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Evaluation of Carbon Footprint During the Life-Cycle of Four Different Pipe Materials

Alhossin Alsadi
Louisiana Tech University

EVALUATION OF CARBON FOOTPRINT DURING THE LIFE-CYCLE OF FOUR DIFFERENT PIPE MATERIALS

by

Alhossin Alsadi, B.S., M.S.

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ABSTRACT

As the world is moving to provide a better and cleaner environment for future generations, there is a critical need to quantify and try to reduce the environmental emission footprints of various industries. The construction industry, which emits a large amount of carbon dioxide (CO_2), is one of the targeted industries to decrease these emissions. Underground utility installations, especially in the development of residential communities in urban areas, are one of the largest construction projects across North America and, consequently, one primary source of emissions. Most of the pipelines in the U.S. are rapidly reaching the end of their useful service life. Now they need replacing or rehabilitating. In general, the selection of a pipeline installation method is currently solved by selecting the lowest cost method. However, with an increase in the public concerns about reducing emissions into the environment generated by human activities, other factors should be taken into account while choosing the pipe material and the installation method for a new pipeline; namely social cost, and environmental impact. The common three greenhouses gases (GHG) are CO_2, methane (CH_4), and nitrous oxide (N_2O). CO_2 is the GHG responsible for the greatest amount of environmental impact.

This parametric study and analysis focuses on the environmental impact (quantitative analysis the CO_2 emissions) for different pipeline materials during the life-cycle of pipeline and develops a framework which will help engineers and decision-makers to choose the most environmentally friendly pipe material with low emission installation or rehabilitation methods. The life-cycle of a pipeline can be categorized into four phases: fabrication, installation, operation, and disposal. This study focuses on four commonly used types of pipe and liners: pre-stressed concrete cylinder pipe (PCCP), polyvinyl chloride (PVC) pipe, cured-in-place pipe (CIPP) liner, and high-density polyethylene (HDPE). The energy consumed in the fabrication phase includes base material extraction, material production material processing, and pipe manufacturing. The major construction activities in the installation stage are transporting pipes and equipment to a job-site, excavation, loading, backfilling, compaction, and repaving. For this study, the pipeline installation analysis and consideration of CO_2 emissions have been made for three different installation methods: open cut with PCCP, pipe bursting with PVC and HDPE, and CIPP lining. The energy consumed in the operation phase includes pumping energy and pipe cleaning for maintenance. For the disposal phase, the study will consist of the energy consumed for disposing of the material of the pipes, which cannot be recycled. The objective of this study was to first quantify the carbon footprint, which has never been done for this application, and then to analyze the environmental sustainability of a 100-foot segment of pipeline during the installation, operation, and disposal phases. This study focused on a large-diameter 36-inch sewer pressure pipe operating at 100 psi internal pressure for 100-years life operation. The results show that the PVC pipe has the lowest environmental impact compared to PCCP, HDPE, or CIPP during the life-cycle of pipeline phases before and after the optimization.

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DEDICATION

I dedicate this dissertation to my loving parents Ahmed Alsadi and Salima Aljadar. I am eternally grateful for your unconditional love, unwavering support, and continuing motivation. Without you, this would not have been possible.

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Pipelines are one of the least understood and least appreciated modes for transport. The public poorly understands pipelines because they are mostly underground and invisible (out of sight, out of mind). Pipes are vitally important to the economy and security of most nations. All modern nations rely on the pipeline to transport water from treatment plants to individual homes, sewage from homes to treatment plants, natural gas all the way from wells to the consumers, crude oil from oil fields to refineries, and refined petroleum products from refineries to cities (Rui, 2011). In the United States, pipelines of various types transport a total of about 2.5 trillion ton-miles of cargo in liquid, gas, and solid form (Liu, 2003). The U.S. has a dense network of underground pipelines in every state and under every city. The pipes can be said to be the lifelines of modern nations (Liu, 2003).

The use of pipelines has a long history. For instance, more than a thousand years ago, the Romans used lead pipes in their aqueduct system to supply water to Rome. As early as 400 B.C., the Chinese used bamboo pipes wrapped with waxed cloth to transport natural gas to Beijing for lighting. In Egypt, clay pipes were used for drainage purpose as early as 4000 B.C. An essential improvement of pipeline technology occurred in the 18th century when cast-iron pipes were manufactured for use as water lines, sewer, and gas pipelines. A subsequent major event was the introduction of steel pipe in the 19th century, which significantly increased the strength of the pipes. In the 19th century, pipelines technology developed at an accelerated pace. The catalysts of this growth were the emerging oil industry, the distribution of natural gas, and the increasing need for steam and water. In 1979, after the discovery of oil in Pennsylvania, the first long-distance oil pipeline was built in the U.S.; it was a 6-inch diameter and 109-mile-long steel pipe. Nine years later, a 8-inch pipeline 87 miles long was constructed to transport natural gas from Kane, Pennsylvania to Buffalo, New York. In the late 1920s, the development of electric arc welding to pipe joints made the possibility to construct leak-proof, high-pressure, large diameter pipelines. Since 1950, significant innovations in pipeline technology have been made, including the introduction of new pipeline materials, such as large diameter concrete pressure pipe, ductile iron pipe, and polyvinyl chloride pipe (PVC). Catholic protection was applied to reduce the corrosion and extend pipeline life (Liu, 2003; Feo, 2014). Since 1970, significant strides have been made in pipeline technology, including trenchless construction (e.g., directional drilling, which allows the pipeline to be laid easily under rivers, lakes, and other obstacles without having to dig a long trench) (Liu, 2003). In the 20th century, pipe technology was poised for unprecedented growth due to improvements in welding, materials, and pumping. At the same time, standardization of materials and design become a financial and safety necessity, and industries came to rely more on codes and standards, while national engineering societies and industry institutes became more essential as source of innovation and improvement (Antaki, 2003).

In many developed countries, the engineered urban infrastructure is in crisis due to various factors, such as increasing populations and insufficient attention to maintenance and replacement of pipelines (Loss, 2016). Globally, increasing population and industrial growth are putting increased pressure on existing water and sewer infrastructure as is the effect of aging (Burian, 2000). Moreover, a major portion of the existing water and sewer infrastructure in North America are rapidly approaching the end of their useful service life, so they will need to be rehabilitated or replaced (Rehan, 2007). New pipelines are typically installed using open cut technology or trenchless technology (i.e., pipe jacking, horizontal directional drilling, horizontal auger boring, etc.) or rehabilitated with trenchless methods such as cured-in-place pipe (CIPP), slip-lining, or pipe bursting.

Urban water and wastewater system are fundamental infrastructures in the development of new residential and commercial areas, and as well are very important for high quality of life and strong urban economy. With ever-increasing population in urban areas, there is a crucial need to develop new lifelines as the municipal areas expand. Also, there is growing attention to consider different factors during replacing an aging pipeline, such as environmental, social cost, safety, etc. in the development of infrastructure (Monfared, 2018). There are an estimated 20 million miles of buried utilities in the U.S. This is approximately 80 times the distance from the earth to the moon (Anspach, 2010). Most of these utilities are nearing approaching the end of their designed life and some have even exceeded it (Joshi, 2012). There are more than one million miles of pipes in the U.S. that need to be replaced (AWWA, 2012). There is thus a global need to replace aging underground infrastructure, and this need, in turn, leads to a higher number of excavation related operations in the presence of existing buried utilities.

There are two aspects related to underground lifelines: installing new facilities and rehabilitating old underground utilities. As the world moves towards providing a better and cleaner environment for future generations, there is a significant need to quantify and reduce the carbon emissions footprint of industries. The construction industry, which emits a large amount of CO_2 , is one of the targeted industries to decrease these emissions. The construction sector accounts for nearly 40% of global GHG emissions, and the construction phase is typically assumed to account around a 1/10 of the overall emissions (Saynajoki, 2012). Which researchers point to evaluate proper alternative construction methods and materials to reduce their emissions. Underground utility installations, particularly in the development of residential communities in urban areas, are one of the largest construction projects across North America and consequently, they are one primary source of emissions (Monfared, 2018).

1.2 Objective of the Study

The objective of this parametric study and analysis is to determine the environmental impact (carbon footprint) during the life-cycle of the most commonly used pipeline materials over a 100-year-lifetime to determine the most environmentally friendly applicable material and develops a framework which will help the engineers and decision-makers to choose the most environmentally friendly pipe material with low emission installation methods. This study focuses on pressure sewer lines (force mains), and the pipeline materials included in this study are pre-stressed concrete cylinder pipe (PCCP), polyvinylchloride (PVC) pipe, high-density polyethylene (HDPE) pipe, and cured-in-place pipe (CIPP). This method developed in this study can be used for any other pipe material, pipe diameter, pipeline length and for any installation methods. This study can be used in the future as a technical support tool during the decision-making process of municipalities and consultants when selecting a replacement or rehabilitation method for an old pipeline. It is recommended however to include all three impact factors together (direct cost, social cost, and environmental impact) and not just one, which will help the engineers and decision-makers to select the pipeline material and installation method.

1.3 Thesis Organization

This dissertation is organized into six chapters: Chapter (1) Introduction, Chapter (2) Literature Review, Chapter (3) Fabrication Phase, Chapter (4) Installation Phase, Chapter (5) Operation and Disposal Phases, Chapter (6) Optimization of Carbon Emissions During the Pipeline Life-Cycle, Chapter (7) Conclusion and Recommendation for Future Study.

Chapter 1 - Introduction: This chapter provides a brief introduction about the study, the goals and objectives of the study, the thesis organization and key contributions are also described.

Chapter 2 - Literature Review: This chapter includes background related to the study, types of pipe, pipeline construction methods, sewer lines, pressure lines, greenhouse gases emissions, climate change, carbon footprint, direct/social cost, social cost of carbon, and previous studies on the environmental impact during the life-cycle of a pipeline.

Chapter 3 - Fabrication Phase: This chapter analyzes and compares CO_2 emissions during the fabrication phase associated with the four types of pipe: PCCP, PVC, HDPE, and CIPP, used for large-diameter 36-inch pressure sewer pipelines.

Chapter 4 - Installation Phase: This chapter discusses the second phase of the pipeline life-cycle (installation phase), and compares three common installation methods: open cut, pipe bursting, and CIPP lining during installation or rehabilitation of a 100-foot long pipe with a 36-inch diameter pipe at a 10-foot depth.

Chapter 5 - Operation and Disposal Phase: This chapter discusses the third and fourth phases of pipeline life-cycle (operation and disposal phases). This chapter includes the consumption of energy during wastewater pumping, pipeline cleaning maintenance, and energy for disposing of the pipe material at end of life.

Chapter 6 - Optimization of Pipeline Life Cycle Regarding the Carbon Emissions: This chapter presents an optimization process of carbon emissions of how to make improvements in each phase to reduce the carbon emissions during the life-cycle of the pipeline.

Chapter 7 - Conclusion and Recommendation for Future Study: This chapter summarizes the research approach and the findings of the study and make the recommendations for future research topics. Also, limitations of the study are defined.

1.4 Key Contributions

The main objective of this study is to make a quantitative analysis of the CO_2 emissions for different pipeline materials during the life-cycle of the pipeline. The study helps determine the environmental benefits of using the right pipeline materials. The main contributions of the work in this dissertation are described below:

1. Evaluated and compared the CO_2 emissions during the life-cycle phases for the four most used sewer pipe materials PCCP, PVC, HDPE, and CIPP.
2. Developed a technical support tool during the decision-making process for municipalities and consultants when selecting a replacement or rehabilitation method for the old pipeline to choose the most environmentally friendly pipeline material.
3. Development of carbon emissions mitigation scenarios during the installation and rehabilitation of the pipeline by giving recommendations for how utilities and engineers could optimize and reduce the carbon emissions.

CHAPTER 2

BACKGROUND AND LITERATURE REVIEW

This chapter consists of a review of findings from a comprehensive literature search conducted as part of this research. The literature review was used as one of the means to understand more about existing studies on this topic and to get more knowledge about the environmental impact on the pipeline life-cycle phases. Most carbon emissions studies to date are about buildings construction, but there are a few studies on pipeline life-cycle carbon emission life-cycle.

2.1 Background

2.1.1 Pipe Background

The role of pipelines initially was to transport waste materials away from inhabited areas to uninhabited areas. However, throughout time, the functions of pipes have changed drastically. As of today, the transportation of fluids in our society takes place via complex pipeline networks (Deshmukh, 2014). Now there are different types of pipelines that perform various functions, and pipelines can be categorized in many ways, depending on the pipe material, commodity transported, where the pipe will be used (environment), and type of burial or support (Liu, 2003).

The conventional method of pipeline construction for replacement or repair has been open-cut or trenching. Based on the type of work, these methods are called dig-and-install, dig-and-repair, or dig-and-replace. The open-cut method includes digging the trench along the length of pipeline proposed, placing the pipe in the trench on suitable bedding materials, and then backfilling. Most of the times, the construction effort is concentrated on such activities as detour roads, management of traffic flow, dewatering, bypass pumping system, and reinstatement of the surface. Advancements in technology and improvements in getting geotechnical data and development of new equipment have led to improved pipe installation methods. These techniques are called trenchless technology (TT) installation and renewal (Najafi, 2005). Trenchless technologies are effective alternatives to traditional open trench construction as these methods offer less trench and less footprint, and they are environmentally friendly (Monfared, 2018). Figure 2-1 shows the trenchless technology methods.

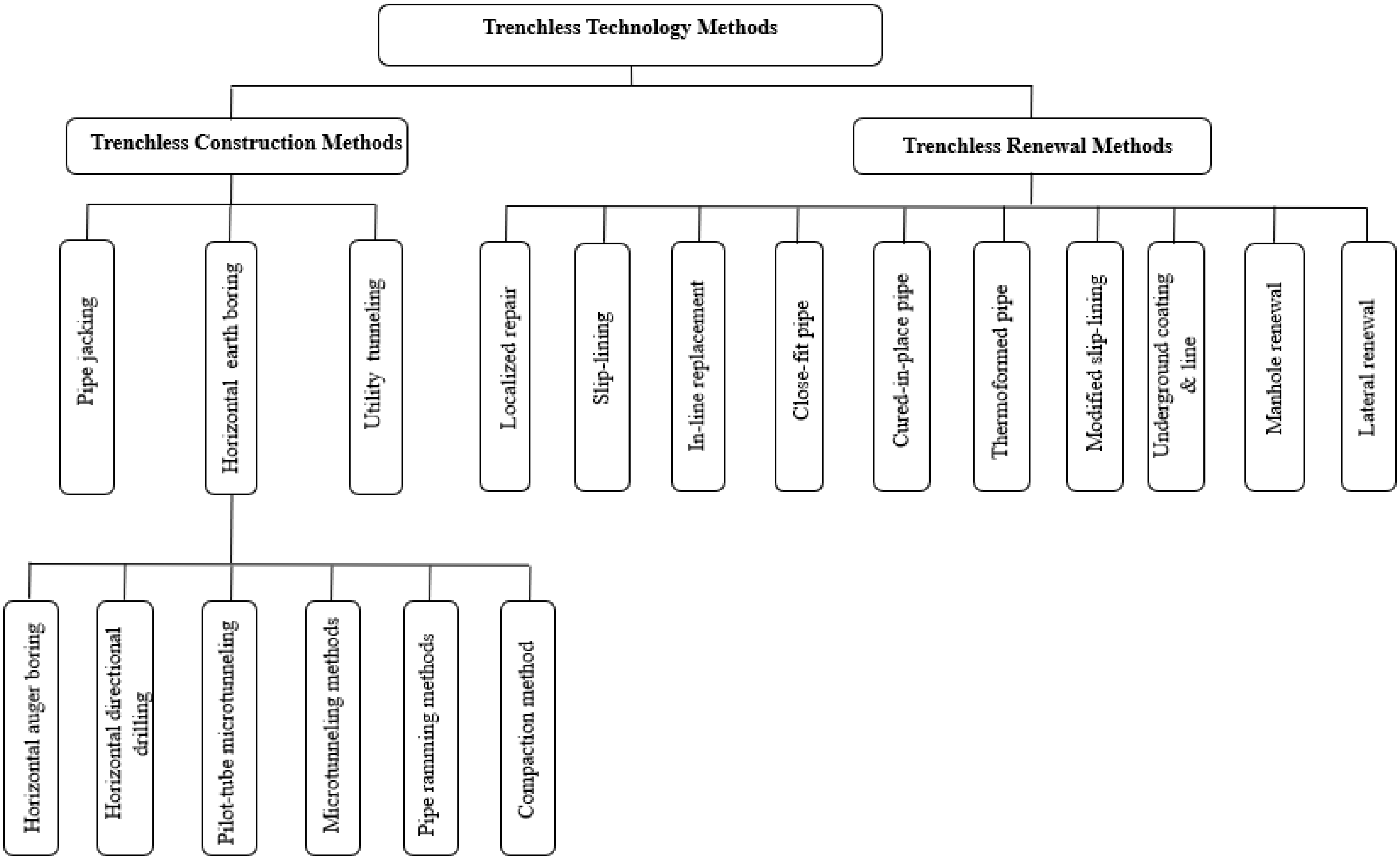


Figure 2-1 Pipeline Construction Methods (Trenchless Technology Methods)

The North American Society for Trenchless Technology (NASTT) defines trenchless technology methods as a family of methods, materials, and equipment capable of the installation of new lines, replacing old lines, or rehabilitating existing underground infrastructure with minimal disruption to the surface, business, and other activities. Trenchless technology methods have many advantages such as (Monfared, 2018):

- Minimal disruption to existing residential, business areas and environment.
- Low risk of interfering with existing pipeline and utilities.
- Safer working area for both workers and the community because of less requirement of openly exposed installation.

The sewer pipeline system is the basic urban infrastructure for public sanitation. The construction of the sewer line needs to invest a huge amount of money and labor (Kim, 2012). The U.S. has 1.2 million miles of water supply mains, and there are nearly an equal number of sewer pipes, 26 miles of sewer pipes for every mile of interstate highway (Bartlett, 2017). Now as a system across the country requires critical repairs and upgrades, the public does not understand that the complicated and expensive systems needed to deliver those services. No one can argue the importance of water and sewer services in maintaining public health, protecting the environment and promoting economic development. The value of these resources is not reflected in the nation's priorities.

There are several pipeline materials used in the sewer collection system, each one of them with unique characteristics used in different installation conditions. Most pipe materials used in sewer lines are ductile iron pipe, concrete pipe, plastic pipe, and vitrified clay pipe. There are some considerations to choose the pipe materials, and these considerations include trench condition, corrosion, temperature, safety requirement, and cost (EPA, 2000).

Force mains are pipelines that carry wastewater under pressure from the discharge side of a pump or pneumatic ejector to a discharge point. Pumps or compressors located in a lift station provide the energy for wastewater conveyance in force mains. The components of force mains are pipe, valves, pressure surge control devices, and force main cleaning system. Force mains are built from various materials and come in a wide range of diameters. The factors that impact the choice of the pipe material are: wastewater quantity and flow volume, operating pressure and pipe properties such as strength and corrosion resistance. Pipe size and wall thickness are determined by wastewater flow, operation pressure, and trench conditions (EPA, 2000).

