. The recycling process and disposal (transporting) also consume energy, and thus release emissions. The methodology presented in this paper is useful during the design phase of a proposed project to evaluate the emissions and consider alternatives. A case study is used to demonstrate the research methodology and applications in quantifying life-cycle CO_2 emissions of a water pipeline.

Case Study: Drinking-Water Pipeline Project

A municipality in Phoenix is looking for options to install a 152.4-m (500-ft) section of a 200-mm (8-in.)-diameter pipeline to carry potable water at a depth of 1.22 m (4 ft) with a required internal pressure of 482.63 kPa (70 psi). The methodology in this research is used to quantify the life-cycle emissions from the different alternatives considered. PVC, PVC-O, HDPE, and ductile iron pipe materials are considered because they are typical water-pipe materials used in the industry. All the pipe-specific data are obtained from the manufacturer’s manuals, as shown in Table 2, which also presents American Water Works Association (AWWA) standards used for manufacturing the respective pipes. The pipe specifications for the four materials chosen in the research according to the AWWA standards are presented in Table 3. Pipes with the same nominal diameter are considered for the case study analysis, and comparison with CO_2 emissions from different phases quantified.

Table 2. Pipe Standards Used in This Research

Pipe material	Standards	Manufacturer
PVC-O	AWWA C909	JM Eagle
PVC	AWWA C900	JM Eagle
HDPE	AWWA C906	JM Eagle
Ductile iron	AWWA C151	American/US

Embodied Energy Calculations

Embodied energy is defined as “the quantity of energy required by all the activities associated with a production process, including the

Table 3. Standard Specifications of Pipes

Pipe material	Nominal diameter (mm)	Pressure (kPa)	Mean outside diameter (mm)	Mean inside diameter (mm)	Mean thickness (mm)	Density (kg/m)
PVC-O	200	1620.27	229.87	215.14	7.37	8.18
PVC	200	1378.95	229.87	194.82	16.40	17.26
HDPE	200	1378.95	216.05	167.39	24.33	15.02
Ductile iron	200	2413.16	229.87	217.17	6.35	31.40

J. Manage. Eng., 2012, 28(1): 22-30

Table 4. Embodied Energy Coefficients for Pipe Materials

Pipe type	Embodied energy (MJ/kg)
Ductile iron	38.2
DICL	40.2
PVC-U	74.9
PE80B	75.2
PE100	75.2
PVC-M	76.6
PVC-O	87.9

Note: Data from Ambrose et al. (2002).

relative proportions consumed in all activities upstream to the acquisition of natural resources and the share of energy used in making equipment and in other supporting functions i.e., direct energy plus indirect energy" (Treloar 1994). Ambrose et al. (2002) estimated the embodied energy for different pipe materials typically used in water and sewer applications. The embodied energy quantified by Ambrose et al. (2002) is the energy consumed from the cradle to the gate (i.e., from the raw-material extraction until the product pipe leaves the manufacturing plant), as shown in Fig. 1. Ambrose et al. derived the embodied-energy coefficients from energy-analysis studies from various international and national sources. Subsequently, it is assumed that the embodied energy values are applicable in North America. Different pipe materials have different manufacturing processes and thus result in different embodied energy values. The embodied energy also may vary with location and time depending on the material extraction methods, manufacturing technologies, and the type of energy consumed in all the processes. Table 4 presents the embodied energy coefficients for typical pipe materials used for water and sewage applications.

The embodied energy coefficients proposed by Ambrose et al. (2002) are used in this research to quantify the energy consumption of different pipe materials, from the raw-material extraction phase until the pipes are ready to leave the manufacturing plant. The embodied energy in megajoules ($1 \text{ MJ} \approx 0.278 \text{ k·Wh}$) for the pipes considered in the proposed case study is presented in Table 5. The embodied energy in MJ/ft is greater for the ductile iron pipe than for the PVC-O pipe, although the MJ/kg embodied energy is greater for the PVC-O pipe. This is caused by the difference in densities of the two materials. The biaxial orientation of the PVC molecular structure makes PVC-O pipe a stronger compound, and it thus requires less wall thickness than standard PVC pipe.

The U.S. EPA (2009) released state-level electricity generation emission factors for the calculation of the emission footprint. The emission factor for the usage of electricity for the state of Arizona is 0.155 kg/MJ. Given that most of the processes consume electricity during the manufacturing phase of the life cycle, an emission factor of 0.155 kg/MJ was used for the embodied energy in the research.

Table 5. Embodied Energy Calculations for the Proposed Project

Pipe type	Density (kg/m)	Length (m)	Embodied energy coefficient (MJ/kg)	Embodied energy coefficient (MJ/m)	Embodied energy (MJ)
PVC-O	8.18	152.4	87.9	719.4554	109,644.62
PVC	17.26	152.4	74.9	1,292.979	197,049.60
HDPE	15.02	152.4	75.2	1,129.167	172,085.69
Ductile iron	31.40	152.4	38.2	1,199.475	182,802.26

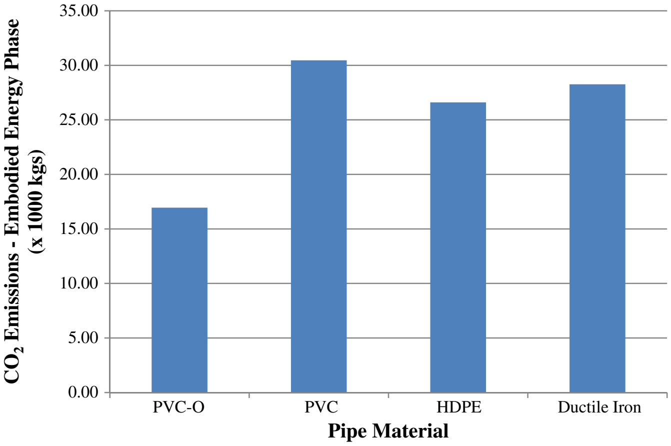

Fig. 2. The CO_2 emissions from embodied energy of different pipe materials

Fig. 2 presents the amount of CO_2 emissions in kilograms for the 152.4-m (500-ft) length of pipe resulting from the raw-material extraction, processing, and pipe manufacturing phases of the life cycle for all four pipe types considered.

Pipeline Installation

Pipes can be installed underground by using open-cut methods or trenchless technology applications. Trenchless applications for installing new pipeline include horizontal directional drilling, pipe jacking, pipe ramming, microtunneling, and auger boring. Ariaratnam and Sihabuddin (2009) quantified and compared the emissions from installing a wastewater line using a traditional open-cut method and pipe bursting. They reported that the option involving the trenchless method reduced the overall average emissions by 80% compared to the open-cut method. This was primarily caused by the number and size of the equipment required for the open-cut installation. Horizontal directional drilling (HDD) is a trenchless method that offers a number of benefits over traditional open-cut methods (Ariaratnam et al. 2009). HDD can be implemented with very little disruption to surface activities, requires less working space, and may also be performed more quickly than open-cut methods (Bennett and Ariaratnam 2008). Installation of municipal underground infrastructure systems using HDD has dramatically increased in recent years. Given the environmental benefits of using the trenchless technologies and the project parameters, the HDD method was selected as an option to consider in the case study.

HDD involves steerable systems for the installation of both small- and large-diameter pipelines. The method involves a two-stage process. The first stage consists of drilling a small-diameter pilot bore along the desired path of the proposed line. The second stage consists of enlarging the pilot bore (with the help of a reamer) to a desired diameter (typically 1.5 times the pipe's outer diameter) to accommodate the new pipeline, and pulling it through the enlarged hole. Sometimes the enlargement process may involve several steps, in which the desired diameter is obtained gradually. Sihabuddin and Ariaratnam (2009) developed an "emission calculator" to quantify emissions resulting from an underground utility project. The tool is user-friendly, and inputs can be obtained from daily project progress reports and equipment data available from company maintenance records. The emission calculator was used in this research to quantify emissions from the installation of the water pipeline in the case study. Table 6 presents the details of the equipment usage requirements for installing 152.4 m (500 ft) of 200-mm (8-in.) water line at a depth of 1.22 m (4 ft). The data were

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Table 6. HDD Equipment Requirements

Activity	Equipment	Model	Rated power (kW)	Useful life (h)	Cum. usage (h)	Load factor (%)	Activity time (h)
Pothole utilities	Excavator	Vac-Tron mini combo 850 SD/DT	36.54	15,000	3,000	85	6
	Crew truck	1 t Ford F350	260.99	100,000	10,000	50	3
Dig pits	Backhoe	John Deere 310J	62.64	20,000	3,000	75	4
	Dump truck[a]	Sterling truck	—	—	—	—	—
Pilot hole	Drill rig	Ditch Witch J4020	141.68	12,000	2,250	50	8
	Excavator	Vac-Tron mini combo 850 SD/DT	36.54	15,000	3,000	85	2
Prereaming	Drill rig	Ditch Witch J4020	141.68	12,000	2,250	85	8
	Excavator	Vac-Tron mini combo 850 SD/DT	36.54	15,000	3,000	85	3
Pull back	Drill rig	Ditch Witch J4020	141.68	12,000	2,250	85	8
	Excavator	Vac-Tron mini combo 850 SD/DT	36.54	15,000	3,000	85	8
	Backhoe	John Deere 310J	62.64	20,000	3,000	50	4
Restoration	Dump truck[a]	Sterling truck	—	—	—	—	—
	Roller	Caterpillar CB214D	22.37	16,000	2,000	40	3

[a]These activities are included in the transportation phase of the emission calculations.