The use of a pressure pipe can significantly reduce the size and depth of the sewer lines compared to gravity sewer lines and decrease the overall costs of sewer system construction. Typically, when gravity sewer lines are installed in trench deeper than 20-feet (6.1-meters), the cost of sewer line increases significantly because more complex and costly excavation equipment is required (EPA, 2000). The diameter of the pressure pipe usually is one to two sizes smaller than the diameter of the gravity sewer pipe conveying the same flow. The installation of the pressure lines is simple because of the shallower trenches and less earthwork compared to the gravity lines. The installation of a pressure pipe is not dependent on site-specific topographic conditions and is not impacted by open terrain slope, which typically limits to gravity lines (EPA, 2000).

2.1.2 Greenhouse Gases Emissions (GHG)

Climatologists believe that increasing atmospheric concentration of carbon dioxide and other GHG released by human activities are warming the earth (Latake, 2015). The mechanism is generally known as the "greenhouse effect" is what makes the Earth habitable. The human activities have changed the chemical composition of the atmosphere through the buildup of greenhouse gases primarily. These gases in the atmosphere act like the glass of a greenhouse, allowing the sunlight in and blocking heat from escaping (Latake, 2015). The common three GHG are CO_2, methane (CH_4), and nitrous oxide (N_2O). CO_2 is the GHG responsible for the greatest amount of warming. CO_2 accounted for 82% of all human GHG emissions in the U.S in 2013 (Rudolph, 2016). The majority of CO_2 is released from fossil fuels, coal, oil, the gas used for electricity production, transportation, and industrial processes. Other important GHG include CH_4, N_2O, black carbon, and various fluorinated gases. Although these gases are emitted in a smaller amount to the atmosphere compared to CO_2, they trap more heat in the atmosphere than CO_2 does (Rudolph, 2016). Table 2-1 shows a summary of the GHG emissions (adopt from Rudolph, 2016).

Table 2-1 Summary of Greenhouse Gas Emissions

Name	Percentage of U.S. GHG emissions	Sources	Lifetime in the atmosphere
CO_2	82%	Industrial processes, transportation, electricity production	50 to 200 years
CH_4	10%	Livestock manure, food decomposition; extraction and use of natural gas	12 years
N_2O	5%	Vehicle, power plant emissions	115 years
Black carbon	less 1%	Diesel engine, wildfires	Days to week
Fluorinated gases	less 5%	Synthetic pollutions found in coolant, aerosols, pesticides, solvents, fire extinguishers.	PECs: 2600 to 50,000 years HFCs: 1 to 270 years NF3: 740 years SF6: 3200 years

Climate change is caused by a change in the earth's energy balance, the amount of energy come from the sun that enters the earth and is released back into space. Since the industrial revolution started 200- years ago, human activities added a large quantity of GHG into the earth's atmosphere. When the concentration of GHG is too high in the atmosphere, too much heat will be trapped, and because of that, the earth temperature rises (Rudolph, 2016). The United States is already experiencing the effects of climate change, and these effects will be much worse without taking action sharply to reduce our global warming emissions. The average U.S. temperature has already increased by 2˚F over the last 50 years and is expected to increase another 7˚F to 11˚F under high emissions scenario by the end of this century, or 4˚F to 6.5˚F under a low emissions scenario as shown in Figure 2-3 (Karl, 2009).

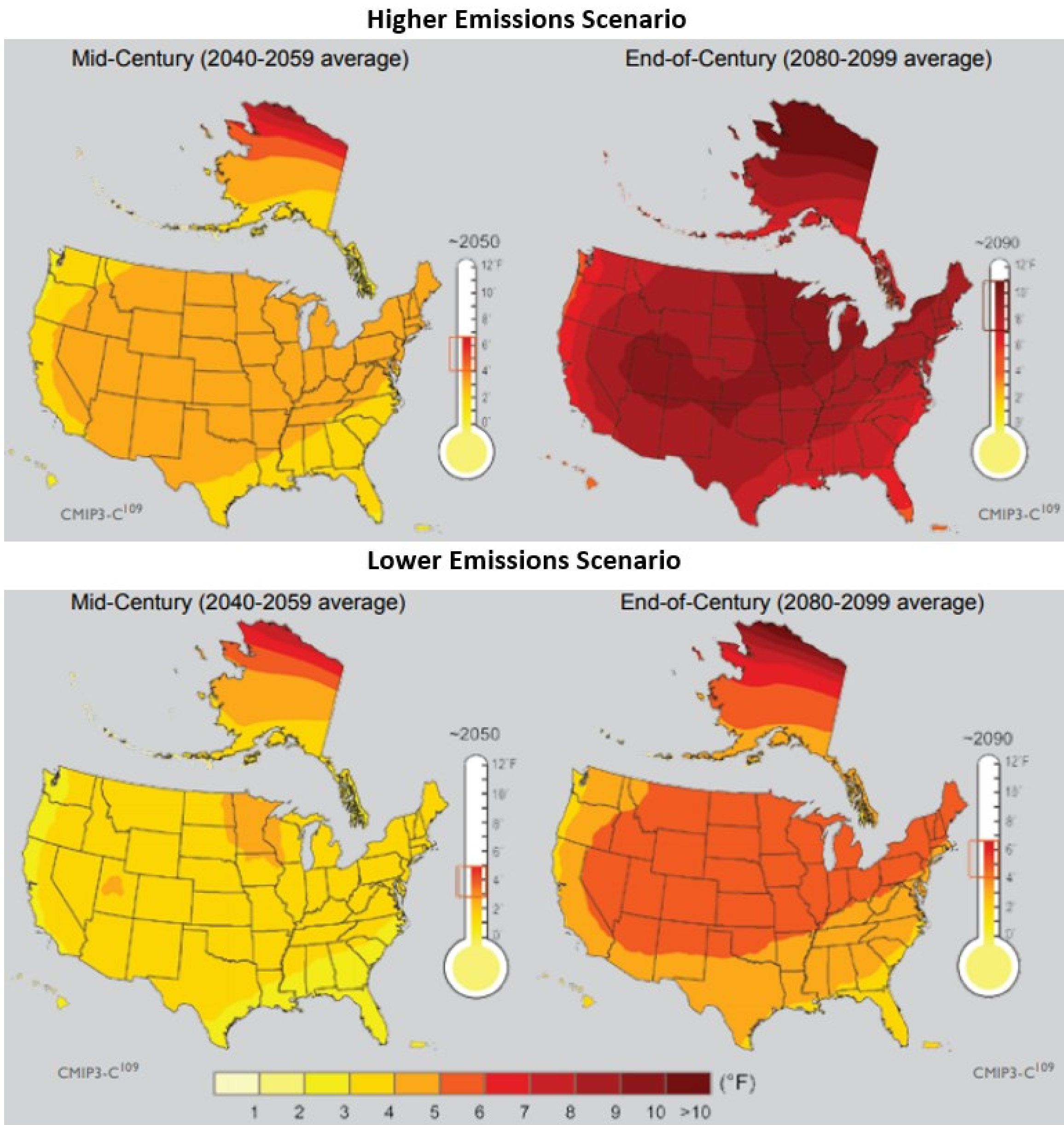


Figure 2-2 The Average of U.S. temperature in Higher and Lower Scenario at the mid-century and end-century

One-sixth of the population in the U.S. (53 million people) lives in the coastal States of the northeast (Union of Concerned Scientists, 2009). Most of the U.S coast has seen rising sea levels over the past 50 years, and that rising will likely continue under a warming climate. A two-foot rise in global sea levels by the end of this century would mean that the ocean would rise another 2.3-feet at New York City, 2.9-feet at Hampton Roads, VA, 3.5- feet at Galveston, TX, and one-foot at Neah Bay, WA. These changes will have serious economic consequences for coastal communities (Karl, 2009). If global warming emissions continue to rise unabated, we will see growing costs related to climate change.

Reacting to the concerns that human activities are increasing concentrations of GHG emissions (such as CO_2 and CH_4) in the atmosphere, most nations of the world joined together in 1992 to sign the United Nation Framework Convention on Climate Change (UNFCCC). The United States was one of the first nations to ratify this treaty. It included a legally non-binding, voluntary pledge that the major industrialized/developed countries would reduce their GHG emissions to 1990 levels by the year 2000, and that all nations would undertake voluntary actions to measure, report, and limit GHG emissions. Negotiations started on a protocol to establish legally binding limitations or reductions in GHG emissions. The countries decided that this round of negotiations would establish limitations only for the developed countries. The Kyoto Protocol was opened for signature March 16, 1998 and entered into force February 16, 2005. On November 12, 1998, the United States signed the Protocol, and in 2001, early in his first term, President George W. Bush rejected the Kyoto Protocol, and U.S. policy has disengaged from formal negotiations on the Protocol (Fletcher, 2005).

Figure 2-4 shows some of the projected damages to our coasts, health, energy and water resources, agriculture, infrastructure, and recreational resources. Choosing to lower our greenhouse gas emissions at least 80% from the 2005 level by 2050 will help to avoid some of the worst consequences of climate change (Union of Concerned Scientists, 2009).

Figure 2-3 The Impacts of Climate Change on the United States

The term carbon footprint is commonly used to explain the total of CO_2 and other GHG in a year generated by an organization, event or product (Khan, 2015). The carbon footprint has become a tremendously popular and widely used term over the last few years. With climate change, carbon footprint calculations are in strong demand. The carbon footprint is a measure of the exclusive total amount of CO_2 emissions that is directly and indirectly caused by an activity or is accumulated over the life stage of a product, and this includes activities of individuals, populations, governments, companies, organizations, industry sectors, etc. All direct carbon emissions (on-site, internal) and indirect carbon emissions (off-site, external, embodied) need to be taken into account (Wiedmann, 2008).

A significant quantity of CO_2 is emitted into the atmosphere through the different phases of a construction life-cycle: in the production of materials and products, in the construction phase, in the operation and rehabilitation, and up to the final demolition. The carbon emissions reduction in the construction of the pipe is perfectly feasible by using environmentally friendly materials with the low emission installation method (Gonzalez, 2006).

2.1.3 Cost Factors

The total cost of every pipeline construction project varies from project to project with many factors such as pipe size, pipe materials, depth and length of installation, subsurface conditions, project site, and type of pipeline construction method (Najafi, 2005). The total cost of the project is called direct cost. Currently, these impacts are only considered either qualitatively by a municipal decision maker based on prior experience or quantitatively through basic preliminary studies which are limited to an evaluation of a few of the actual impacts that are attributable to the project. As society strives to achieve social, economic and environmental sustainability, it is essential that the indirect and external costs be considered to help minimize the total social burden of buried municipal infrastructure (Najafi, 2005).

There is a study covered a cost analysis for two installation methods, pipe bursting and open-cut methods, the study provides a basis for cost comparison of pipe bursting as trenchless technology and traditional open-cut method. The study included a case study as an example of a cost comparison for replacing sewer pipeline in the city of Troy, Michigan. The results of the study found that the pipe bursting method is much less expensive than the open-cut method for replacing the underground sewer pipelines. Also, the results from the case study found that the cost of installation per-inch-per-foot of both methods, pipe bursting shows a cost of $11per-inch-per-foot while open-cut costs $18 per-inch-per-foot. Consequently, there is $7 per-inch-per-foot or about 40% saving by using pipe bursting (Hashemi, 2008). The cost range for CIPP method is from $100 per linear foot (perhaps less for large quantities) for 18-inch diameter pipe ($5.50 per-inch-per-foot) to $800 or more per linear foot for large-diameter pipe (Piehl,2005).

Communities that surround an operating construction site often found themselves subjected to negative impacts. Construction activities can have a significant effect on their surrounding environment, and the negative impacts are often called social cost as shown in Figure 2-5. Social cost, while widely acknowledged, is rarely considered in the design, planning, or bid evaluation phases of the construction project in North America. Social cost can range from costs associated with traffic conditions (e.g., delays and increased on vehicle operation expenses), environmental costs (e.g., pollution), costs resulting from decreased safety (e.g., higher rate of traffic accidents and risk to pedestrians), accelerated deterioration of road surfaces (e.g., due to pavement cuts), lower business turnovers, decreased property values, and damage to existing utilities (Matthews, 2014).

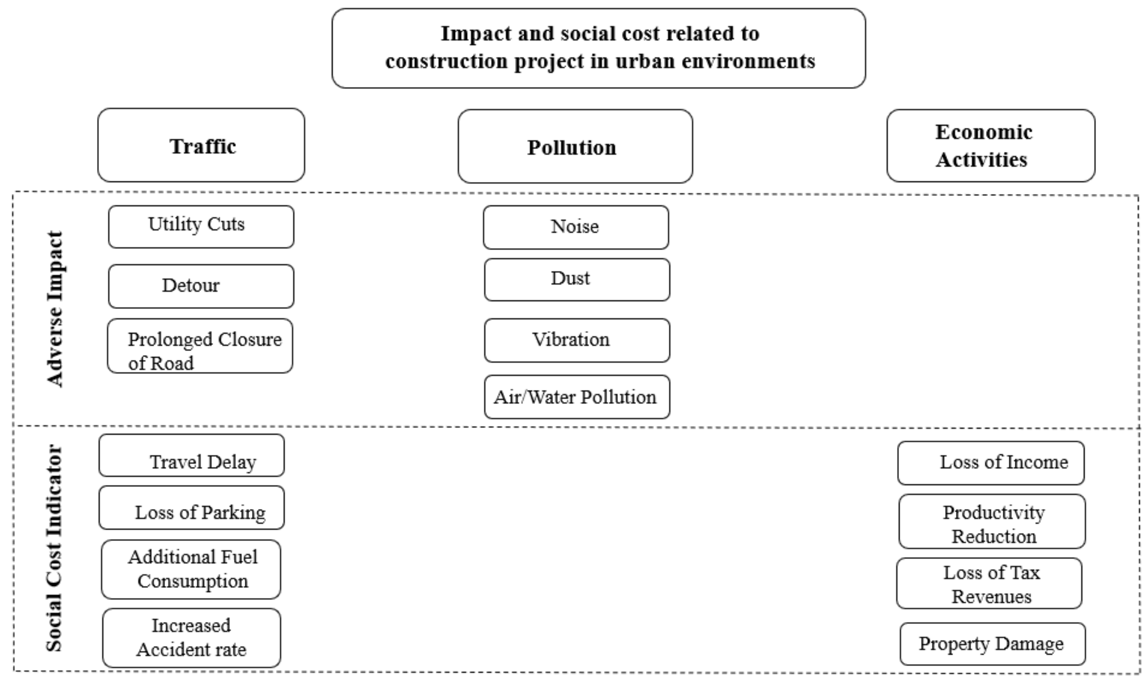


Figure 2-4 Breakdown of Potential Impacts and Social Cost Related to Construction Projects (Gilchrist, 2004)

The carbon price is based on the social cost of carbon (SC- CO_2) which generally refers to the cost to mitigate climate change or the marginal social damage from one ton of emitted carbon. However, the actual carbon price is often determined by the market value (Khan and Tee 2015). EPA and other federal agencies are using the estimates of the social cost of carbon to evaluate the climate impacts. The social cost of carbon is measured in dollars. The SC- CO_2 is meant to be a general estimate of climate change damages and includes, among other things, changes in net agricultural productivity, human health, property damages from increased flood risk and change in energy system costs, such as reduced cost for heating and increased costs for air conditioning. Estimates of the SC- CO_2 are a helpful measure to assess the climate impacts of CO_2 emissions change (EPA, 2016).

The British Columbia Chapter of the North America Society for Trenchless Technology in 2008, started a carbon calculator on the website to help companies to estimate the CO_2 emissions during pipeline construction methods (open-cut and trenchless construction methods), and demonstrate that the trenchless construction methods has substantially lower emissions than the open-cut construction method. To use the calculator, you input date about factors like surface conditions, length, and depth of backfill, and traffic flow. The calculation can be shown for open-cut, horizontal direction drilling (HDD), slip-lining, pipe bursting, and CIPP lining. This allows you to demonstrate the emissions for your trenchless method versus an open-cut method, and in British Columbia, the difference between the two can be used as a carbon credit. (*BC' Magazine for Trenchless Construction*, 2018)

Table 2-2 summarize the SC- CO_2 estimates for the years between 2010 to 2050. The central value is the average of SC- CO_2 estimates based on the 3 percent discount rate. For purposes of capturing uncertainty around the SC- CO_2 estimates in regulatory impact analysis, the interagency working group emphasizes the importance of considering all four SC- CO_2 values (TSD, 2016).

Table 2-2 Social Cost of CO_2 , 2010 to 2050 (in 2007 dollars per metric ton of CO_2)

Year	5% discount rate average	3% discount rate average	2.5% discount rate average	High impact at 3% discount rate
2010	10	31	50	86
2015	11	36	56	105
2020	12	42	62	123
2025	14	46	68	138
2030	16	50	73	152
2035	18	55	78	168
2040	21	60	84	183
2045	23	64	89	197
2050	26	69	95	212

One of the most important factors affecting SC- CO_2 estimates is the discount rate. To understand the effect that the discount rate has on present value calculation, consider the following example. Let's say that you have been promised that in 50 years you will receive $1 billion dollars (EPA, 2016). In current value terms, that sum of money is worth 291 million dollars today with a 2.5 percent discount rate. In other words, if you invested 291 million dollars today at 2.5 percent and let it compound, it would be worth 1 billion dollars in 50 years. A higher discount rate of 3 percent would reduce the value today to 228 million dollars, and the value would be even lower at 87 million dollars with a 5 percent discount rate. The value of 1 billion dollars in 100 years is 85 million, 52 million, and 8 million, for discount rates of 2.5, 3, and 5 percent, respectively (EPA, 2016).

2.2 Previous Research Related to Carbon Footprint in Pipeline Construction Project

A significant quantity of CO_2 is emitted into the atmosphere through the different phases of the construction life-cycle (Gonzalez, 2006). Few studies, however, have been conducted on pipeline carbon emissions (Chilana, 2016). Life-cycle assessments (LCA) have been primarily used to assess environmental performance (Piratla, 2012). The literature provides some examples of studies that have explored the life-cycle aspects of pipe pipeline.

Du researched to compared six types of pipe material regarding global warming potential (GWP) through four life-cycle phases: pipe production, transport, installation, and use. The six pipe materials were PVC, ductile iron pipe (DIP), cast iron pipe (CIP), HDPE, concrete pipe (CP), and reinforced concrete (RCP). LCA results in this study showed that the concrete pipe has the lowest GWP across the entire range of pipe size investigated. For pipe diameters less than or equal to 24 in, the ductile iron pipe was the highest GWP among the others, and for pipe diameters greater than or equal to 30 in, the GWP of PVC was the highest (Du, 2013).

Piratla's study demonstrated a model for estimating the life-cycle emissions for a water pipeline of a pipe with an 8-inch diameter and 500-feet in length, with a 50 years' life-cycle period considered for this research, four different pipe materials were used in the study: molecular-oriented PVC (PVC-O), PVC, HDPE, DIP. The results of this study indicate that PVC-O provides the best environmental saving compared to other pipe materials in the study (Piratla, 2012).

Chilana's research analyzed and compared the CO_2 footprint of two pipeline materials used for large diameter water transmission pipelines, steel pipe (SP) and PCCP, for 150-miles of a pipeline of different large diameters (66, 72, 84 and 108-inch), and the installation method was open-cut construction method. Three life-cycle phases were considered: fabrication, installation, and operation. The result found that pipe manufacturing consumed a large amount of energy and thus contributed more than 90% of life-cycle carbon emissions for both pipes. SP had 64% larger CO_2 emissions from manufacturing compared to PCCP. For the transportation stage, PCCP had larger CO_2 emissions due to the heavy weight of the PCCP pipe. In this study, fuel consumption by construction equipment for installation of pipe in the trench was found to be similar for both PCCP and SP. Overall, PCCP was found to have smaller carbon footprint emissions due to the greater energy used during manufacturing of SP (Chilana, 2016).

Khan and Tee (2015) analyzed the life-cycle assessment of underground gravity and pressured pipeline between SP, DIP pipe and PVC, for 5000-feet long with a 15.7-inch diameter. The results indicate that PVC emitted less carbon compared to SP and DIP.

Kyung did a study to estimate the total (GHG) emissions for whole life-cycle stages of the sewer pipeline system for pipeline materials, PVC, polyethylene (PE), CP, and CIP. The results show that the CP generated less amount of GHG than pipes made from other materials (Kyung, 2017).

There is another study was funded by PVC pipe manufacturers. The study compared and evaluated the environmental impact for PVC pipe with other pipe materials (HDPE, DIP, and PCCP) during 100 years of the life-cycle. Their result founded that PVC pipe has the lowest carbon footprint when compared to most other pipe materials for pressure and gravity applications during the life-cycle of the pipeline phases: fabrication, installation, operation, and the end of life (Parvez, 2018).

For the installation phase of the pipeline life-cycle, Joshi did a study to compare between open-cut and pipe-bursting construction methods regarding the environmental aspect; the research is aimed at determining the CO_2 emission due to the use of the construction machinery as well as the CO_2 emissions due to traffic delay during the construction process. The outcome of the study found that the pipe-bursting installation method had 72.6% less CO_2 emissions compared to open-cut installation method. Therefore, it was concluded that this extreme reduction in the CO_2 emissions was due to the less excavation, less traffic disruption, and shorter job duration (Joshi, 2012).

There was another study also focused on the installation phase of the pipeline, the study evaluated and compared the environmental impact between the open cut installation method with pipe bursting installation method. The study presents a comparative LCA of the traditional open cut and pipe bursting. The study considered two pipe diameters (8-inch and 20-inch) and two different pipe materials, namely asbestos cement pipe (ACP) and pig iron. This study focuses only on the installation phase. The results demonstrated that the pipe bursting installation method generates less environmental impacts in most of the impact categories. The gap between the environmental impact of the two methods increases with increasing diameter of the replaced pipeline (Loss, 2016).

Mohit did a study to investigate pollutant emissions from two trenchless installation method: hand tunneling and pilot-tube method (PTM). In this case study, both installation methods were used in the installation of a new 27-inch diameter clay sewer line with a depth of 42-foot and a length of 197-foot. The results showed that the number of airborne emissions was reduced between 17% to 36% in the case of using PTM compared to the traditional hand tunneling method (Mohit, 2017).

Rehan compared and determined the CO_2 emissions associated with open cut and trenchless methods for the installation of municipal pipelines (water and sewer). This study considered only: the increased fuel consumption due to the traffic delays and increased travel distance for detours; fuel consumption of construction machinery and equipment involved in excavation, compaction, backfilling and repaving operations. The result of this study found that large amounts of CO_2 are released due to traffic disruptions associated with the construction of sewers under major roads. It was also shown that trenchless construction methods are considerably efficient in reducing CO_2 emissions, this reduction due to the shorter job duration and limited or no disruption to traffic flow. Three case studies evaluated in this research and the result found that 78 to 100% reduction in GHG can be realized through the use of trenchless construction method (Rehan, 2007).

Monfared investigated an environmental impact comparison between open-cut, auger boring, and horizontal directional drilling (HDD) installation methods through two case studies in new residential development area in Edmonton, Alberta, which consists of three main lines: water, sanitary, and storm. The result found that the GHG emissions generated from open-cut were significantly higher compared to the trenchless options. The total GHG emissions released into the environment was significantly reduced by 70% to 99% in auger boring and by 90% to 99% in HDD. Based on the study, higher GHG emissions in the open-cut installation method is a result of a longer project duration and more equipment requirements compared to smaller underground excavation when using the auger boring or HDD (Monfared, 2018).

Ariaratnam and Sihabuddin compared open-cut and pipe bursting. The results found that emissions generated from the open-cut construction method were about 77% higher in greenhouse gases and approximately 80% greater in criteria pollutant emissions compared to the pipe bursting construction method (Ariaratnam and Sihabuddin 2009). Tavakoli and Najafi did a study to compare open cut and tunneling methods regarding carbon emission during the installation stage for a 25-mile pipeline. The results showed that the total CO_2 produced using the open cut method is approximately six times more than the CO_2 produced using the tunneling method (Tavakoli, 2017).

The construction of the building has a significant impact on the environment, and the process of manufacturing and transporting of building materials and installing and constructing of buildings consumes great energy and emits a large quantity of GHG. Yan did a study to evaluate and analyze the GHG emissions during the construction of buildings, and the research presented a case study of GHG emissions in building construction in Hong Kong. The study defines four sources of GHG emissions in building construction, which is: manufacture and transportation of building materials; the energy consumption of construction equipment, the energy consumption of processing resources; and disposal of construction waste. The result found that 82-87% of the total GHG emissions are from building materials, 6-8% of the total emissions are from the transportation of building materials, and 6-9% is from energy consumption of construction equipment. Also, the result indicates that GHG emissions of steel and concrete account for 94-95% of all building materials. Thus, the use of recycled materials, specially reinforced steel, would decrease the GHG emissions (Yan, 2010).

Hong's study analyzed GHG emissions during the construction phase of a case study building in China. The focus of this study was the use of the CO_2 footprint method under the guidance of ISO 14064. The result found that the onsite electricity generated the most GHG direct emissions, and the indirect emissions such as emissions from building materials production and construction-supporting offsite human activities were responsible for 97% of the total emissions. The focus of concern in the study has widened to include human activities by the extended system boundary and detailed process data. also, the result found that in the construction phase 64.3% of the total building materials by weight discharged 86.6% of all carbon emissions, suggests that choosing alternative building materials with low embodied CO_2 or energy and including a higher share of renewable energy are a significant challenge for future construction projects (Hong, 2015).

Fu did a study to evaluate the CO_2 emissions during the building construction phase. Five LCA tools have been compared and analyzed the study. The result found that the primary contributors regarding the CO_2 emissions amongst construction materials to the total embodied CO_2 were steel, concrete, and blocks used in the building, accounting for over 60%. However, an opportunity for decreasing the CO_2 emissions is through the use of recycling materials in the construction phase. Therefore, builders should pay more attention not only to these quantities but also to the recycling of the key contributors amongst the materials used in the building, improving the sustainable design as a result (Fu, 2014).

Gonzalez's research presented a case study for three terraced houses built in Spain. The houses have been constructed following low environmental impact criteria, compared them with other building with similar characteristics but built in a conventional way and with no selection of materials. The result of this research found that the CO_2 emissions reduction in the construction of buildings is perfectly feasible by following different working lines. Also, there is another way to reduce CO_2 consumption starting in the early construction phase. In the design phase, the designer can make important decisions to establish future lines in selecting low environmental impact construction materials for the building phase. A correct selection of materials and products must be made in order to save energy, as well as to reduce CO_2 emissions (Gonzalez, 2006).

The gaps in the most previous studies are most of the study they don't include the entire life-cycle phases, most of the study they look only for open cut construction method during the installation phase, and most of the studies focus on steel and concrete pipe. Few studies are evaluating the CO_2 emissions during the operation phase but, due to the lack of data they are not that accurate, and they do not include enough information and data to help the engineers and decision-maker to choose the environmentally friendly pipe materials and installation method. Most of the studies focused only on the gravity pipeline. No research has been evaluated and analyzed the CO_2 footprint for the rehab method.

To overcome the limitations and fill the research gaps in the previous studies, this study included all the life-cycle phases: fabrication, transport and installation, operation, and disposal for replacing old pipeline as shown in Figure 2-6, which has never been done. In this study, different pipeline installation methods are used to help the decision-maker not only to choose the pipe material but also to choose the environmentally friendly material with the right installation method, the installation methods are open-cut, pipe bursting, and cured-in-place pipe. New backfill materials are used, and the carbon emissions for backfill materials has been calculated in the study.

In this study, CIPP has been added to evaluate and compare the carbon emissions with other methods to make the study unique, and no study before assessed or compared CIPP with other pipe materials regarding CO_2 emissions. This is the first study that focuses on pressure pipe and calculated and analyzes energy consumed during the pumping wastewater and cleaning the pipeline during the 100 years of operation. In this study, recommendations are given for how utilities and engineers could optimize and reduce the carbon emissions during pipeline installation and rehabilitation.

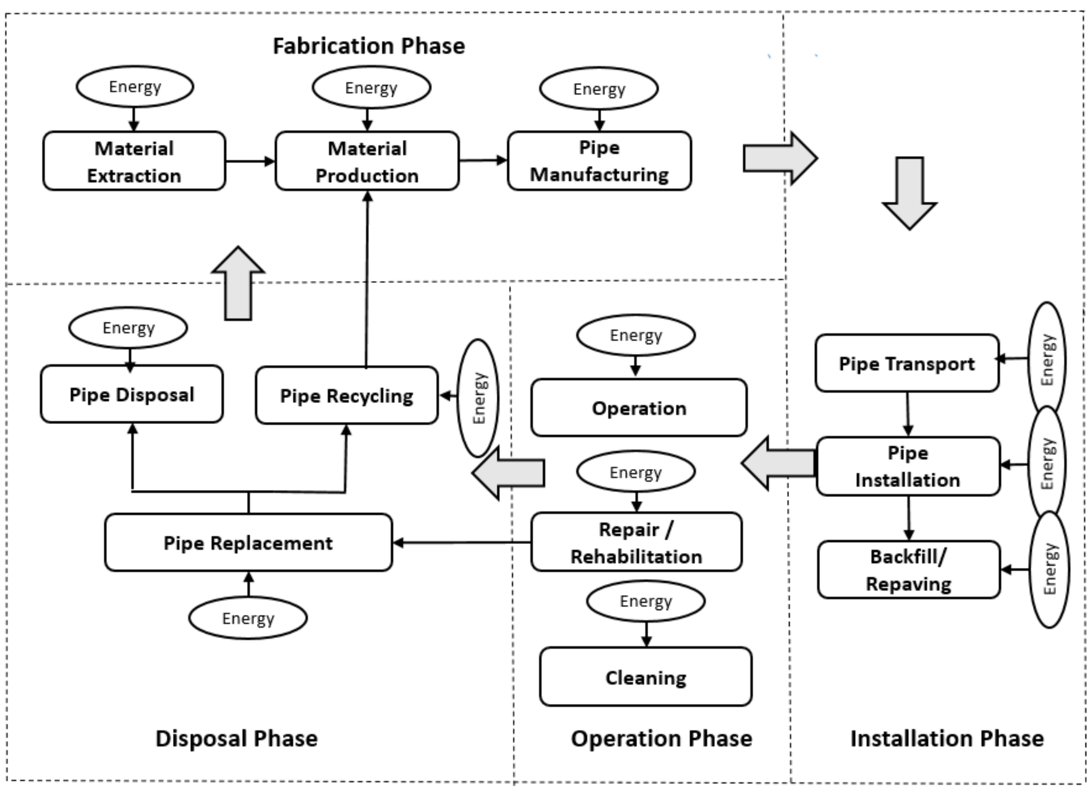


Figure 2-5 Life-Cycle Energy Analysis and Life Stages

CHAPTER 3

FABRICATION PHASE

3.1 Introduction

With growing attention to considering sustainability factors, such as environmental, cost, and social cost, when developing infrastructures, responsible management is also needed to protect the natural environment from irreversible and remarkable effects, such as air and water pollutions, and waste. Dissipating non-renewable natural resources is a serious loss for future generations. As a result, it is considered indispensable to improve construction practices and develop infrastructures in ways that facilitate sustainable construction (Monfared, 2018).

When selecting a pipeline material or method to be used for the pipeline construction or repair, the direct cost is typically the primary, if not the only, factor used in the selection of applicable methods and materials. However, with the consistent increase in global population, sustainable construction has become a trend that will need to be practiced in perpetuity. In sustainable construction, social costs and environmental impacts must also be considered when making decisions. Social costs have long been considered when selecting pipeline methods (Matthews, 2015), but environmental sustainability is a relatively new impact being considered. In the pipeline industry, carbon footprint analyses for the construction phase have been performed to identify less carbonintensive methods. The pipeline industry, however, has yet to evaluate the environmental sustainability of its construction materials during the fabrication stages.

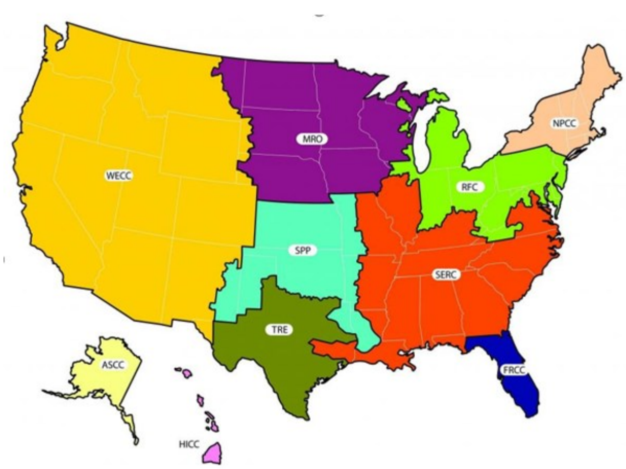
This phase deals with energy consumed during material production and pipeline fabrication (embodied energy). Embodied energy is the total of all the energy required to produce any goods or services. The concept can be useful in determining the effectiveness of energy generating or energy saving device to decide whether a product contributes or mitigates global warming. One fundamental purpose for measuring this quantity is to compare the amount of energy produced or saved for a different product in production and fabrication process.

The goal of this chapter is to calculate and analyze the environmental sustainability, as determined by carbon footprint and embodied energy, of 100-feet of pipeline during the fabrication stages. The fabrication stage deals with energy consumed during material extraction, material production, and pipe manufacturing, which includes all energy until the factory gate. The objective of this chapter is to analyze and compare CO_2 emissions during the fabrication phase associated with the four types of pipe: PCCP, PVC, HDPE, and CIPP, used for large diameter 36-inch pressure sewer pipelines.

The Inventory of Carbon and Energy (ICE) database version 2.0 (2011), which was published by the University of Bath in the U.K., was used for this chapter. The ICE database provides an embodied energy for each material used in the construction of each pipe and liner material studied. The ICE database contains both embodied energy and embodied carbon, but the embodied energy coefficients are more accurate (Hammond & Jones, 2011) so in this study, embodied energy coefficients were used. The ICE database has the boundaries of cradle to gate. Hammond and Jones defined the embodied energy

(EE) as the total primary energy consumed during direct and indirect processes associated with a product or service within the cradle to gate boundaries, and this includes all activities from material extraction until the product is ready to leave the final factory gate (Hammond & Jones, 2011).

The emissions and generation resource integrated database (eGRID214) was used for this study. The eGRID is a general source of data on the environmental aspects of almost all electric power generated in the United States. The eGRID is based on available plant-specific data for all U.S. electricity generating plants that produce energy to the electric grid and report data to the U.S. government. The eGRID is developed from a variety of data collected by the U.S. Environmental Protection Agency (EPA), and the Energy Information Administration (EIA). Texas regional entity (TRE) = 1.2038 lb CO_2 emission/kWh for electricity usage (eGRID, 2014). Figure 3-1 shows the map dividing the U.S. into various sub-regions.



NERC	NERC Region Name	Emissions Rate
ASCC	Alaska Systems Coordinating Council	0.894
FRCC	Florida Reliability Coordination Council	1.084
HICC	Hawaiian Islands Coordinating Council	1.429
MRO	Midwest Reliability Organization	1.418
NPCC	Northeast Power Coordinating Council	0.557
RFC	Reliability First Corporation	1.266
SERC	SERC Reliability Corporation	1.179
SPP	Southwest Power Pool	1.509
TRE	Texas Regional Entity	1.203
WECC	Western Electricity Coordinating Council	0.914

Figure 3-1 Sub Region for Greenhouse Gases (GHG) Emissions (eGRID, 2014)

For this study, four pipe materials were used, namely PCCP, CIPP, PVC, and HDPE. These materials are briefly described below.

3.2 Pre-stressed Concrete Cylinder Pipe (PCCP)

Pre-stressed Concrete Cylinder Pipe has been manufactured and in use since 1942 for pressure pipeline applications. PCCP can be designed for operating pressures greater than 400 psi and underground covers of 100-feet. There are two types of PCCP: lined concrete (LC) PCCP and embed cylinder (EC) PCCP. LC PCCP is designed with a steel cylinder core lined with concrete and subsequently wrapped with a pre-stressing wire directly on the steel cylinder and coated with mortar. The diameter range of LC-PCCP is between 16 to 60-inches. EC PCCP is designed with a core composed of a steel cylinder encased in concrete and subsequently wire-wrapped with pre-stressing wire over the concrete core and coated with cement mortar. The pipe diameter is manufactured mostly in a size range of 48-inches and larger. For both types of PCCP, the lengths in general, are between 16 to 24-feet (AWWA M9) (AWWA C301). Key differences are highlighted in Table 3-1 and Figure 3-2.