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Table 7. Emissions from Installation Phase of Project

Equipment	HC (kg)	CO (kg)	NO_x (kg)	PM (kg)	CO_2 (t)	SO_x (kg)
Backhoe	0.35	2.58	2.18	0.21	0.29	0.59
Excavator	0.23	1.89	3.56	0.36	0.47	0.95
Crew truck	0.09	0.68	1.37	0.12	0.28	0.57
Drill rig	0.68	4.05	9.50	1.77	1.77	3.59
Roller	0.01	0.09	0.16	0.01	0.02	0.05
Total	1.37	9.29	16.76	2.47	2.83	5.74

obtained from contractor estimates. Table 7 presents the estimated emissions for each piece of equipment on the job site. This research is concerned only with CO_2 emissions, which amount to approximately 2,830.4 kg (3.12 short tons; 1 short ton $= 0.907$ t). The equipment in Table 6 can be used to install any of the four pipe materials considered in the case study. Consequently, the CO_2 emissions from installation of the water line would be approximately 2,830.4 kg (3.12 short tons). The emissions from transportation (shipping pipes, equipment, and hauling excavated material) are estimated separately, and are not included in these calculations.

Usage Phase

The usage phase of a pipeline can be divided into three categories when accounting for the CO_2 emissions. First, water needs to be pumped to a certain pressure head and flow rate using pumps, typically centrifugal, which involves energy consumption and emissions. The second category is the maintenance/inspection activities, which also consume energy and release emissions. The third category is the emissions associated with pipe-break repairs or pipe rehabilitation.

A centrifugal pump converts the input power to kinetic energy in the liquid, which later transforms into pressure energy. Liquid (in this case, water) enters the pump suction and then the eye of the impeller. When the impeller rotates, it spins the liquid outward, giving the liquid some kinetic energy; when the liquid is faced with resistance, pressure energy is created. Water must be pumped at a pressure greater than a minimum required pressure H_s [in this case $H_s = 482.63$ kPa (approximately 70 psi), equivalent to 49.3 m of pressure head]. Friction losses (H_f) also must be considered all along the length of the pipe; these are calculated using the Hazen-Williams equation. All plastic pipes are corrosion-free, whereas ductile iron pipes require corrosion protection. The C value in ductile iron pipes typically decreases with age because of internal corrosion. Subsequently, the head loss caused by friction in ductile iron pipe increases with age. Sharp and Walski (1988) proposed the following roughness growth model [Eqs. (1) and (2)] to predict the change in the friction coefficient, C, with the age of the pipe:

$$C = 18.0\text{–}37.2 \log X \tag{1}$$

$$X = (e_0 + \mathrm{at})/D_i \tag{2}$$

where X = relative roughness of the pipe; e_0 = initial wall roughness at the time the pipe is installed (mm); a = roughness height growth rate (mm/year); t = time in years; and D_i = inside diameter of the pipe (mm) (25.4 mm = 1 in.). The value of e_0 (0.114 mm) is estimated at $t = 0$ using a C value of 140, as assumed for the ductile iron pipe. The C value at the end of the life (i.e., 50 years) is assumed to be approximately 80 for the ductile iron pipe based on industry input. Subsequently, the growth rate a is calculated as 0.08 mm/year for the ductile iron pipe. This corresponds to the 0.025–0.76 mm/year range reported by Lamont (1981). Subsequently, the energy requirements are calculated using Eqs. (3) and (4)

$$\mathrm{Power} = \rho \times g \times H \times Q/n \tag{3}$$

Eq. (3) can be rewritten as shown in Eq. (4) after adjusting the units and considering water as the fluid. H_f can be estimated using Eq. (5).

$$\mathrm{Power\ (kW)} = \frac{H \times Q \times \mathrm{S.G.}}{1{,}618.5 \times \eta} \tag{4}$$

$$H_f(\mathrm{m}) = 0.002083 \times L \times (100/C)^{1.85} \times \left(\frac{Q^{1.85}}{D^{4.8655}}\right) \tag{5}$$

where H = head in meters $= H_s + H_f$; Q = flow rate in gallons per minute (1 gpm $= 0.227$ $\mathrm{m^3/h}$); $S.G.$ = specific gravity of the fluid; η = pump efficiency; L = length of the pipe (m); C = Hazen-Williams friction coefficient; and D = inside diameter of the pipe (1 in. = 25.4 mm). The flow rate, Q, is calculated for PVC-O pipe assuming a flow velocity of 1 m/s (or 3.28 ft/s).

Table 8. Emissions from Pumping Energy for Proposed Project

Pipe	H_s (m)	C	Energy (MJ)	Emissions (kg of CO_2)
PVC-O	49.3	150	9,332,938	1,442,866.99
PVC	49.3	140	9,425,284	1,457,143.65
HDPE	49.3	140	9,646,139	1,491,287.74
Ductile iron	49.3	140-82	9,658,364	1,493,177.70

PVC-O pipe was selected to calculate the flow because of its greater hydraulic capacity. The same flow rate is assumed for other types of pipes. Assuming the pump efficiency (η) to be 75%, the pumping energy required is calculated by using Eqs. (4) and (6) and is presented in Table 8. It is assumed that the pump is operated for 6 h daily throughout its 50-year lifetime.

$$\text{Energy (k·Wh)} = \int_0^{50\,\text{years}} \frac{(H_s + H_f) \times Q \times \text{SG}}{1{,}618.5 \times \eta} \times dt \qquad (6)$$

The energy consumed is obtained by multiplying the power by the number of working hours. The emissions are calculated using an emission factor of 0.155 kg/MJ because most of the centrifugal pumps use electricity to power the engines. The total amount of energy consumed and the emissions released from pumping water through the pipeline in the case study are calculated and presented in Table 8. For the same flow rate and pressure head, PVC-O pipes would consume less energy than other pipe materials with the same nominal diameters.

The second category in the usage phase of a pipe life cycle is cleaning and inspection works. Internally, water mains are relatively clean compared to sewer mains. Sewer mains require significant cleaning using high-pressure water jetting technologies. Leak detection is an important aspect that needs constant attention, because leaky pipes cause a lot of water to be lost every year. Leaks inflate downstream demands, increase energy expenditures, erode utility revenue, and compromise water quality (Colombo and Karney 2002). Numerous leak-detection tools are currently used in the water industry, including acoustic and infrared tools. The energy consumption for the usage of leak-detection tools is considered to be negligible compared to the pumping energy.

The third category considered is the pipe-break repair energy. Pipe breaks occur because of a number of factors. The physical mechanisms that lead to pipe breakage are often very complex and are not completely understood (Kleiner and Rajini 2001). Subsequently, the physical modeling of deterioration is often not possible due to lack of data. Statistical models are very prominent, and are often used in predicting future break rates. Shamir and Howard (1979) conducted a regression analysis to obtain a break prediction model [Eq. (7)] that relates break rate to the exponent of the pipe's age. This model was used to estimate the number of breaks in the proposed pipeline

$$N(t) = N(t_0)e^{A(t-t_0)} \qquad (7)$$

where t = time in years; t_0 = base year for the analysis; $N(t_0)$ = number of breaks per km in year t_0; $N(t)$ = number of breaks per km in year t; and A = growth rate coefficient (1/year), which was estimated to range from 0.01–0.15.

Numerous studies confirm the exponential behavior of pipe breaks (Walski and Pelliccia 1982; Kleiner et al. 1998; Kleiner and Rajani 1999). The total number of breaks per unit length in a pipe i in year t can be obtained by Eq. (8):

$$n_i = \int_{t-1}^{t} N(t_0)_i e^{A(t-t_0)} dt \qquad (8)$$

Kleiner and Rajani (1999) reported values of $N(t_0)_i$ ranging between 0.009 and 0.134 breaks/km/year for spun cast-iron pipes. Because of the lack of pipe-break data for plastic and ductile iron pipes, $N(t_0)_i = 0.009$ breaks/km/year was assumed in this research for all pipe types. The growth rate coefficient, $A = 0.08$, used in this research was an average value of the range proposed by Shamir and Howard (1979). The estimated number of breaks on a 152.4-m (500-ft) water line with $N(t_0)_i = 0.009$ breaks/km/year and $A = 0.08$ is less than one for the entire life cycle of 50 years considered in this research. Subsequently, the emissions from this phase are considered negligible for this particular case study. An emission estimation methodology, presented in this paper, could be used if there were many breaks estimated over the lifetime of a pipe segment or system of pipes. The pipe can be repaired using either open-cut methods or trenchless rehabilitation techniques such as cured-in-place pipe (CIPP) point patch. CIPP point patch techniques can be used to seal the leaky/break areas of the pipe. The energy requirements for the CIPP patch technique could not be quantified because of the lack of data on CIPP material's embodied energy. Consequently, it was assumed that repairs would be conducted using open cut, which is currently the preferred choice of municipalities. The emissions resulting from open-cut rehabilitation of the pipe are estimated and presented in this research. When the leak location has been identified, the soil cover above the pipe is excavated, and the pipe requires clamping with a stainless steel clamp with a rubber layer inside that protects the steel from corrosion. A typical break length of 0.6 m was assumed, and the life-cycle energy required to repair the break calculated on the basis of the sum of the embodied energy of the stainless steel clamp and the energy required for operating the equipment, handling materials (including spoils), and transportation during the repair process. The emissions from the equipment and transportation can be estimated using the emission calculator. The embodied energy and CO_2 emission factors for stainless steel are presented in Alcorn (2003). These values are used to estimate the CO_2 emissions for different diameters of clamps according to American National Standards Institute/National Science Foundation (ANSI/NSF) ANSI/NSF 61 standards. The repair equipment consists of a backhoe that is used depending on the dimensions of the excavated area. For the case study, it was estimated to be used for 1 h to repair a single break on a 200-mm (8-in.) nominal diameter pipe at 1.22-m (4-ft) depth. It can also be assumed that the excavated soil will be used to backfill the pit after the pipe repair. The emissions calculator was used to estimate the CO_2 emissions from the use of the backhoe. Table 9 presents the CO_2 emissions per break repair, including the embodied energy of the clamp material and 1 h of backhoe usage. The estimated number of breaks in the project considered in this research is less than one, and subsequently the emissions from pipe-break repair are considered negligible. However, these values could be used on any project to estimate the CO_2 emissions from pipe-break repairs.