Table 3-1 Differences Between Lined Cylinder Pipe and Embedded Cylinder Pipe (Romer, 2007)

Parameter	**Lined Cylinder Pipe (LCP)**	**Embedded Cylinder Pipe (ECP)**
Diameter	16 to 60 in.	30 to 256 in.
Design	Steel cylinder lined with a cast concrete core	Steel cylinder embedded in a concrete core
Pre-stressing wire	Wrapped over steel cylinder	Wrapped over concrete core

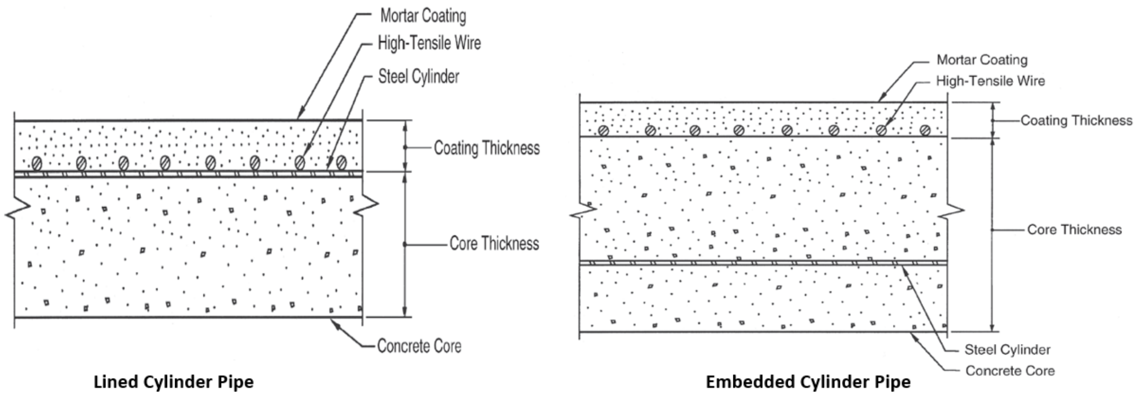


Figure 3-2 Schematic Shows the Different in Wall Cross Sections Between LCP and ECP Pipe (AWWA C304-14)

To determine the carbon emissions involved with the manufacturing of PCCP, the steps of manufacturing must be understood. There are eight steps to manufacture PCCP (AWWA M9) (Manda, 2012):

1. Manufacture and fabricate the steel cylinder.
2. Attach the joint rings to the steel cylinder pipe. After acquiring the desired shape and sizes of the steel cylinder, attach and weld the joints to the steel cylinder.
3. Perform hydrostatic test for steel cylinder. There are two ways to do the test: horizontally or vertically.
4. Place the concrete core around the steel cylinder. The main components of concrete are cement, coarse aggregate, fine aggregate, water, and admixtures.
5. Cure concrete core. Curing is a process of maintaining satisfactory moisture content at a certain temperature for a certain period.
6. Wrap the pre-stressing wire around the concrete core to give it a high tensile strength.

7. Apply external mortar coating. After the concrete has been wrapped with pre-stressed wire, apply an exterior mortar coating. The mortar coating minimum thickness is ¾ in, and the mortar coating should cover the wire.
8. Cure mortar coating.

From the steps of manufacturing PCCP, we are able to determine the types and order of materials used when making the pipe. To determine the amount of each material, the pipe design method is used as described below. Assumptions for the design of all three pipe materials in this study include an outside diameter of 36-inches, internal operating pressure is 100 psi; and a total length of 100-feet.

In this study, we used LC-PCCP, which is more common for 36-inch diameter pipes. The minimum design thickness of the core including the thickness of the steel cylinder should be $\frac{1}{16}$ of the design pipe diameter based on AWWA C301. So, the core thickness is as follows:

$$\frac{36}{16} = 2.25\ in$$

Where the thickness of the steel cylinder is 16 gauge (0.0598 in); the size of pre-stressing wire is 6 gauge (0.192 in); the design spacing between pre-stressing wire is 2.75 wire diameter per AWWA C301. Therefore, the space between wire centers is $2.75 \times 0.192 = 0.528\ inch$. The mortar coating thickness is 0.75 inches per AWWA C301. The materials densities per AWWA are:

1. Concrete: 0.0839 lb./ in³ (2322.61 kg/ m³)
2. Pre-stressing wire: 0.2829 lb./ in³ (7832.80 kg/ m³)
3. Steel Cylinder: 0.2829 lb./ in³ (7832.80 kg/ m³)

4. Mortar coating: 0.0423 Ib./ in³ (1170 Kg/ m³)

The total energy consumption for each pipe of PCCP is calculated using the following Eq. 3-1:

$$\begin{aligned} Total\ Energy_{PCCP} \\ &= Embodied\ Energy_{Concrete} \times Weight_{Concrete} \\ &+ Embodied\ Energy_{Steel\ Cylider} \\ &\times Weight_{Steel\ Cylinder} \\ &+ Embodied\ Energy_{Mortar\ Coating} \\ &\times Weight_{Mortar\ Coating} \\ &+ Embodied\ Energy_{Prestressing\ Wire} \\ &\times Weight_{Prestressing\ wire} \end{aligned}$$ **Eq. 3-1**

The total CO_2 emissions = Total Energy consumption × CO_2 Emission Rate. The inputs for the PCCP calculation are shown in Table 3-2.

Table 3-2 Energy Consumption and CO_2 Emission for PCCP Pipe

	Description	Unit	Quantity	Remark/ Reference
A	Outside diameter	in	36	Assumption
B	Inside diameter	in	30	OD- wall thickness
C	Length of pipe section	ft.	20	Assumption
D	Design life	years	100	Assumption
E	Core thickness	in	2.25	(AWWA C301-14)
F	Steel cylinder thickness	in	0.0598	(AWWA C301-14)
G	Concrete core thickness	in	2.19	F= D- E
H	Diameter of pre-stressing wire	in	0.193	(AWWA C301-14)
I	Mortar coating thickness	in	0.75	(AWWA C301-14)
J	Total length of segment	ft.	100	Assumption
K	Weight of steel cylinder	lb.	459.2	Weight= Volume×Density
L	Weight of concrete core	lb.	4,987.35	Weight= Volume×Density
M	Weight of mortar coating	lb.	861.12	Weight= Volume×Density
N	Weight of pre-stressing wire	lb.	421.5	Weight= Volume×Density
O	Pipe weight	lb.	6,729.17	N= K+L+M+V
P	Embodied energy of concrete core	MJ/kg kWh/lb	0.95 0.12	ICE version 2.0 1 MJ/kg = 0.126 kWh/lb
Q	Embodied energy of steel cylinder	MJ/kg kWh/lb	34.7 4.37	ICE version 2.0 1 MJ/kg = 0.126 kWh/lb
R	Embodied energy of pre-stressing wire	MJ/kg kWh/lb	36 4.54	ICE version 2.0 1 MJ/kg = 0.126 kWh/lb
S	Embodied energy of mortar coating	MJ/kg kWh/lb	1.33 0.17	ICE version 2.0 1 MJ/kg = 0.126 kWh/lb
T	Energy consumption of each pipe	kWh/ pipe	4,665.19	$S = K \times Q + L \times P + M \times S + N \times R$
V	Total energy consumption	kWh	23,326	$V = T \times 5\, pipes$
W	CO_2 emission rate	lb/kWh	1.2038	eGRID2014
X	Total CO_2 emission	lb	28,079.8	$X = V \times W$

3.3 Polyvinylchloride (PVC) Pipe

Polyvinylchloride was found in the late nineteenth century, and in the 1920s, scientists brought PVC to public attention again. In the 1930s, scientists in Germany developed and produced limited quantities of PVC pipe. PVC pipe has been installed regularly in Europe since the early 1970s and early 1990s in North America. The fundamental raw materials of PVC pipe resin are derived from ethylene (mostly natural gas or petroleum-based) and chlorine (mostly salt based). PVC pipe is manufactured by mixing PVC resin with heat stabilizers, lubrication materials, and fillers. The purpose of adding heat stabilizers to the PVC resin mix is to delay heat degradation so the mix can be formed into a product before it degrades. Lubrication materials control the melting point in the extruder to achieve the best processing and physical properties. The filler is added to the PVC resin mix to lower material cost and provide coloring (AWWA M23). Figure 3-3 details the flow of PVC pipe production.

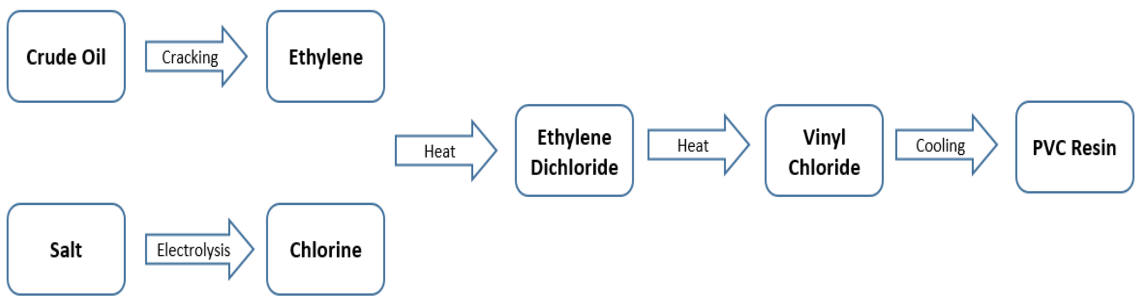


Figure 3-3 Cradle to Resin Flow Diagram of PVC Production (Krock, 2013)

The assumptions for the design of the PVC in this study are a diameter of 36-inches, an internal pressure of 100 psi, and a length of 100-feet. The pipe wall thickness is 0.878-inch per AWWA C905 and the standard pipe length is 20-feet per ASTM D2665. The PVC pipe embodied energy is 67.5 MJ/kg per ICV version 2.0. The total energy consumption for each pipe of PVC is calculated using the following Eq. 3-2:

$$Total\ Energy_{PVC} = Embodied\ Energy_{PVC} \times Weight_{PVC} \qquad \textbf{Eq. 3-2}$$

The total CO_2 emissions = Total Energy consumption × CO_2 Emission Rate. The inputs for the PVC calculation are shown in Table 3.3.

Table 3-3 Energy consumption and CO_2 Emission for PVC Pipe

	Description	Unit	Quantity	Remark/ Reference
A	Outside diameter	in	36	Assumption
B	Length of pipe section	ft	20	Assumption
C	Wall thickness	in	0.875	AWWA C905
D	Design life	years	100	Assumption
E	Density of rigid PVC	lb/in³ kg/m³	0.0524 1,380	(Martins, 2009)
F	Weight of each pipe	lb	1,183.95	Weight = Volume × Density
G	Embodied energy for PVC pipe	MJ/kg kWh/lb	67.50 8.505	ICV version 2.0 1 MJ/kg = 0.126 kWh/lb
H	Energy consumption for each pipe	kWh	10,069.57	G= F×G
I	Total energy consumption	kWh	50,347.87	5 pipes
J	CO_2 emission rate	lb/kWh	1.2038	eGRID2014
K	Total CO_2 emission	lb	60,608.8	K= I×J

3.4 High-Density Polyethylene (HDPE)

High-Density Polyethylene is widely utilized. Recent HDPE resins are resistant materials, which facilitate the handling operations and implementation for above and underground applications (Alimi, 2017). In the 19th century, Hans von Pechmann, the German chemist, noted a precipitate while working with a form of methane in ether. In 1900, German chemists Eugen Bamberger and Friedrich Tschirner identified this compound as polyethylene, a very close cousin to polyethylene. The growth in the thermoplastic market is increasing rapidly as a replacement of cement, metal, and wooden products. The growth in plastic production has increased around 9% since the1950s. HDPE pipes are commonly used thermoplastic for the municipal pipelines, industrial pipelines, mining, cable duct, etc. as HDPE costs less and require fewer repairs (Sangwan, 2017).

Polyethylene comes in three different general grades: low-density polyethylene (LDPE), medium-density polyethylene (MDPE) and high-density polyethylene (HDPE). The increase in density results in the variation of material properties. In general, the yield strength, the modulus of elasticity, and the melting temperature increase with density, while elongation and toughness decrease. Medium density polyethylene and higher density polyethylene are being extensively used for water, gas, sewage, and wastewater distribution systems (Merah 2006). A typical HDPE pipe production includes extrusion, cooling, hot embossing, and cutting. The raw materials used are HDPE pellets made from virgin polyethylene granulates and recycled HDPE (Sangwan, 2017). Figure 3-4 shown HDPE pipe.

Figure 3-4 HDPE Pipe (https://www.kuzeyborugroup.com/hdpe-pipe)

The designs of the HDPE in this study remain the same as they were for the other materials, i.e. diameter of 36-inches, internal pressure of 100 psi, and length of 100-feet. The pipe wall thickness is 2.18-inch per AWWA C906, and the standard pipe length is 20-feet per ASTM D2665. The HDPE pipe embodied energy is 84.4 MJ/kg per ICV version 2.0. The total energy consumption for each pipe of HDPE is calculated using the following Eq. 3-3:

$$Total\ Energy_{HDPE} = Embodied\ Energy_{HDPE} \times Weight_{HDPE} \qquad \textbf{Eq. 3-3}$$

The total CO_2 emissions = Total Energy consumption × CO_2 Emission Rate. The inputs for the PVC calculation are shown in Table 3-4.

Table 3-4 Energy consumption and CO_2 Emission for HDPE Pipe

	Description	**Unit**	**Quantity**	**Remark/ Reference**
A	Outside diameter	in	36	Assumption
B	Length of pipe section	ft	20	Assumption
C	Wall thickness	in	2.18	AWWA C906
D	Design life	years	100	Assumption
E	Density of HDPE	lb/in³	0.03486	Merah, 2006
F	Weight of each pipe	lb	2,004	Weight = Volume × Density
G	Embodied energy for HDPE pipe	MJ/kg kWh/lb	84.4 10.634	ICE version 2.0 1 MJ/kg = 0.126 kWh/lb
H	Energy consumption for each pipe	kWh	21,311.34	G= F×G
I	Total energy consumption	kWh	106,557	5 pipes
J	CO_2 emission rate	lb/kWh	1.2038	eGRID2014
K	Total CO_2 emission	lb	128,273	K= I×J

3.5 Cured-in-Place Pipe (CIPP)

Cured-in-Place Pipe is the most widely used trenchless pipe repair technology for sewer pipelines and has been in use since the 1970s. CIPP liner typically consists of a felt tube and resin with some form of fiber reinforcement such as glass fiber when repairing pressure pipes. The tube contains one or more layers of flexible felt, one or more layers of fiberglass-reinforced, and the outside PE to keep the resin inside the tube. Also, the tube should be fabricated to fit and take the shape of the host pipe. The general purpose of the resin is to fill out all the voids in the tube and saturate it to get the shape of the host pipe. There are three main types of resin: vinyl ester, polyester, and epoxy. CIPP can be installed by an inversion process or pulled in and can be cured with hot water, steam, or UV light. (Matthews, 2014). A typical pressure CIPP tuber is shown in Figure 3-5.

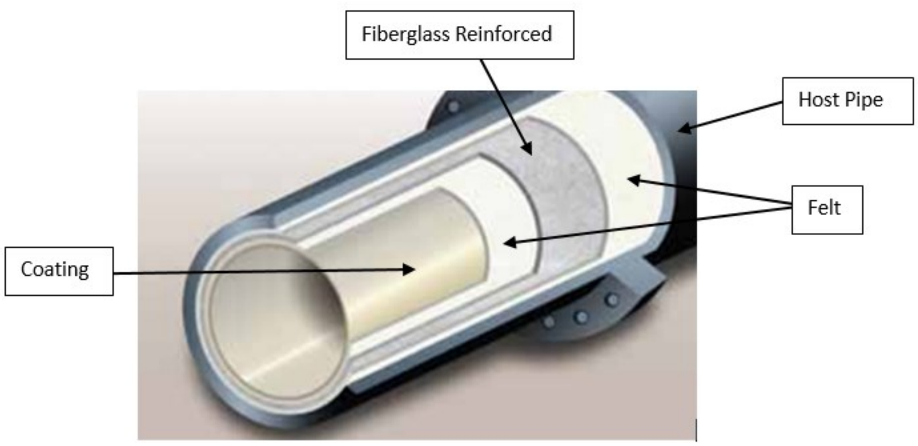


Figure 3-5 Schematic Cross Section for CIPP (http://www.premierpipeusa.com)

Assumptions for the design of the CIPP in this study remain the same as they were for the other materials, i.e. diameter of 36-inches, internal pressure of 100 psi, and length of 100-feet. The design thickness for CIPP is determined by ASTM F1216 per the Eq. 3-4 below for the governing design parameter, which is internal pressure in this case.

$$p = \frac{2\,Q_{TL}}{(DR-2)N} \qquad \textbf{Eq. 3-4}$$

Where,

p = internal pressure (100 psi)

Q_{TL} = $long\ term\ tensil\ strength\ for\ CIPP$ (6000 psi)

N = factor of safety (typically 2)

$t = \frac{D}{DR} = \frac{36}{62} = 0.58\ in$ (14.7 mm)

The CIPP tube thickness calculated from the ASTM above is 0.58 inch (14.7 mm). Two layers of felt would be 6.125 mm thickness per layer. The three layers of fiberglass reinforced would have a total thickness of 0.75 mm per layer. The thickness of the inner and outer PE tube liner is 0.10 mm per layer. The amount of resin should be sufficient to fill out all voids in the tube material with adding 5 - 10% extra amount of resin to ensure complete saturation. We assumed that the felt is 100% saturated by the resin, so the thickness of the resin equals the thickness of the felt.

The total energy consumptions for CIPP is calculated using the follow Eq. 3-5:

$$\begin{aligned} Total\ Energy_{CIPP} &= Embodied\ Energy_{Felt} \times Weight_{Felt} \\ &+ Embodied\ Energy_{Resin} \times Weight_{Resin} \\ &+ Embodied\ Energy_{Fiberglass\ Reinforced} \\ &\times Weight_{\text{Fiberglass Reinforced}} + Embodied\ Energy_{\text{Tube Liner}} \\ &\times Weight_{\text{Tube Liner}} \end{aligned} \qquad \textbf{Eq. 3-5}$$

The total CO_2 emissions = Total Energy consumption × CO_2 Emission Rate. The inputs for the CIPP calculation are shown in Table 3-5.

Table 3-5 Energy consumption and CO_2 Emission for CIPP Pipe

	Description	Unit	Quantity	Remark/ Reference
A	Outside diameter	in	36	Assumption
B	Length of the section	ft	100	Assumption
C	Design life	years	50	Bueno, 2010
D	Tube thickness	in mm	0.58 14.7	F1216 Standard
E	Thickness of fiberglass reinforced	in mm	0.088 2.25	Three layers of fiberglass with thickness 0.75 mm per layer
F	Liner and exterior layer thickness	in mm	0.010 0.20	Each layer 0.005 in 0.10 mm D 3567 Standard
G	Thickness of felt	in mm	0.502 12.25	F= C – (D + E) Two layers of felt each with 6.125 mm per layer
H	Weight of fiberglass reinforced	lb	1,096.13	Weight = Volume × Density Density 158.6 lb/ft^3
I	Weight of felt	lb	1,080.24	Weight = Volume × Density Density 27.4 lb/ft^3
J	Weight of resin	lb	3,706.13	Weight = Volume × Density Density of epoxy 94 lb/ft^3
K	Weight of tube liner and exterior layer	lb	4.71	Weight = Volume × Density Density of Polyurethane $6lb/ft^3$
L	Embodied energy for felt	MJ/kg kWh/lb	36 4.54	ICE version 2.0 1 MJ/kg = 0.126 kWh/lb
M	Embodied energy for resin	MJ/kg kWh/Ib	137 17.26	ICE version 2.0 1 MJ/kg = 0.126 kWh/lb
N	Embodied energy for fiberglass reinforced	MJ/kg kWh/lb	100 12.6	ICE version 2.0 1 MJ/kg = 0.126 kWh/lb
O	Embodied Energy for tube liner	MJ/kg kWh/lb	80.10 10.1	ICE version 1.6a 1 MJ/kg = 0.126 kWh/lb
P	Total energy consumption	kWh	82,730.9	P = H×N + I×L + J×M + K×O
Q	CO_2 emission rate	lb/kWh	1.2038	eGRID2014
R	Total CO_2 emission	lb	99,591.5	R= P×Q

Epoxy resin was chosen due to the following advantages cited for pressure pipes (Moore 2011). Epoxy resin typically has shorter catalyzed stability (seven hours or fewer) than polyester and vinyl ester resins. Epoxy resin has lower polymerization shrinkage than polyester and vinyl ester resin during curing. Epoxy resin has very low odor levels and does not cause any odor issues in CIPP application.