Transportation in Different Phases of Life Cycle

Fig. 1 shows that between any two phases of the life cycle, a transportation link generally exists in which material (raw materials, pipe spools, equipment, spoils, or recyclable material) needs to be transported using trucks of different sizes. Transportation using trucks generally consumes energy in the form of diesel and releases CO_2 emissions. The transportation requirements for the case study are listed in Table 10, along with the travel distances. The distance traveled from the manufacturing plant to the local distributor plus the distance from distributor to the project site is taken as the total distance covered by a truck to deliver the pipe on the project site. The emission calculator has a provision to quantify emissions

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J. Manage. Eng., 2012, 28(1): 22-30

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Table 9. Total Emissions per Pipe-Break Repair (kg of CO_2)

Nominal pipe size (mm)	Length of clamps (mm)							
	152.4	190.5	254	317.5	381	508	609.6	762
50.8	37.12	37.12	39.59	39.59	44.54	Not applicable	Not applicable	Not applicable
76.2	37.12	39.59	39.59	42.07	49.49	Not applicable	Not applicable	Not applicable
101.6	39.59	42.07	44.54	47.02	51.97	61.87	66.82	79.20
152.4	Not applicable	44.54	49.49	51.97	61.87	69.29	79.20	94.05
203.2	Not applicable	47.02	51.97	54.44	64.34	74.25	86.62	101.47
254	Not applicable	54.44	61.87	66.82	86.62	96.52	106.42	131.18
304.8	Not applicable	59.39	66.82	71.77	94.05	101.47	116.32	146.03

Table 10. Transportation Requirements for Case Study

Truck					Activity			
Name	Model	Model year	GVW or class	Mileage (km)	Name	One-way distance (km)	Return distance (mi)	Trips
Transport	Peterbilt	2009	Class 8A	48,280	Transporting equipment	32	32	1
Transport	Sterling	2008	Class 8A	72,420	Transporting pipe spools	603[a]	0	1
Haul truck	Sterling	2007	Class 8A	72,420	Hauling excavations	16	16	3

[a] The one-way distance between the manufacturing plant storage and storage construction site is assumed to be 603 km for all plastic and ductile iron pipes, assuming that the manufacturing plants are located near Los Angeles. This assumption is made for consistency among all pipe materials when estimating CO_2 emissions and does not indicate that there really is a ductile iron pipe manufacturing plant in Los Angeles.

resulting from transportation trucks. Heavier pipes such as ductile iron consume more fuel in transportation than the other pipes. Consequently, a load factor for the transportation trucks was estimated using the following equation [Eq. (9)]. It is assumed that the value in the denominator of Eq. (9) is approximately equal to the gross vehicle weight (GVW). Table 11 presents the emissions generated from the transportation trucks for the distances specified in Table 10.

$$\text{Load factor}_i(\%) = \frac{\text{Weight of empty truck} + \text{Weight of pipes}_i}{\text{Weight of empty truck} + \text{Maximum }(\text{Weight of pipes}_i)} \tag{9}$$

where i = either of PVC-O, PVC, HDPE or ductile iron.

Table 11. CO_2 Emissions from Transportation Activities

Pipe	CO_2 emissions (kg) (100% load)	Weight of pipe (kg)	Load factor (%)	CO_2 emissions (kg)
PVC-O	707.6	1,247.4	0.82	581.07
PVC	707.6	2,630.8	0.89	630.54
HDPE	707.6	2,288.4	0.87	618.30
Ductile iron	707.6	4,785.4	1.00	707.60

End-of-Life Phase

After the pipe's life cycle, the pipe is disposed, recycled, or abandoned. All the materials considered in this research are recyclable materials. Discussions with various contractors revealed that water pipes are generally abandoned because of the resources required to unearth the pipe. Considering that a lot of energy needs to be spent on trenching the cover above the pipe to be able to recycle, it is assumed in this research that the pipes are abandoned after their life period usage. Currently, this is the most common practice in the water industry.

Life-Cycle CO_2 Emissions

The CO_2 emissions from different phases of the life cycle have been added. Table 12 presents the total life-cycle emissions from the project in the case study for the different pipe materials considered. The life-cycle CO_2 emissions ranged from 1,463.23 t to 1,524.98 t, depending on the pipe material chosen. Table 12 shows that ductile iron pipe results in a 4.22% (61.75 t) increase in life-cycle CO_2 emissions compared to the PVC-O pipe type. Fig. 3 compares the total life-cycle emissions for different pipe materials considered in the case study. The pumping-energy phase is a dominant contributor to the CO_2 emissions, as can be observed from Table 12. The pumping phase is the cause of 97.7%–98.6% of the emissions. The installation and transportation phases contribute very little to the CO_2 emissions compared to the pumping phase; however, accounting for all the phases completes the life-cycle emissions estimation.

Table 12. Life-Cycle CO_2 Emissions of Project in Case Study (kg)

Life-cycle phase	PVC-O	PVC	HDPE	Ductile iron
Embodied energy	16,951.00	30,463.76	26,604.35	28,261.13
Pipe installation	2,830.40	2,830.40	2,830.40	2,830.40
Usage phase	1,442,866.99	1,457,143.65	1,491,287.74	1,493,177.70
Transportation	581.07	630.54	618.30	707.60
Total	1,463,229.45	1,491,068.35	1,521,340.78	1,524,976.83

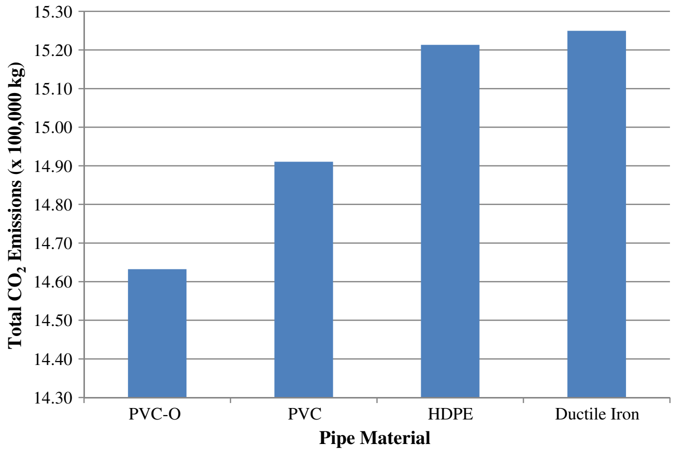

Fig. 3. Comparison of life-cycle emissions from different pipe materials

Pumping energy is the biggest and dominant contributor to the CO_2 emissions in the life cycle of a water pipeline. Consequently, much focus and attention needs to be devoted to making pumps more efficient. The pumps need to be designed optimally after the demands in the system have been estimated as accurately as possible. The power required to drive a pump depends on the flow rate and pressure head. The energy required to drive the pumps also depends on the amount of use time. The CO_2 emissions increase with the increase in the flow rate, the pressure head, and/or the use time. From a sustainability point of view, it is also important to develop strategies to conserve water and use it sustainably. This will reduce the demand on the water that needs to be pumped, and thus will reduce the emissions.

The design life of each pipe type is made consistent in this research for easy comparison. However, in reality certain pipe types last longer than others, and such long-lasting pipes would be beneficial in the long run. To estimate the benefits with regard to emissions from such long-lasting pipes, the analysis period has been extended to 100 years. Each pipe type is assumed to last for 100 years in different scenarios, whereas the other pipe types last only 50 years. One scenario will have the PVC-O pipe last 100 years; the other pipe types need to be replaced after 50 years. There are four such scenarios included in the analysis, and the total emissions from each scenario are illustrated in Fig. 4. The design life of the pipe types in each scenario is presented in Table 13. It can be observed from Fig. 4 that PVC-O pipe would result in smaller emissions, even in scenarios in which it lasts only 50 years. After the PVC-O pipe type, the PVC pipe type results in the smallest emissions. This analysis tool in addition to the cost information should help utility managers make decisions that are sustainable.

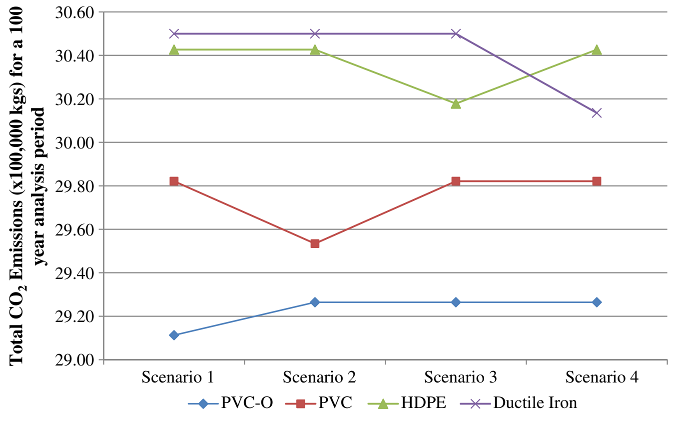

Fig. 4. Comparison of emissions if each pipe type were to last 100 years in different scenarios

Table 13. Design Life of Pipe Types in Different Scenarios (Years)

Scenario	PVC-O	PVC	HDPE	Ductile iron
1	100	50	50	50
2	50	100	50	50
3	50	50	100	50
4	50	50	50	100

Conclusions and Recommendations

A methodology is presented to quantify CO_2 emissions from different life-cycle phases of an underground potable water pipeline project. Different approaches were taken for different phases of the life cycle. The input information for the developed tool is taken from different AWWA pipe standards and based on discussions with contractors. The estimated potential generated emissions during the design phase of the project would help decision makers such as municipalities, contractors, and engineers choose environmentally friendly alternatives.