3.6 Results and Discussion

This chapter focused on CO_2 emissions during the fabrication phase for the four commonly used pressure pipe materials: PCCP, PVC, HDPE and CIPP. For this comparison, the four types of pipe have a 36-inch diameter and are assumed to be 100-feet long and for the lifetime is assumed to be 100 years. CO_2 emissions for the fabrication phase for the four pipe types are provided in Figure 3-6. For the pipe fabrication phase, the result shows PCCP has less energy consumption compared to PVC, HDPE and CIPP pipe, which should be expected based on the raw materials (i.e., steel and concrete versus petroleum-based resins). CIPP has the highest energy consumption during the material production and fabrication phase because the epoxy resin has high embodied energy and the life expectancy for CIPP in this study assumed to be 50 years compared to other materials, which mean installing CIPP two times in the 100 years.

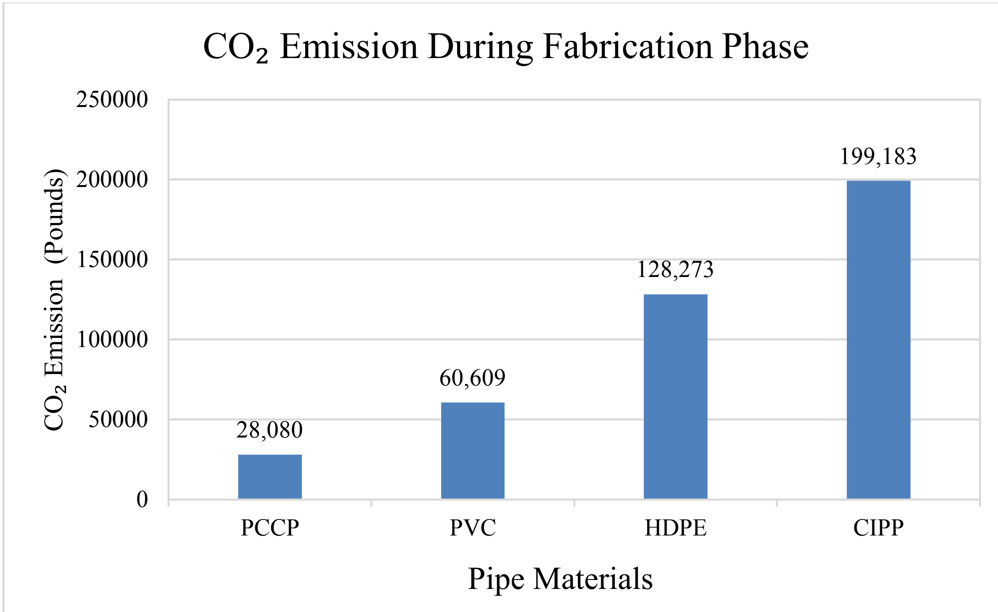


Figure 3-6 CO_2 Emission During the Fabrication Phase

The total CO_2 emissions for each pipe is provided in Figure 3-6 CIPP CO_2 emission was almost six times more than the amount of carbon as compared with PCCP, and PVC pipe CO_2 emissions were almost the double amount of carbon emissions as compared to PCCP, and for HDPE is more than four times compared to PCCP during the fabrication phase. For the 100-feet section, the PCCP has a massive weight compared to PVC, HDPE and CIPP, and at the same time has less energy consumption compared to the same pipes. The primary materials in PCCP are concrete, steel cylinder, pre-stressing wire, and mortar coat. In this study, PCCP was 74% concrete, and, due to the small concrete embodied energy (i.e., 0.12 kWh/lb), PCCP has less carbon emissions in the fabrication stage. In this study, CIPP liner consists of a fiber reinforced felt tube impregnated with resin. The tube contains two layers of felt saturated with the epoxy resin and three layers of reinforced fiberglass. The amount of epoxy resin is 63% of the total CIPP weight, and, due to the high embodied energy for epoxy resin (i.e., 17.26

kWh/lb), CIPP has a higher energy consumption. For PVC and HDPE pipes, the pipes are 100% resin. The primary raw materials for PVC resin are crude oil and salt. PVC pipe embodied energy is 8.505 kWh/lb, and the embodied energy for HDPE is 10.6344 kWh/lb, so it is less embodied energy compared to CIPP resin and higher than concrete embodied energy. The study shows that small savings in the quantity of material make a big change in the total carbon emission, for example, the pipe thickness, pipe diameter, and amount of resin in CIPP.

Understanding the carbon footprint of the pipeline and choosing the right pipe materials will result in significant carbon savings, which will help to mitigate greenhouse gas emissions and meet international emission targets. The procedure used in this study, which is the first know attempt to compare carbon emissions from the fabrication stage of CIPP materials to other pipe materials, could be applied to any pipeline project to analyze the environmental impact of product selection. This study had been done for 100-feet long but can be used for any length, diameter, and material by scaling up the material qualities using proper design procedures.

3.7 Chapter Conclusion

In the first phase of the pipeline life-cycle (fabrication phase), this study shows that PCCP generated a lower amount of carbon compared with PVC, HDPE and CIPP, for a 36-inch, 100-feet long pressure pipe project for 100-years lifetime. PVC has a higher energy consumption than PCCP and less than CIPP. HDPE has a higher energy consumption compared to PVC and PCCP and less than CIPP. Finally, CIPP has the highest energy consumption compared to PCCP, PVC, and HDPE. Small savings in the quantity of material makes a big change in the total carbon emission. Pipes with smaller diameters emitted less carbon than the large pipes with the same pipe material.

Of the three cost/impact factors that should be considered when choosing pipeline material (direct cost, social cost, and environmental impact), this study is only focused on environmental impact. There are some studies on the direct cost, and a few have been done on social cost (Matthews 2015 did a study about social cost impact evaluations for pipeline), but there is no study that has been done regarding the environmental impact for trenchless options over the entire life-cycle. It is recommended to include all three cost/impact factors together, helping the decision maker to obtain the best results for selecting a pipe material and method. This study benefits the pipeline industry and decision makers to monitor their resulting carbon footprints, thus helping them to set their carbon emissions targets. For future research, it is recommended that field studies should be conducted to obtain the necessary data to overcome dependence on assumptions made in this study.

CHAPTER 4

INSTALLATION PHASE

4.1 Introduction

Globally, increasing population and industrial growth is putting increased pressure on existing water and sewer infrastructures as is the effect of aging. A major portion of the existing water and sewer pipelines are rapidly approaching the end of their useful service life, so they will need to be undertaken for rehabilitation or replacement. New pipelines are typically installed using open cut technology or trenchless technology (i.e., pipe jacking, horizontal directional drilling, horizontal auger boring, etc.) or rehabilitated with trenchless methods such as cured-in-place pipe (CIPP), slip-lining, or pipe bursting. The second phase of the pipeline life-cycle is the installation. The energy consumed in this phase varies from one method to another depending on several factors, for example, the amount of equipment, the time required to finish the project, and the location of the project. In this study, three installation methods are used: open cut, pipe bursting, and cured-in-place pipe.

4.2 Open Cut Installation Method

The traditional method for construction, replacement, and repair of underground utilities is the open cut method. Open-cut is the most common method used for underground utility construction because of the basic approach of excavating soil and laying the pipeline as shown in Figure 4-1. Over a century ago, the solution of using the open cut method may have been considered as an economically appropriate method for installation of the new pipeline (Monfared, 2018). The open cut method consists of excavating a trench for manual pipeline installation. The open cut method requires more equipment and time to remove the large volume of soil during pipeline installation compared to trenchless technology.

Figure 4-1 Schematic Diagram Shown the Open Cut Method (ISTT website)

4.3 Cured-in-Place Pipe (CIPP)

Cured-in-place pipe (CIPP) is a common technology used to repair existing pipelines. CIPP is an economical trenchless technology method compared to the open cut method. CIPP has been in use since the 1970s in London (Najafi, 2005). The CIPP liner typically consists of a lining tube saturated with resin which is installed into the existing pipeline. Also, the tube should be fabricated to fit and take the shape of the existing pipeline. CIPP can be installed by pulling the liner into the existing pipe. CIPP can be cured with hot water, steam, or UV light (Matthews, 2014). Figure 4-2 shows the schematic for a CIPP installation.

Figure 4-2 Schematic Diagram Shown the CIPP Installation Method (ISTT website)

4.4 Pipe Bursting Installation Method

Pipe bursting is one of the trenchless technology methods that is widely used for rehabilitation of deteriorated pipeline when the new pipeline is the same or larger size and in the same location (TTC Report, 2001). Pipe bursting is an economical method compared to open cut because it uses less equipment, time, and reduces disturbance to residents. Figure 4-3 shows the pipe bursting operation layout. Pipe bursting was first developed for in the UK in the late 1970s by D. J. Ryan and Sons. This method was patented in the UK in 1981 and in the U.S. in 1986. There are three methods of pipe bursting: hydraulic, pneumatic, and static pull. The difference between the three pipe bursting methods is the way of breaking the old pipe, the source of energy, and the operation. Selecting the pipe bursting method is dependent on the soil's conditions, the upsizing required, the type of new pipeline, the depth of the existing pipeline, and the availability of experienced contractors (TTC Report, 2001).

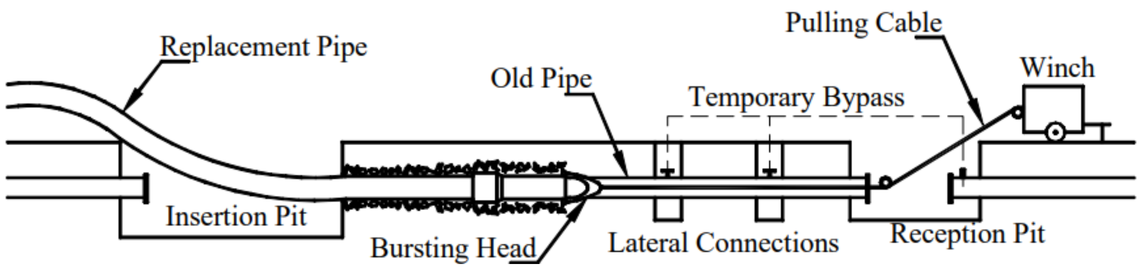


Figure 4-3 Pipe Bursting Operation Layout (TTC Report, 2001)

4.5 Transporting Pipe and Equipment to the Job-Site

The first step of a pipeline installation project is to transport the equipment and pipe to the job-site before starting the installation. The transport is based on the mileage from manufacturing/company to the job-site. In this study, 20-miles is the distance between job-site and manufacturing. To quantify the carbon emissions for the transport stage, it is required to count the trucks and the number of trips for each truck. By knowing the truck fuel consumption rate per mile and CO_2 emissions rate from each gallon, the total CO_2 emissions can be calculated as shown in Table 4-1.

The following considerations are used at this stage:

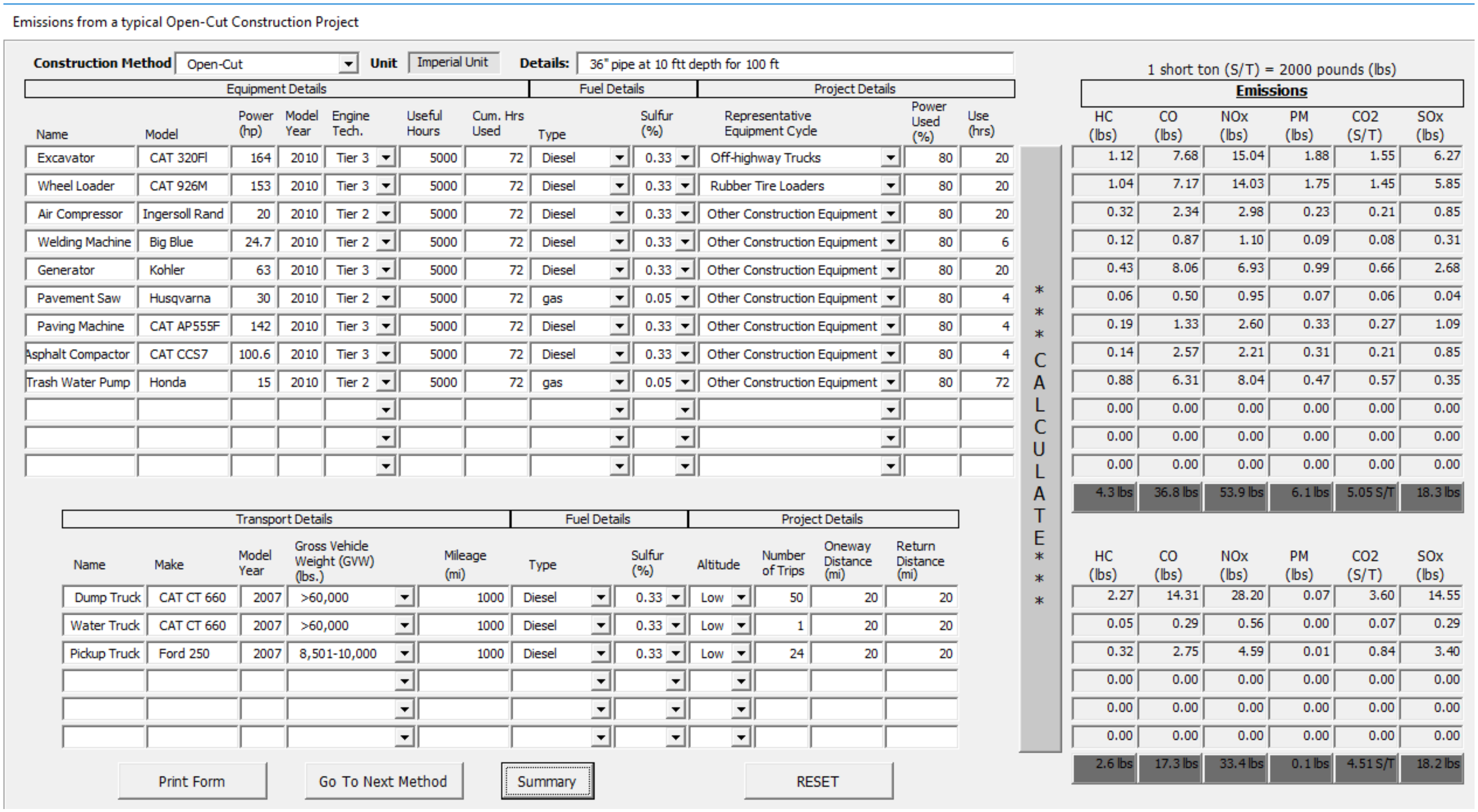
- 2010 flat-bed trucks are used to transport pipe and equipment to the job-site.
- The distance between the job-site and pipe and equipment storage is 20 miles.
- The diesel fuel consumption is 5.9 miles per gallon for each truck (Transportation energy data book, 2015)
- CO_2 emissions from a gallon of diesel is 22.2 pounds/ gallon (U.S. EPA, 2005)

Table 4-1 CO_2 Emissions from Transportation Pipe and Equipment to The Job-Site

Method	Description	Unit	For Pipe	For Equipment	Total
Open Cut	Number of trips required to transport pipe and equipment to the job-site and returning the equipment after the construction finish	trip	1	6	7
	Total miles	mi.	40	240	280
	Diesel Required to transport to job-site	gal.	6.8	40.6	47.4
	CO_2 Emissions	lb.	151	902	1053
	Total CO_2 Emissions			**1,053 pounds**	
Pipe Bursting	Number of trips required to transport pipe and equipment to the job-site and returning the equipment after the construction finish	trip	1	2	3
	Total miles	mi.	40	80	120
	Diesel Required to transport to job-site	gal.	6.8	13.6	20.4
	CO_2 Emissions	lb.	151	302	453
	Total CO_2 Emissions			**453 pounds**	
Cured-in-Place Pipe	Number of trips required to transport pipe and equipment to the job-site and returning the equipment after the construction finish	trip	0	1	1
	Total miles	mi.	0	80	80
	Diesel Required to transport to job-site	gal.	0	13.6	13.6
	CO_2 Emissions	lb.	0	302	302
	Total CO_2 Emissions			**302 pounds**	

4.6 Carbon Emissions During Pipeline Installation

This stage requires more energy and time compared to other stages in the installation phase. The energy consumed in this stage is varies from installation method to another depending on several factors. The energy consumption rate depends on three factors: pipe, equipment, and job-site. The energy consumption rate depends on pipe weight, pipe size, and pipe length. The factors are related to the equipment: the age of equipment, power, capacity, cycle time, operator efficiency, and equipment efficiency. In the job-site, the CO_2 emissions depend on the location, trench cross section, volume of earthwork, type of soil, hauling distance, water table, and weather conditions (Chilana, 2016). Emission calculation (e-calc) software is used to estimate and quantify the carbon emissions during the installation. Figure 4-4 shows an example for e-calc software used to calculate the carbon emission during pipe installation for the open-cut construction method.



Emissions from a typical Open-Cut Construction Project

Construction Method Open-Cut **Unit** Imperial Unit **Details:** 36" pipe at 10 ftt depth for 100 ft

1 short ton (S/T) = 2000 pounds (lbs)

Equipment Details							Fuel Details		Project Details			Emissions					
Name	Model	Power (hp)	Model Year	Engine Tech.	Useful Hours	Cum. Hrs Used	Type	Sulfur (%)	Representative Equipment Cycle	Power Used (%)	Use (hrs)	HC (lbs)	CO (lbs)	NOx (lbs)	PM (lbs)	CO2 (S/T)	SOx (lbs)
Excavator	CAT 320Fl	164	2010	Tier 3	5000	72	Diesel	0.33	Off-highway Trucks	80	20	1.12	7.68	15.04	1.88	1.55	6.27
Wheel Loader	CAT 926M	153	2010	Tier 3	5000	72	Diesel	0.33	Rubber Tire Loaders	80	20	1.04	7.17	14.03	1.75	1.45	5.85
Air Compressor	Ingersoll Rand	20	2010	Tier 2	5000	72	Diesel	0.33	Other Construction Equipment	80	20	0.32	2.34	2.98	0.23	0.21	0.85
Welding Machine	Big Blue	24.7	2010	Tier 2	5000	72	Diesel	0.33	Other Construction Equipment	80	6	0.12	0.87	1.10	0.09	0.08	0.31
Generator	Kohler	63	2010	Tier 3	5000	72	Diesel	0.33	Other Construction Equipment	80	20	0.43	8.06	6.93	0.99	0.66	2.68
Pavement Saw	Husqvarna	30	2010	Tier 2	5000	72	gas	0.05	Other Construction Equipment	80	4	0.06	0.50	0.95	0.07	0.06	0.04
Paving Machine	CAT AP555F	142	2010	Tier 3	5000	72	Diesel	0.33	Other Construction Equipment	80	4	0.19	1.33	2.60	0.33	0.27	1.09
Asphalt Compactor	CAT CCS7	100.6	2010	Tier 3	5000	72	Diesel	0.33	Other Construction Equipment	80	4	0.14	2.57	2.21	0.31	0.21	0.85
Trash Water Pump	Honda	15	2010	Tier 2	5000	72	gas	0.05	Other Construction Equipment	80	72	0.88	6.31	8.04	0.47	0.57	0.35
												0.00	0.00	0.00	0.00	0.00	0.00
												0.00	0.00	0.00	0.00	0.00	0.00
												0.00	0.00	0.00	0.00	0.00	0.00
												4.3 lbs	36.8 lbs	53.9 lbs	6.1 lbs	5.05 S/T	18.3 lbs

CALCULATE

Transport Details					Fuel Details		Project Details									
Name	Make	Model Year	Gross Vehicle Weight (GVW) (lbs.)	Mileage (mi)	Type	Sulfur (%)	Altitude	Number of Trips	Oneway Distance (mi)	Return Distance (mi)	HC (lbs)	CO (lbs)	NOx (lbs)	PM (lbs)	CO2 (S/T)	SOx (lbs)
Dump Truck	CAT CT 660	2007	>60,000	1000	Diesel	0.33	Low	50	20	20	2.27	14.31	28.20	0.07	3.60	14.55
Water Truck	CAT CT 660	2007	>60,000	1000	Diesel	0.33	Low	1	20	20	0.05	0.29	0.56	0.00	0.07	0.29
Pickup Truck	Ford 250	2007	8,501-10,000	1000	Diesel	0.33	Low	24	20	20	0.32	2.75	4.59	0.01	0.84	3.40
											0.00	0.00	0.00	0.00	0.00	0.00
											0.00	0.00	0.00	0.00	0.00	0.00
											0.00	0.00	0.00	0.00	0.00	0.00
											2.6 lbs	17.3 lbs	33.4 lbs	0.1 lbs	4.51 S/T	18.2 lbs

Print Form | Go To Next Method | Summary | RESET

Figure 4-4 e-calc Software Used to Evaluate the Carbon Emission for Open-Cut Construction Method

As shown in Table 4-2, 4-3 and 4-4, the open-cut construction method includes these activities: digging the trench, hauling the spoil, and laying the pipeline. The pipe bursting method includes digging the entrance and exit pits, hauling the spoil, and breaking the old pipe. The cured-in-place pipe method includes digging the entrance and exit pits, hauling the spoil, pulling in the liner inside the host pipe, and curing the new pipe.

The following considerations are used at this stage:

- Emission calculation (e-calc) software is used to estimate and quantify carbon emissions.
- All equipment and trucks are assumed to be manufactured in 2010, which means they are 8 years old.
- For open cut, the trench length is 120-feet, the trench width is10-feet, and the trench depth is 10-feet.
- For pipe bursting, the size of the two pits are 12-feet long, 10-feet wide, and-10 feet deep.
- For CIPP, the size of the two pits are 8-feet long, 8-feet wide, and 10-feet deep.
- The capacity of the dump truck used to haul the spoil is 15 cubic yards.
- The swell factor is assumed to be 40% for hauling spoil.

Table 4-2 CO_2 Emissions During Pipeline Installation for Open Cut Method

Equipment Details					
Equipment	**Type/ Model**	**Power**	**Fuel**	**General Use**	**Use (hrs)**
Wheel Loader	CAT 926M	153 hp	Diesel	Load material into dump trucks	20
Excavator	CAT 320FL	164 hp	Diesel	Excavate the trench, lower pipe, and backfill	20
Air Compressor	Ingersoll Rand 10T3NLH200	20 hp	Diesel	Power pneumatic tools	20
Welding Machine	Big Blue 400 PipePro	24.7 hp	Diesel	Weld pipe joints	6
Generator	Kohler 40REOZK4	63 hp	Diesel	Provide electricity to power equipment	20
Pavement Saw	Husqvarna Fs 3500 E	30 hp	Gas	Cut pavement	4
Trash Water Pump	Honda GX 270	15 hp	Gas	Bypass for existing pipeline	72
Water Pump	Honda GX 270	15 hp	Gas	De-watering	72
Truck Details					
Equipment	**Type/ Model**	**Weight**	**Fuel**	**General Use**	**Number of Trips**
Dump Truck	CAT CT 660	>60000 lb.	Diesel	Haul spoil	70
Pickup Truck	Ford 250 (4*4)	6695 lb.	Diesel	Transport workers and materials	24
Water Truck	CAT CT 660	>60000 lb.	Diesel	Dust Control	1
Total CO_2 emissions			**21,990 Pounds**		

Table 4-3 CO_2 Emissions During Pipeline Installation for Pipe Bursting Method

Equipment Details					
Equipment	**Type/ Model**	**Power**	**Fuel**	**General Use**	**Use (hrs)**
Backhoe	CAT 415F2	68 hp	Diesel	Excavate the access pits and backfill	4
Tension Winch	TT Technologies RW20	48 hp	Diesel	Pull the new pipe into the host pipe	2
Air Compressor	Ingersoll Rand 10T3NLH200	20 hp	Diesel	Power pneumatic tools	10
Fusion Machine	Ritmo Delta 1000 Trailer	33.5 hp	Electricity	To connecting the PVC pipes	2
Generator	Kohler 40REOZK4	63 hp	Diesel	Provide electricity to power equipment	10
Chainsaw	ICS 680PG 10	5 hp	Gas	Clean and cut extra PVC pipe	1
Pavement Saw	Husqvarna Fs 3500 E	30 hp	Gas	Cut pavement	2
Trash Water pump	Honda GX 270	15 hp	Gas	Bypass for existing pipeline	48
Equipment	Type/ Model	Power	Fuel	General Use	Use (hrs)
Water Pump	Honda GX 270	15 hp	Gas	De-watering	48
Truck Details					
Equipment	**Type/ Model**	**Weight**	**Fuel**	**General Use**	**Number of Trips**
Dump Truck	CAT CT 660	>60000 lb.	Diesel	Haul spoil	11
Pickup Truck	Ford 250 (4*4)	6695 lb.	Diesel	Transport workers and materials	8
Total CO_2 emissions				**5,071 Pounds**	

Table 4-4 CO_2 Emissions During Pipeline Installation for CIPP Method

Equipment Details					
Equipment	Type/ Model	Power	Fuel	General Use	Use (hrs)
Backhoe	CAT 415F2	68 hp	Diesel	Excavate the access pits and backfill	2
Air Compressor	Ingersoll Rand 10T3NLH200	20 hp	Diesel	Power pneumatic tools	10
Generator	Kohler 40REOZK4	63 hp	Diesel	Provide electricity to power equipment	10
Tension Winch	TT Technologies RW20	48 hp	Diesel	Pull the tube into the host pipe	2
Chainsaw	ICS 680PG 10	5 hp	Gas	Clean and cut the extra liner	0.5
Pavement Saw	Husqvarna Fs 3500 E	30 hp	Gas	Cut pavement	1
Trash Water Pump	Honda GX 270	15 hp	Gas	Bypass for existing pipeline	36
Water Pump	Honda GX 270	15 hp	Gas	De-watering	36
Truck Details					
Equipment	**Type/ Model**	**Weight**	**Fuel**	**General Use**	**Number of Trips**
Dump Truck	CAT CT 660	>60000 lb.	Diesel	Haul spoil	4
Pickup Truck	Ford 250 (4*4)	6695 lb.	Diesel	Transport workers and materials	4
Utility Van	Ford E-350	7124 lb.	Diesel	Closed circuit television CCTV inspection	1
Box Truck	Ford E-350	7124 lb.	Diesel	CIPP cure control	1
Vacuum Truck	CAT CT 660	>60000 lb.	Diesel	Cleaning the host pipeline	1
Total CO_2 emissions			**3,741 Pounds**		

4.7 Carbon Emissions from Backfill Materials and Repaving

4.7.1 Carbon Emissions from Backfill Materials

Backfilling refers to refilling the trench with the same material or new material. In this study, new backfilling materials are used. Backfill should not contain debris, big stones, or unstable material. As shown in Figure 4-5, the depth of the trench for the three methods is 10-feet: the first 2-feet is gravel as a foundation, 4-feet of sand surrounds the pipe, and the last 4-feet is soil. Thickness of the pavement is assumed to be 4-inches. This part of the study focuses on the CO_2 emissions created during the production of the backfill materials, transport of the materials to the job-site and repaving activity.

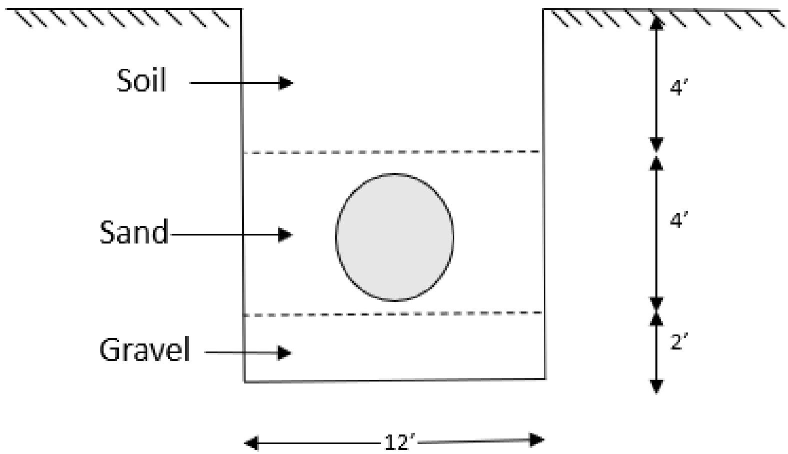


Figure 4-5 Pipeline Backfill Materials

The following considerations are used at this stage:

- New backfill material is used to fill the trench.
- The materials used in backfill are gravel, sand, and dirt as shown in Figure 4-5.
- The distance between the job-site and the plant is 20-miles.
- The thickness of asphalt/ concrete is 4-inches.
- The embodied energy database (ICE version 2.0) is used to quantify the carbon emission for backfill materials.
- The excavation for the three methods is as follows:
    a. The size of the trench for open-cut is 12-feet wide, 10-feet deep, and 120-feet long.
    b. The size of the exit and enter pit for pipe bursting is 12-feet wide, 10-feet deep, and 10-feet long.

c. The size of the exit and enter pit for CIPP is 8-feet wide, 10-feet deep, and-8 feet long.

- The density and embodied energy for backfill materials are shown in Table 4-3.

Table 4-5 Density and Embodied Energy for Backfill Materials

Material	**Density**	**Embodied Energy (EE)**
Gravel	105 lb./ft³	0.01046 kWh/lb.
Sand	100 lb./ft³	0.01021 kW/lb.
Asphalt	145 lb./ft³	0.63 kWh/lb.
Soil	76 lb./ft³	Assumed to be neglected

The ICE database is used to evaluate the carbon emissions for the backfill material production. The EPA's fuel consumption is used to evaluate the carbon emission from transporting the backfill materials to the job-site (see Table 4-4).

Table 4-6 CO_2 Emissions from Backfill Materials

Method	Material	Unit	Gravel	Sand	Soil	Asphalt	Total
Open Cut Method	Amount	lb.	338,688	550,032	612,864	69,600	1,572,184
	Energy Consumption during material production	kWh	3,542	5,616	/	43,848	53,006
	CO_2 Emission from Material Production	lb.	4,264	6,761	/	52,784	63,809
	Number of the trip required to transport the material	trip	13	22	24	3	62
	Diesel Required to Transport the Material to job-site	gal.	88	149	163	20	420
	CO_2 Emission From transport material to job-site	lb.	1,954	3,308	3,619	444	9,325
	Total CO_2 Emission			**73,134 Pounds**			
Pipe Bursting Method	Amount	lb.	56,448	91,728	102,144	11,600	261,920
	Energy Consumption during material production	kWh	590	937	/	7,308	8,835
	CO_2 Emission from Material Production	lb.	710	1,127	/	8,797	10,634
	Number of the trip required to transport the material	trip	2	4	4	1	11
	Diesel Required to Transport the Material to job-site	gal.	14	27	27	7	75
	CO_2 Emission From transport material to job-site	lb.	311	599	599	155	1,664
	Total CO_2 Emission			**12,298 Pounds**			
Cured-in-Place Pipe Method	Amount	lb.	30,106	44,688	54,477	6,187	135,458
	Energy Consumption during material production	kWh	315	456	/	3,898	4,669
	CO_2 Emission from Material Production	lb.	379	549	/	4,692	5,620
	Number of the trip required to transport the material	trip	1	2	2	1	6
	Diesel Required to Transport the Material to job-site	gal.	7	14	14	7	42
	CO_2 Emission from transport material to job-site	lb.	155	311	311	155	932
	Total CO_2 Emission			**6,552 Pounds**			

4.7.2 Carbon Emissions from Repaving

Repaving is a significant energy consuming activity after installing the pipeline. The energy consumed in this stage dependents on the size of the trench, type of pavement (concrete or asphalt), and thickness of the pavement. In this study, the pavement is assumed to be asphalt with 4-inch thickness. e-calc software is used to evaluate the carbon during surface repaving as shown in Table 4-5. The open cut method is shown consuming more energy compared to pipe bursting and CIPP, and that is because of the size of the trench and open cut needs more equipment and asphalt.

Table 4-7 CO_2 Emissions from Repaving Activities

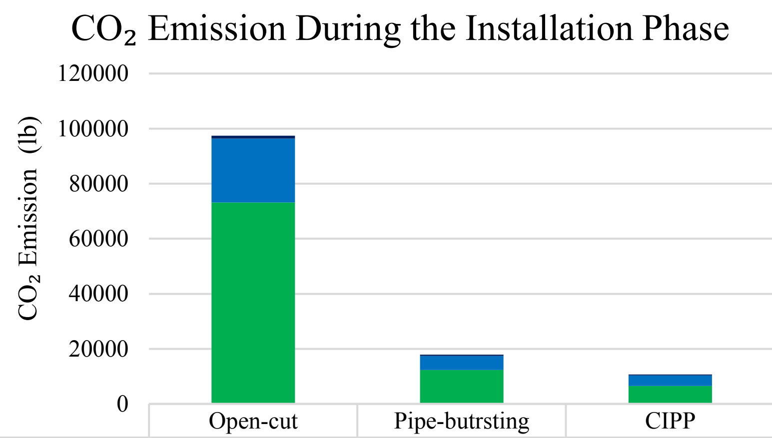
Open Cut Method					
Equipment	**Type/ Model**	**Power**	**Fuel**	**General Use**	**Use (hrs)**
Paving Machine	CAT AP555F	142 hp.	Diesel	Resurface road following pipe installation	4
Asphalt Compactor	CAT CCS7	100.6 hp.	Diesel	Resurface road following pipe installation	4
CO_2 Emission			**1,280 Pounds**		
Pipe Bursting Method					
Asphalt Compactor	CAT CCS7	100.6 hp.	Diesel	Resurface road following pipe installation	1
CO_2 Emission			**100 Pounds**		
Cured-in-Place Pipe Method					
Asphalt Compactor	CAT CCS7	100.6 hp.	Diesel	Resurface road following pipe installation	0.5
CO_2 Emission			**60 Pounds**		

4.8 Discussion

The energy consumed in the second phase of the pipeline life-cycle is high and depends on the installation methods and pipeline life expectancy. In this phase, there is a big difference in energy consumption between tradition open-cut method and trenchless technology methods and this difference is significant for energy saving. This study compares three installation methods: traditional open cut, pipe bursting, and cured-in-place pipe (CIPP). This phase is divided into three sections: the transport pipe and equipment to job-site, pipeline installation, and backfill materials and repaving. For the first section (transport pipe and equipment to job-site), CIPP is more environmentally friendly due to the less equipment and materials to take to the job-site, and open-cut method is the higher energy consumption because of more equipment and heavy pipe required to take to job-site. In the pipeline installation section, open-cut is the higher energy consumption due to the bigger trench needed to dig to lay down the pipeline compared to other methods, the trenchless method they required only entrance and exit pits to enter the pipeline. The size of the pits depends on the type of installation methods. In this study, the pits size for pipe bursting is 10-feet ×10-feet and 8-feet×8-feet for CIPP. For the backfill materials and repaving, this section depends on the size of the trench. Open-cut is the higher energy consumption due to the big trench required more materials and more asphalt/ concrete to repave the trench compare to other methods.

4.9 Chapter Conclusion

During the second phase of pipeline life-cycle (installation phase), all the energy consumed in this phase: transporting pipe and equipment to the job-site, installation/ repaving activities, and backfill materials for the three installation methods shown in figure 4.6. The results show that the CIPP method is the more environmentally friendly method compared to open-cut and pipe bursting installation method for a 36-inch, 100-feet long pressure pipe project due to less installation equipment, short duration time, and the small entrance and exit pits. The open-cut construction method is the more energy consuming method during the installation phase compared to the other two methods because of the more equipment, long time and bigger trench are required in this method.



	Open-cut	Pipe-butrsting	CIPP
Transport Pipe and Equipment to Jobsite	1053	453	302
Installation and repaving	23270	5171	3801
Backfill	73134	12298	6552

Figure 4-6 CO_2 Emissions During the Installation Phase

The lifetime of CIPP in this study assumed to be 50 years, while the lifetime for PCCP (open-method), and PVC/ HDPE (pipe bursting method) are 100 years (Bueno, 2010). Which means in the 100 years of pipeline life, the CIPP installed twice while the other pipe materials one time only, that will make a small increase in carbon emissions of the CIPP method during the installation phase compared to pipe bursting method. The carbon emissions for CIPP for 100 years for installation phase is 21,310 pounds, for PVC/ HDPE is 17,922 pounds (pipe bursting method) and for PCCP (open-cut method) is 97,457 pounds.

CHAPTER 5

OPERATION AND DISPOSAL PHASES

5.1 Operation Phase

5.1.1 Introduction

The operation phase of a pipeline can be divided into three categories when accounting for the CO_2 emissions. Regarding the first category, pumping energy for a pressured pipeline, the wastewater needs to be pumped to a certain pressure and flow rate using pumps, which involves energy consumption and CO_2 emissions. On the other hand, for gravity wastewater pipelines, there is no need to pumping energy; therefore, the energy consumption due to pumping for a gravity pipeline is zero over the life-cycle of the pipeline. The second category in the operation phase of a pipeline's life-cycle is cleaning work, which is considered in this study. There are too many types of pipeline cleaning methods to individually evaluate each method. In this study, the pig cleaning method is chosen. The third category is pipe repair over the life-cycle of the pipeline. The pipe needs to be repaired or replaced within the estimated working life (which is considered in this study 100 years). In this category, the study considers only the emitted carbon for replacing the CIPP pipe after 50 years of the working life.

5.1.2 Pumping Energy

The wastewater pressure pipeline needs to be pumped at a pressure higher than the minimum required at a specific flow rate. Factors affecting the pump energy consumption are the cross-sectional area, a coefficient of friction, and pump efficiency. The higher the C factor, the less friction between the fluid and the surface. The pump efficiencies vary depending on the manufacturer, age, and condition. The impact on pumping energy is primarily related to the decreases in roughness, decreasing in pipe roughness in an energy saving from 0.20 % to 0.70 % (Speight, 2014). In this study, pump efficiency is assumed to be 70%, and the flow rate is 20 ft^3/sec (8,977 gallons/ minute).