The methodology is demonstrated using a case study of a 152.4-m (500-ft), 200-mm (8-in.)-diameter potable water line at 1.22-m (4-ft) depth. Four different pipe materials, PVC-O, PVC-U, HDPE, and ductile iron, are considered as alternatives for the pipe design. A life-cycle period of 50 years is considered in this research for all the pipe materials considered. The results indicate that the life-cycle emissions in the case study range between 1,463.23 and 1,524.98 t, depending on the pipe material chosen. On the basis of the amount of CO_2 emissions, the PVC-O pipe was found to be relatively environmentally friendly, whereas the ductile iron pipe was the least environmentally friendly in the class of materials considered. The choice of ductile iron pipe in the case study would result in 4.22% more emissions than the PVC-O pipe. It is clearly evident from the results that pumping energy contributes the most to CO_2 emissions in the entire life-cycle process, ranging from 97.7 to 98.6%, which is in agreement with Recio et al. (2005).

The procedure presented in this research can be applied to any water pipeline project to understand the resulting life-cycle emissions. This research could be used as a managerial-decision support tool for utility projects. The writers feel that the results of such a tool are only as accurate as the input data. It is recommended that field studies be conducted in the future to acquire the necessary data and reduce reliance on the assumptions made in this research. Estimating the emissions is the first step in curbing them. The EPA (2002) estimated a huge investment in the drinking-water industry before 2019; consequently, it is important to take measures to use energy efficiently and reduce the emissions associated with water systems. Many countries have set their own CO_2 emission targets. This methodology helps policy makers to monitor the carbon footprint resulting from water pipeline projects.

Acknowledgments

This research was sponsored in part by the Sustainable Infrastructures for Energy and Water Supply grant (#0836046) from the National Science Foundation Division of Emerging Frontiers in Research and Innovation (EFRI), Resilient and Sustainable Infrastructures (RESIN) program.

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Notation

The following symbols are used in this paper:

CIPP = cured-in-place pipe;
CO = carbon monoxide;
CO_2 = carbon dioxide;
HC = hydrocarbon;
HDPE = high-density polyethylene pipe;
hp = horsepower;
MJ = million joules;
NO_x = nitrogen oxides;
PM = particulate matter;
PVC = polyvinyl chloride pipe;
SO_x = sulfur oxides;
PVC-O = molecular-oriented polyvinyl chloride pipe; and
Tg = teragram.

References

Alcorn, A. (2003). "Embodied energy and CO_2 coefficients for NZ building materials." *Centre for Building Performance Research Report*, Centre for Building Performance Research, Wellington, New Zealand.

Ambrose, M. D., Salomonsson, G. D., and Burn, S. (2002). "Piping systems embodied energy analysis." *CMIT Doc. No. 02/302*, CSIRO Manufacturing and Infrastructure Technology (CMIT), Highett, Australia.

Ariaratnam, S. T., Botteicher, R. B., Ghosh, A., Piratla, K. R., and Vilfrant, E. (2009). "Predictive modeling of installation loads for directional drilled fusible PVC pipe." *Tunnelling and Underground Space Technol.*, 25(6), 766–772.

Ariaratnam, S. T., and Sihabuddin, S. S. (2009). "Comparison of emitted emissions between trenchless pipe replacement and open cut utility construction." *J. Green Build.*, 4(2), 126–140.

Bennett, D., and Ariaratnam, S. T. (2008). "Horizontal directional drilling good practices guidelines," 3rd Ed., *HDD Consortium*, North American Society for Trenchless Technology, Arlington, VA.

Colombo, A. F., and Karney, B. W. (2002). "Energy and costs of leaky pipes: Toward comprehensive picture." *J. Water Resour. Plann. Manage.*, 128(6), 441–450.

Dandy, G., Roberts, A., Hewitson, C., and Chrystie, P. (2006). "Sustainability objectives for the optimization of water distribution networks." *Proc., WDSA 2006*, ASCE, Reston, VA, 1–11.

Dennison, F. J., Azapagic, A., Clift, R., and Colbourne, J. S. (1998). "Assessing management options for wastewater treatment works in the context of life cycle assessment." *Water Sci. Technol.*, 38(11), 23–30.

Dennison, F. J., Azapagic, A., Clift, R., and Colbourne, J. S. (1999). "Life cycle assessment: Comparing strategic options for the mains infrastructure—Part I." *Water Sci. Technol.*, 39(10–11), 315–319.

Electric Power Research Institute (EPRI). (2002). "U.S. electricity consumption for water supply and treatment—The next half century." *Water and Sustainability: Technical Rep. No. 1006787*, Vol. 4, EPRI, Palo Alto, CA.

Emmerson, R. H. C., Morse, G. K., Lester, J. N., and Edge, D. R. (1995). "The life-cycle analysis of small scale sewage-treatment processes." *J. Inst. Water Environ. Manage.*, 9, 317–325.

Filion, Y. R., MacLean, H. L., and Karney, B. W. (2004). "Life-cycle energy analysis of a water distribution system." *J. Infrastruct. Syst.*, 10(3), 120–130.

Ghimire, S. R., and Barkdoll, B. D. (2007). "Incorporating environmental impact in decision making for municipal drinking water distribution systems through eco-efficiency analysis." *Proc., EWRI 2007*, ASCE, Reston, VA, 1–10.