Hazen- Williams's equations are used to calculate the pump break power (Khan 2015). The energy consumed for the pump is obtained by the pump power in a certain number of working hours. Usually, the pump operating time is considered to be 6 to 8 hours daily throughout the service life of the pipe (Piratla, 2012). However, the operating time is varied over the day. The demand for pumping is high from 6 AM – 9 AM, 1 PM – 2 PM and 7 PM – 9 PM. In this study, the operation time is assumed to be 6 hours every day. The pumping design, amount of energy consumed, and CO_2 emissions released from pumping wastewater in this study are calculated and presented in Table 5-1. In this study, the operating life of the pipeline is assumed to be 100 years. Usually, PCCP, PVC, and HDPE are designed for an average life of 100 years, and CIPP for an average of 50 years (Bueno, 2010). Because the operating life in this study is 100 years and the average life of CIPP is 50 years, CIPP is replaced after 50 years of service, that means the inside diameter is different in the first 50 years from the last 50 years of life service.

Table 5-1 CO_2 Emissions During Pumping Wastewater

Description	**Quantity**	**Unit**	**Remark/ Reference**
Pre-stress concert cylinder pipe (PCCP)			
Wall thickness	3	in	AWWA C301
Inside diameter	30	in	Outside diameter – (2×wall thickness)
Flow rate	20	ft³/sec	Assumption
Hazen- Williams Coefficient (C)	130		Gupta 2008
Cross section Area (A)	4.9	ft²	$A = \frac{\pi}{4}(\mathrm{d})^2$
Velocity of flow	4.08	ft/sec	$V = \frac{Q}{A}$
Equivalent roughness of PCCP (ε)	$40 * 10^{-4}$		Gupta 2008
Kinematic Viscosity (υ)	$0.93 * 10^{-5}$	ft²/sec	Gupta 2008
R_e	1,096,774		$R_e = \frac{Vd}{\upsilon}$
Fraction factor (f)	0.0225		From moody diagram for frication factor for pipes
Friction head lose	0.23	ft	$h_f = \frac{fL}{d}\frac{V^2}{2g}$
Pump head Hp	1.23	ft	$\mathrm{Hp} = \Delta\mathrm{Z} + \mathrm{h_{loss}}$ ΔZ= 1 ft.
Pump Efficiency	70%		Assumption
Specific weight (γ)	62.418	lb/ ft³	Gupta 2008
Pump break power	4	hp	$BHP = \frac{\gamma Q \mathrm{Hp}}{550\eta}$
Working hours per day	6	hours	Assumption
Energy consumed per one year	6,535	kWh	1 hp = 0.746 kW
CO_2 emissions rate	1.2038	lb/kWh	eGRID2014
CO_2 emissions for 100 years	786,700	lb	Total energy for 100 years × CO_2 emissions rate
Polyvinylchloride (PVC) Pipe			
Wall thickness	0.875	in	AWWA C905
Inside Diameter	34.25	in	Outside diameter – (2× wall thickness)
Flow rate	20	ft³/sec	Assumption
Hazen- Williams Coefficient (C)	140		Gupta 2008
Cross section Area (A)	6.38	ft²	$A = \frac{\pi}{4}(\mathrm{d})^2$

Table 5-1 Continued

Description	Quantity	Unit	Remark/ Reference
Velocity of flow	3.14	ft/sec	$V = \frac{Q}{A}$
Equivalent roughness of PVC (ε)	$5 * 10^{-6}$		Gupta 2008
Kinematic Viscosity (v)	$0.93 * 10^{-5}$	ft²/sec	Gupta 2008
R_e	962,258		$R_e = \frac{Vd}{v}$
Fraction factor (f)	0.0118		From moody diagram for frication factor for pipes
Friction head lose	0.063	ft	$h_f = \frac{fL}{d}\frac{V^2}{2g}$
Pump head Hp	1.063	ft	$\text{Hp} = \Delta Z + h_{loss}$ ΔZ= 1 ft
Pump Efficiency	70%		Assumption
Specific weight (γ)	62.418	lb/ ft³	Gupta 2008
Pump break power	3.45	hp	$BHP = \frac{\gamma Q \text{Hp}}{550\eta}$
Working hours per day	6	hours	Assumption
Energy consumed per one year	5,636	kWh	1 hp = 0.746 kW
CO_2 emissions rate	1.2038	lb/kWh	eGRID2014
CO_2 emissions for 100 years	678,500	lb	Total energy for 100 years × CO_2 emissions rate
High-density polyethylene HDPE			
Wall thickness	2.12	in	AWWA C906
Inside Diameter	31.76	in	Outside diameter – (2× wall thickness)
Flow rate	20	ft³/sec	Assumption
Hazen- Williams Coefficient (C)	140		Gupta 2008
Cross section Area (A)	5.52	ft²	$A = \frac{\pi}{4}(\text{d})^2$
Velocity of flow	3.62	ft/sec	$V = \frac{Q}{A}$
Equivalent roughness of HDPE (ε)	$5 * 10^{-6}$		Gupta 2008
Kinematic Viscosity (v)	$0.93 * 10^{-5}$	ft²/sec	Gupta 2008
R_e	1,027,613		$R_e = \frac{Vd}{v}$

Table 5-1 Continued

Description	**Quantity**	**Unit**	**Remark/ Reference**
Fraction factor (f)	0.0115		From moody diagram for frication factor for pipes
Friction head lose	0.088	ft	$h_f = \frac{fL}{d}\frac{V^2}{2g}$
Pump head Hp	1.088	ft	$\text{Hp} = \Delta Z + h_{loss}$ ΔZ= 1 ft
Pump Efficiency	70%		Assumption
Specific weight (γ)	62.418	lb/ ft³	Gupta 2008
Pump break power	3.52	hp	$BHP = \frac{\gamma Q \text{Hp}}{550\eta}$
Working hours per day	6	hours	Assumption
Energy consumed per one year	5,751	kWh	1 hp = 0.746 kW
CO_2 emissions rate	1.2038	lb/kWh	eGRID2014
CO_2 emissions for 100 years	692,277	lb	Total energy for 100 years ×CO_2 emissions rate
Cured-in-Place Pipe (CIPP)			
From 0 to 50 Years			
Wall thickness	0.58	in	F1216
Inside Diameter	28.84	in	Hosting pipe is PCCP with 30 in inside diameter – (2 × wall thickness)
Flow rate	20	ft³/sec	Assumption
Hazen- Williams Coefficient (C)	140		Gupta 2008
Cross section Area (A)	4.52	ft²	$A = \frac{\pi}{4}(\text{d})^2$
Velocity of flow	4.425	ft/sec	$V = \frac{Q}{A}$
Equivalent roughness of CIPP (ε)	$5 * 10^{-6}$		Gupta 2008
Kinematic Viscosity (v)	$0.93 * 10^{-5}$	ft²/sec	Gupta 2008
R_e	1,141,878		$R_e = \frac{Vd}{v}$
Fraction factor (f)	0.011		From moody diagram for frication factor for pipes
Friction head lose	0.14	ft	$h_f = \frac{fL}{d}\frac{V^2}{2g}$
Pump head Hp	1.14	ft	$\text{Hp} = \Delta Z + h_{loss}$ ΔZ= 1 ft

Table 5-1 Continued

Description	Quantity	Unit	Remark/ Reference
Pump Efficiency	70%		Assumption
Specific weight (γ)	62.418	lb/ ft³	Gupta 2008
Pump break power	3.7	hp	$BHP = \frac{\gamma Q \text{Hp}}{550\eta}$
Working hours per day	6	hours	Assumption
Energy consumed per one year	6,045	kWh	1 hp = 0.746 kW
CO_2 emissions rate	1.2038	lb/kWh	eGRID2014
CO_2 emissions from 0 to 50 years	363,850	lb	Total energy for 50 years * CO_2 emissions rate
From 50 to 100 Years			
Wall thickness	0.58	in	F1216
Inside Diameter	27.68	in	Hosting pipe is PCCP with 28.84 in inside diameter – (2 × wall thickness)
Cross section Area (A)	4.17	ft²	$A = \frac{\pi}{4}(\text{d})^2$
Velocity of flow (V)	4.80	ft/sec	$V = \frac{Q}{A}$
R_e	1,190,193		$R_e = \frac{Vd}{v}$
Fraction factor (f)	0.011		From moody diagram for frication factor for pipes
Friction head lose	0.17	ft	$h_f = \frac{fL}{d}\frac{V^2}{2g}$
Pump head Hp	1.17	ft	$\text{Hp} = \Delta\text{Z} + \text{h}_{\text{loss}}$ ΔZ= 1 ft
Pump break power	3.79	hp	$BHP = \frac{\gamma Q \text{Hp}}{550\eta}$
Energy consumed per one year	6,192	kWh	1 hp = 0.746 kW
CO_2 emissions from 50 to 100 years	372,689	lb	Total energy from (50 to 100) years × CO_2 emissions rate
CO_2 emissions for 100 years	736,539	lb	Emissions (0 to 50) + Emissions (50 to 100)

5.1.3 Pipe Cleaning

The second category in the operation phase of a pipeline life-cycle is cleaning. Proper cleaning for a sewer pipeline can improve capacity and hydraulic performance.

Operational records can show when a force main needs cleaning. One useful indicator is the volume of flow per electricity consumed; if the flow rate is significantly reduced, then it indicates a build-up of debris or encrustation on the pipeline. Cleaning methods can be categorized into two groups: the first group is those that remove the solids (pigging, vacuum jetters, and bucket); the second group dislodges the solids and carries them out with water flow (high-pressure water jetting and mechanical rodding) (Morrison, 2010). In this study, the pigging method is used and is assumed to be used every ten years, which mean it will be used 10 times in the life of the pipeline.

Pigging has become a popular cleaning method, and it is currently the most popular cleaning method for sewer pressure pipes. Pigging requires a high volume of water at high pressure to force the pig to move through the pipeline, which will remove debris and clean the interior pipeline wall. A pumper truck is used to push the pig into the pipe. The most commonly used pig is the poly pig, as Figure 5-1 shows. Attention must be given not to exceed the design pipeline pressure during the pipeline cleaning using the pigging method. Access to a pipeline is required for pig insertion, so this may be a significant problem for using the pigging cleaning method for a pressure pipeline unless access can be provided at the pump station (Morrison, 2010).

Figure 5-1 Polyurethane Pigs (Morrison, 2010)

The processes of pumping and water treatment are the largest consumers of energy in water use and recycling (EPA, 2013). For pipeline cleaning, in this study, two things are taken into consideration: the amount of water, that will be used for cleaning the pipeline and the fuel consumption for the pumper truck to transport the water to the job-site. The water that will be used for pipeline cleaning will go into the system and to the plant for treatment. Thus, this research will focus on how much energy will be used to treat the water that is used for cleaning. According to the EPA in 2013 (energy efficiency in water and wastewater facilities), the energy used for water treatment is 100 to 16,000 kWh/MG. By knowing the distance to the job-site and the number of trucks needs to finish the job, the CO_2 emissions can be calculated during the pipeline cleaning. Table 5-2 shows the total CO_2 emissions during the pipeline cleaning stage.

The following considerations are used at this stage:

- The pigging method is used for pipeline cleaning every ten years, which mean it will be used ten times in the life of the pipeline.
- The distance between the job-site and truck storage is 20-miles.
- Fuel consumption is 5.9 miles per gallon of diesel (transportation energy data book, 2015).
- CO_2 emissions per gallon of diesel are 22.2 pounds/ gallon (U.S EPA, 2005).
- The energy used for water treatment is 0.002502 kWh/gallon (EPA 2013).
- Because of interior roughness in PCCP, the amount of water used for cleaning is assumed to be 1.2 times the volume of the pipeline.
- The CO_2 emission rate used in this study is 1.2038 lb/kWh (eGRID, 2014).

Table 5-2 CO_2 Emissions During Pipeline Cleaning

Description	PCCP	PVC	CIPP	HDPE
Inside diameter (ft)	2.5	2.85	2.4	2.65
Volume of pipeline (gal)	3,672	4,772	3,384	4,126
Number of trucks for one-time cleaning	1	1	1	1
CO_2 emissions from trucks (lb) in ten times of cleaning	1,505	1,505	1,505	1,505
Amount of water (gal) for ten times of cleaning	36,720	47,720	33,840	41,260
Energy consumed in water treatment (kWh)	92	119	85	103
CO_2 emissions from water treatment (lb)	111	143	102	124
Total CO_2 emissions (lb)	1,616	1,648	1,607	1,629

5.2 Disposal Phase

5.2.1 Introduction

At the end of the useful service life of the pipeline, the pipe is disposed of, recycled or abandoned. This phase of the study focuses on embodied energy for pipe materials recycling, and the energy required to dispose the rest of the pipe materials that cannot be recycled. Recycling consumes energy, that energy is generally small compared to the initial embodied energy. Total energy used through the life-cycle of a pipeline is high and impacts the environment by CO_2 emissions. Recycling provides the opportunity to reduce energy in the fabrication phase by using recyclable/ reusable materials.

5.2.2 Recycling Energy

At a global level, civil works and building construction consumes 60% of the raw materials. Of this volume, building represents 40%, in other words, 24% of the world's material extraction (Bribian, 2011). Recycling is the reprocessing of recovered materials at the end of the product life and returning them to use again. Recycling is widely assumed to be environmentally beneficial, although the disassembly, collection, sorting, and processing of materials into new products also requires significant environment impacts (Gao, 2001). This study assumes that the new pipeline is used at the end of the working life of the old pipe. The study looks for each type of pipe materials and finds what content can be recycled and the percentage of materials that can be used again to produce new pipe, and how energy is required to dispose the materials that cannot be recycled. Table 5-3 shows the energy consumed for each of the pipeline material.

Table 5-3 Embodied Recycling Energy for Pipeline Materials

Material	Weight	Unit	Embodied energy for recycling (Ashby 2009)	Energy consumption for recycling
Pre-stressed Concrete Cylinder pip (PCCP)				
Steel cylinder	459.2	lb	5.5 MJ/kg (0.693 kWh/lb)	318 kWh
Concrete core	4,987.35	lb	0.018 MJ/kg (2.27×10^{-3}kWh/lb)	11.3 kWh
Mortar coating	861.12	lb	0.015 MJ/kg (1.89×10^{-3} kWh/lb)	1.6 kWh
Pre-stressing wire	421.5	lb	9.8 MJ/kg (1.235 kWh/lb)	520.6 kWh
Total Energy for 100 ft of PCCP pipeline = 4,257.5 kWh				
Polyvinylchloride pipe (PVC)				
PVC resin	1,328.44	lb	39.9 MJ/kg (5.03 kWh/lb)	6,682 kWh
Total Energy for 100 ft of PVC pipeline = 33,410 kWh				
Cured-in-Place Pipe (CIPP)				
Epoxy resin	3,706.13	lb	No recycling	0
Felt	1,080.24	lb	No recycling	0
Fiberglass reinforced	1,096.13	lb	No recycling	0
Tube liner	4.71	lb	No recycling	0
Total Energy for 100 ft of CIPP liner = 0				
High-Density Polyethylene Pipe (HDPE)				
HDPE resin	2,004	lb	36 MJ/kg (4.536 kWh/lb)	9,090 kWh
Total Energy for 100 ft of HDPE pipeline = 45,450 kWh				

5.2.3 Disposal Energy

The use of environmental and recyclable materials is the key to lowering the high CO_2 emissions and improving environmental impact. Many materials have a significant environmental impact from CO_2 emissions. Using recyclable materials can reduce CO_2 emissions by more than half. Table 5-4 shows the differences between fabricating the pipe from virgin material versus from recycled material. The CIPP pipe cannot be recycled because of the epoxy resin.

Table 5-4 Different Between Fabricate Form Virgin Materials and Recycled Materials

Pipe	Fabrication from virgin material	Fabrication from recycled material
PCCP	23,326 kWh	4,256 kWh
PVC	56,492 kWh	33,410 kWh
HDPE	106,557 kWh	45,450 kWh
CIPP	82,731 kWh	0

From this study, most of the energy consumed to fabricate PCCP comes from steel, and small energy comes from product concrete. The concrete in PCCP is assumed to be recycled to aggregate; 80% of steel and 20% of concrete are considered to be recycled in the study. Aggregate can be used again for pipeline bedding or in the concrete core for PCCP. In this study, 50% of PVC and HDPE pipes are considered to be recycled at the end of their service life. CIPP cannot be recycled because of the epoxy resin, so CIPP is made from 100% virgin materials. The energy consumed to dispose of the material that cannot be recycled is considered to be 3.5% of the fabrication energy (ImpEE Project, 2005) as shown in Table 5-5.

Table 5-5 Energy Consumed for Pipe Materials Disposal

Materials		Recycling		Disposal	
PCCP	Steel cylinder	Percentage of Recycling	Energy consumption by recycling	Percentage of disposal	Energy required for disposal (3.5%)
		80 %	1,272 kWh	20%	70 kWh
	Concrete core	20 %	11.3 kWh	80%	83.8 kWh
	Mortar coating	0 %	0	100%	10.6 kWh
	Pre-stressing wire	80 %	2,082 kWh	20%	67 kWh
		Total of Recycling Energy = 3,365.3 kWh		Total of Disposal Energy = 231.4 kWh	
PVC	PVC resin	50 %	16,705 kWh	50%	881.1 kWh
		Total of Recycling Energy = 16,705 kWh		Total Disposal Energy = 881.1 kWh	
HDPE	HDPE resin	50 %	22,725 kWh	50%	1,864.74 kWh
		Total of Recycling Energy = 22,725 kWh		Total Disposal Energy = 1,864.74 kWh	
CIPP	Epoxy resin	0 %	0	100%	4,477.6kWh
	Felt	0 %	0	100%	343.3 kWh
	Fiberglass reinforced	0 %	0	100%	966.8 kWh
	Tube liner	0 %	0	100%	3.32 kWh
		Total of Recycling Energy = 0		Total Disposal Energy = 5,791 kWh	

5.3 Result and Discussion

In the operation phase, the energy consumed can be divided into three categories when accounting for the CO_2 emission: pumping energy, cleaning energy and repairing energy. The pumping energy is the energy required to pump the sewer water at a specific flow rate. In the first category, PCCP is more energy consuming than the other pipelines due to the interior pipe roughness compared to PVC, HDPE, and CIPP. PCCP requires a bigger pump, which requires more energy, while the PVC pipe has the most energy saving compared to other pipe materials due to the smaller wall thickness and bigger inside diameter, which means a smaller pump size is required. In pipeline cleaning, HDPE line gives the most energy saving in this category due to the smaller inside diameter compared to other pipe materials. The small inside diameter requires less water to clean the line, while the PVC line is more energy consuming because of the bigger inside diameter, which means more water is required to clean the inside line. Figure 5.2 shows the CO_2 emissions during the operation phase.