Kleiner, Y., Adams, B. J., and Rogers, J. S. (1998). "Long-term planning methodology for water distribution system rehabilitation." *Water Resour. Res.*, 34(8), 2039–2051.

Kleiner, Y., and Rajani, B. (1999). "Using limited data to assess future needs." *J. Am. Water Works Assoc.*, 91(7), 47–61.

Kleiner, Y., and Rajani, B. (2001). "Comprehensive review of structural deterioration of water mains: Statistical models." *Urban Water*, 3(3), 131–150.

Lamont, P. A. (1981). "Common pipe flow formulas compared with theory of roughness." *J. Am. Water Works Assoc.*, 73(5), 274–280.

Lundin, M., Bengtsson, M., and Molander, S. (2000). "Life cycle assessment of wastewater systems: Influence of system boundaries and scale on calculated environmental loads." *Environ. Sci. Technol.*, 34(1), 180–186.

Racoviceanu, A. I., and Karney, B. W. (2010). "Life-cycle perspective on residential water conservation strategies." *J. Infrastruct. Syst.*, 16(1), 40–49.

Raluy, G., Serra, L., and Uche, J. (2006). "Life cycle assessment of MSF, MED, and RO desalination technologies." *Energy*, 31(13), 2361–2372.

Recio, J. M. B., Guerrero, P. J., Ageitos, M. G., and Narváez, R. P. (2005). "Estimate of energy consumption and CO_2 associated with the production, use and disposal of PVC, HDPE, PP, ductile iron and concrete pipes." *Rep. PVC-Tub-200512-2*, Universitat Politècnica de Catalunya, Barcelona, Spain.

Salem, O., AbouRizk, S., and Ariaratnam, S. (2003). "Risk-based lifecycle costing of infrastructure rehabilitation and construction alternatives." *J. Infrastruct. Syst.*, 9(1), 6–15.

Savic, D. A., and Walters, G. A. (1997). "Evolving sustainable water networks." *Hydrol. Sci. J.*, 42(4), 549–564.

Shamir, U., and Howard, C. D. D. (1979). "An analytic approach to scheduling pipe replacement." *J. Am. Water Works Assoc.*, 71(5), 248–258.

Sharp, W. W., and Walski, T. M. (1988). "Predicting internal roughness in water mains." *J. Am. Water Works Assoc.*, 80(11), 34–40.

Sihabuddin, S. S., and Ariaratnam, S. T. (2009). "Methodology for estimating emissions in underground utility construction operations." *J. Eng. Des. Technol.*, 7(1), 37–64.

Skipworth, P., Engelhardt, M., Cashman, A., Savic, D., Saul, A., and Walters, G. (2002). *Whole life costing for water distribution network management*, Thomas Telford, London.

Stokes, J., and Horvath, A. (2005). "Life cycle energy assessment of alternative water supply systems." *Int. J. Life Cycle Assess.*, 11(5), 335–343.

Treloar, G. J. (1994). "Energy analysis of the construction of office buildings." M.Arch. thesis, Deakin Univ., Geelong, Australia.

U.S. Energy Information Administration (EIA). (2009). "Independent statistics and analysis." ⟨http://www.eia.doe.gov/cneaf/electricity/epm/table1_1.html⟩ (Oct. 29, 2010).

U.S. EPA. (2002). "The clean water and drinking water infrastructure gap analysis." *EPA-816-R-02-020*, Washington, DC.

U.S. EPA. (2009). "eGRID2007 Version 1.1 state file (year 2005 data)." ⟨http://www.epa.gov/cleanenergy/egrid/index.htm⟩.

U.S. EPA. (2010). "Inventory of U.S. greenhouse gas emissions and sinks: 1990–2008." *EPA 430-R-10-006*, Washington, DC.

Venkatesh, G., and Brattebo, H. (2011). "Energy consumption, costs and environmental impacts for urban water cycle services: Case study of Oslo (Norway)." *Energy*, 36(2), 792–800.

Venkatesh, G., Hammervold, J., and Brattebo, H. (2009). "Combined MFA-LCA for analysis of wastewater pipeline networks: Case study of Oslo (Norway)." *J. Ind. Ecol.*, 13(4), 532–550.

Vidal, N., Poch, M., Marti, E., and Rodriguez-Roda, I. (2002). "Evaluation of the environmental implications to include structural changes in a wastewater treatment plant." *J. Chem. Technol. Biotechnol.*, 77(11), 1206–1211.

Walski, T. M., and Pelliccia, A. (1982). "Economic analysis of water main breaks." *J. Am. Water Works Assoc.*, 74(3), 140–147.

Wu, W., Maier, H. R., and Simpson, A. R. (2010). "Single-objective versus multi-objective optimization of water distribution systems accounting for greenhouse gas emissions by carbon pricing." *J. Water Resour. Plann. Manage.*, 136(5), 555–565.

Zhang, Z., and Wilson, F. (2000). "Life cycle assessment of a sewage treatment plant in South-East Asia." *J. Inst. Water Environ. Manage.*, 14(1), 51–56.