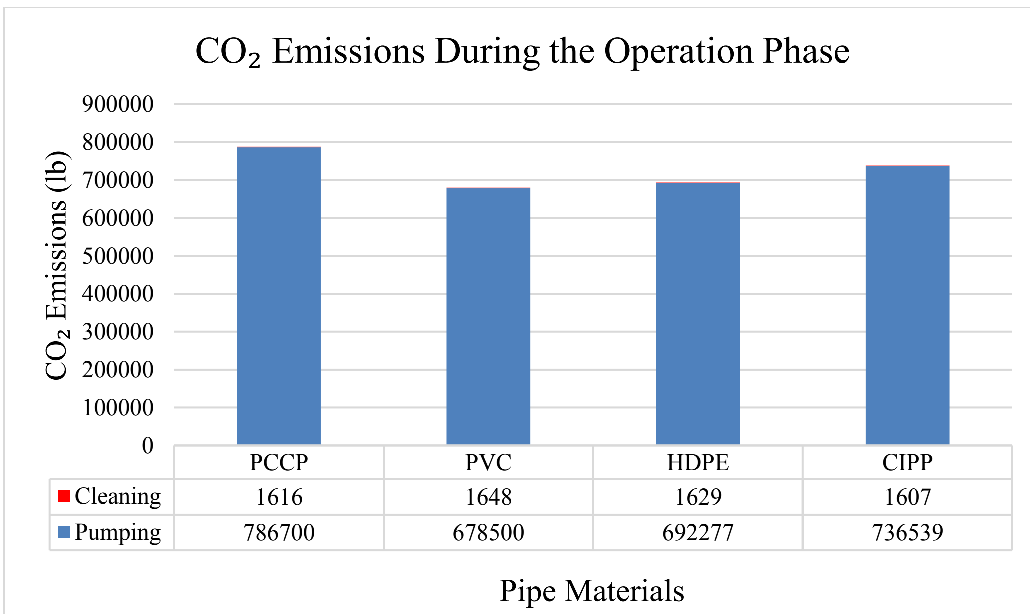


Figure 5-2 CO_2 Emissions During the Operation Phase

The disposal phase is the last phase of the pipe life-cycle when the pipe is disposed of, recycled or abandoned. At the end of the useful service life of pipe materials, some of the material can be recycled, but others cannot be. Energy is required for both options: recycling or disposing. Embodied energy for recycling materials database is used, and for the pipe materials disposal energy 3.5 % of fabrication energy is used in this study. Figure 5.3 shows the CO_2 emissions of the disposal and recycling of each pipe materials. For recycling, CIPP is the less environmentally friendly option because the

CIPP cannot be recycled and needs more energy to dispose of the materials compared to other materials. HDPE pipe is the second less environmentally friendly option compared to other pipe materials due to the high energy required for disposal and recycling of the materials compared to PCCP and PVC. PCCP is the good option for this phase because less energy is required for disposal and recycling of the PCCP's materials.

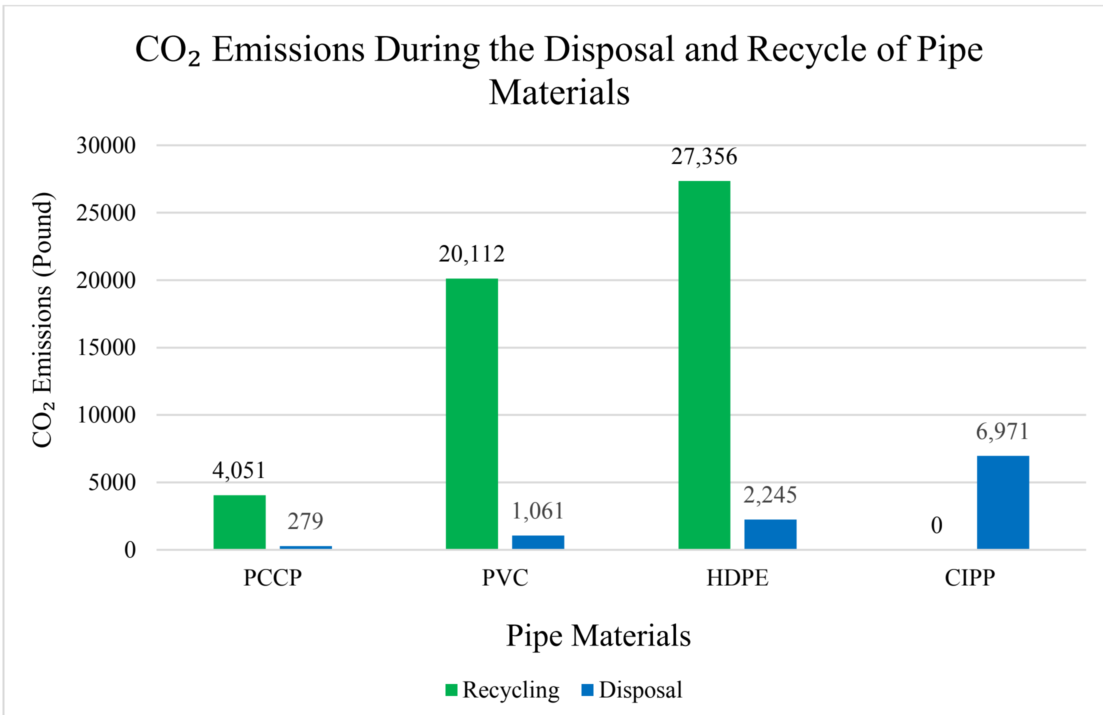


Figure 5-3 CO_2 Emissions During the Disposal Phase

5.4 Chapter Conclusion

In the operation phase, PVC pipe is the most environmentally friendly pipe compared to the other pipe materials due to the smoother pipe interior and the bigger inside diameter. The PCCC pipe has the highest CO_2 emissions because of the pipe interior roughness and smaller inside diameter.

The last phase of the pipeline life-cycle is the disposal phase. This study quantifies the energy consumed and carbon emissions during the disposal and recycles the pipe materials. in the conclusion for this phase, PCCP is the most pipe material that emits the least carbon to the environment compared to other materials because of the basic PCCP materials (concrete and steel) which can be recycled and used again. While the CIPP has the highest carbon emissions in this phase, the CIPP cannot be recycled, that means it requires more energy to dispose of the pipeline materials.

CHAPTER 6

OPTIMIZATION OF PIPELINE LIFE-CYCLE REGARDING CARBON EMISSIONS

This chapter focused on the optimization of the carbon emissions during all life-cycle phases of a pipeline. The author in this chapter makes recommendations for saving energy consumption and reducing carbon emissions during the life-cycle phases of a pipeline. These decisions will help decision-makers and engineers in the future to choose (1) the more environmental materials to produce the pipe with least environmental impact; (2) the lowest environmental installation method for the environment; (3) and how to emit less carbon dioxide during the operation and disposal phases.

6.1 Fabrication Phase Optimization

The basic materials for PCCP pipe are concrete and steel. Steel has a higher energy consumption compared to concrete. In the fabrication phase of PCCP pipe, most of the CO_2 emissions came from the steel. The CO_2 emission from the steel is approximately 83% of the total PCCP pipe emissions during fabrication. Thus, small savings on the production of steel will make significant savings in energy consumption. Using recycled steel will save a significant amount of energy. By using recycled steel, the embodied energy for recycled steel is 9.40 MJ/ kg (average recycled content 59 %) (ICE version 2.0, 2011), by following Table 3-2 in Chapter 3 in this study. The total CO_2

emissions for PCCP pipe using recycled steel is 10,762 pounds while the CO_2 emissions by using the virgin steel is 28,080 pounds as shown in Figure 6-1, which means 38% less CO_2 emissions from using the recycled steel to manufacture the PCCP pipe.

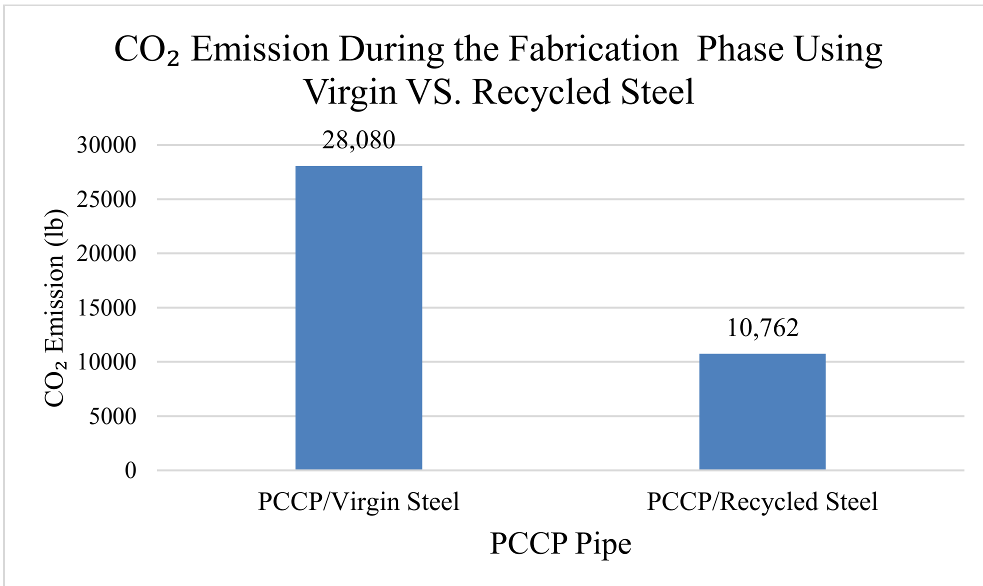


Figure 6-1 CO_2 Emissions During the Fabrication Phase for PCCP Pipe Using Virgin VS. Recycled Steel

Concrete is the most widely used construction material in the world (Tuner, 2013). The most common binder of traditional concrete is Portland cement. Cement production needs high-temperature calcination which is an energy-intensive process. It is estimated that 5% to 6% of all carbon dioxide greenhouse gases generated by human activities originate from cement production (Lloyd, 2009). The global cement production is expected to grow from 3.27 billion metric tons in 2010 to 4.83 billion metric tons in 2030 (Nath, 2018). The substitution of 40% of the cement with fly ash in concrete has been found to increase the service life by 1.6 to 1.75 times more than the conventional concrete (Nath, 2018). By replacing 40% of cement with fly ash, about 36% to 43% of the carbon footprint and 36% to 38% of embodied energy consumption can be avoided for different concrete covers (Nath, 2018). Geopolymer is an alternative binder based on fly ash (a small waste collected from the emissions liberated by coal-burning power stations) (Tuner, 2013). Geopolymer cement is manufactured differently than Portland cement. It does not require extreme high-temperature kilns with a significant expenditure of fuel, nor do they require such a large capital investment in production plants and equipment. The reduction of greenhouse gas emissions from using the geopolymer cement instead of ordinary Portland cement is in the range of 70 % to 90% (Davidovits, 2015). Figure 6-2 shows the difference in CO_2 emissions when Portland cement, Fly ash, and geopolymer concrete are used during the fabrication of PCCP Pipe.

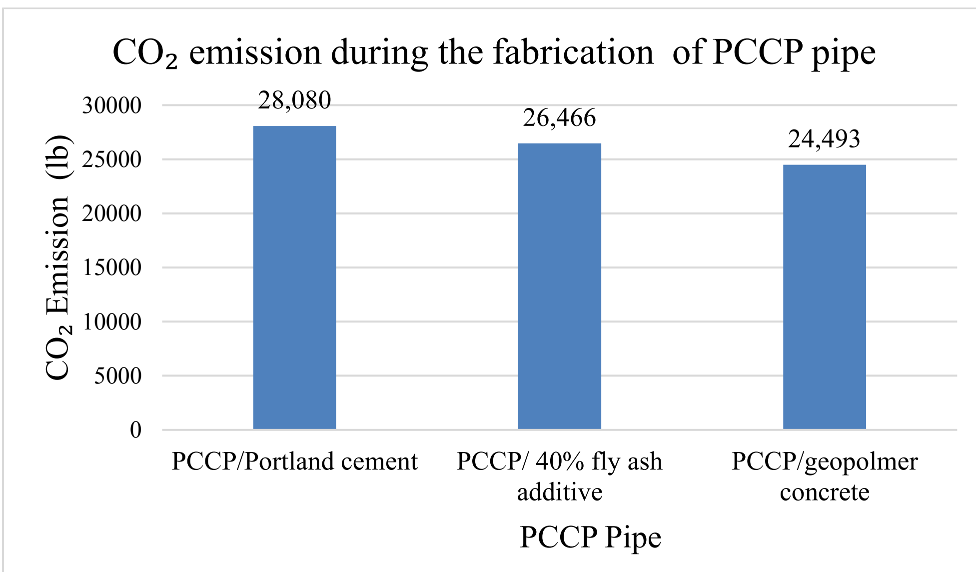


Figure 6-2 Comparing the CO_2 Emissions by Using Portland Cement, Fly Ash and Geopolymer Concrete During the Fabrication Phase of PCCP Pipe

Plastic has become an integral part of society as population growth and technological development have resulted in the global production of plastic increasing by 500% over the last 30 years and it is expected to continue to grow to 850 million tons per year by 2050 (Keriger, 2014). For PVC and HDPE pipes, there is a big saving in energy consumption by producing pipe from recycled material as shown in Table 6-1. Figure 6-3 shows the difference between producing PVC and HDPE pipes from virgin materials versus recycled materials.

Table 6-1 Embodied Energy for PVC and HDPE pipes

Material	Embodied Energy (Mj/kg)	Reference
PVC/virgin	67.50	ICE version 2.0
PVC/recycled	40	ImpEE project
HDPE/ virgin	84.4	ICE version 2.0
HDPE/recycled	45	ImpEE project

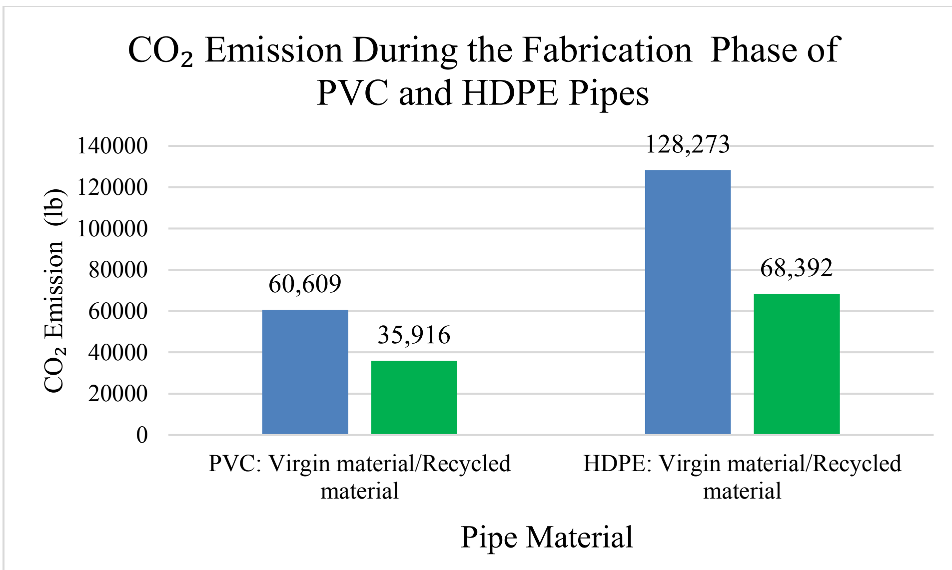


Figure 6-3 Comparing the CO_2 Emissions Between Virgin VS. Recycled Materials for PVC and HDPE Pipes

In the fabrication phase, CIPP pipe had the highest CO_2 emission compared to other pipe materials. The epoxy resin is the main factor that increased the energy. Choosing other resins can reduce carbon emissions and save more energy. The main types of resin used in CIPP applications are vinyl ester, polyester, and epoxy (Matthews, 2014). Polyester resins most typically are qualified and specified for gravity and storm sewer pipe rehabilitation (National Liner Specifications). This study focuses on the pressure sewer line; therefore, it was recommended to use the epoxy or vinyl ester resin in the sewer pressure line application because polyester resin cannot be used for pressure pipelines.

Resin choices are determined by the owner and contractor to achieve the final product properties desired. Table 6-2 shows the embodied energy for the most commonly used resin in sewer line applications.

Table 6-2 Embodied Energy for CIPP Resin

Resin	Embodied Energy (MJ/kg)	References
Epoxy resin	137	ICE version 2.0
Vinyl ester resin	119.3	EuCIA 2016

As shown and calculated in Table 3-5, the weight of the resin in CIPP pipe is almost two-thirds of the total weight of the CIPP lining. That means a small energy savings in producing the resin will help save energy in the fabrication phase of CIPP. In case of using vinyl ester resin instead of epoxy resin and by following Table 3-5, the total CO_2 emissions for fabrication phase for the CIPP lining using the polyester resin for a 100-foot section with a 36-inch diameter is 89,650 pounds, while it is 99,591 pounds when using epoxy resin. The total saving on CO_2 emissions by using the vinyl ester resin instead of the epoxy resin on the fabrication phase of CIPP lining for 36-inch diameter with 100-foot-long is 9,941 pounds. Figure 6-4 shows the different CO_2 emissions during the fabrication phase of CIPP lining with different resin types.

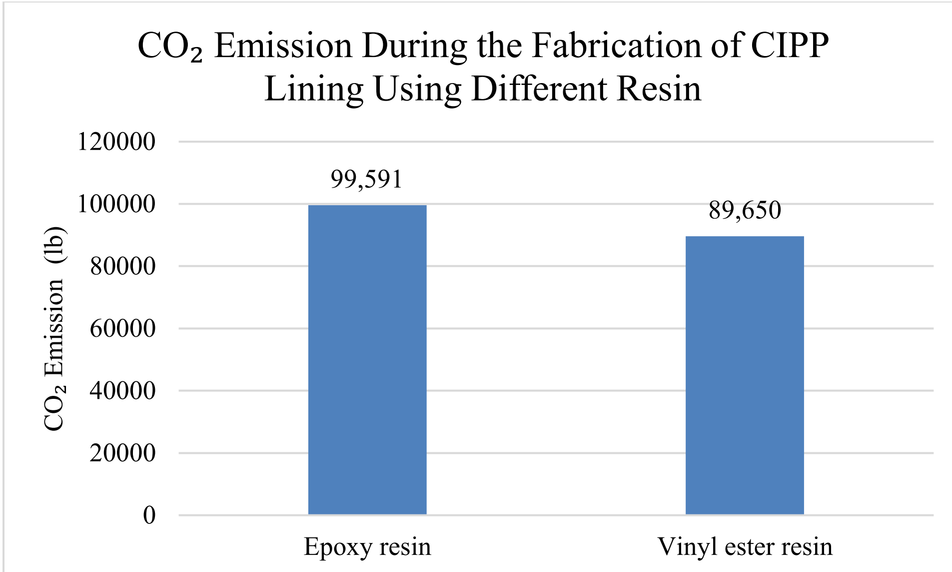


Figure 6-4 CO_2 Emissions During the Fabrication Phase for CIPP Lining Using Different Resin

Figure 6-5 shows the difference between the pipeline materials before and after the optimization during the fabrication phase. The results found that the savings in carbon emissions after the optimizing are 75% in PCCP pipe, 41% in PVC pipe, 47% in HDPE pipe, and 10% in CIPP pipe as shown in Figure 6-5.

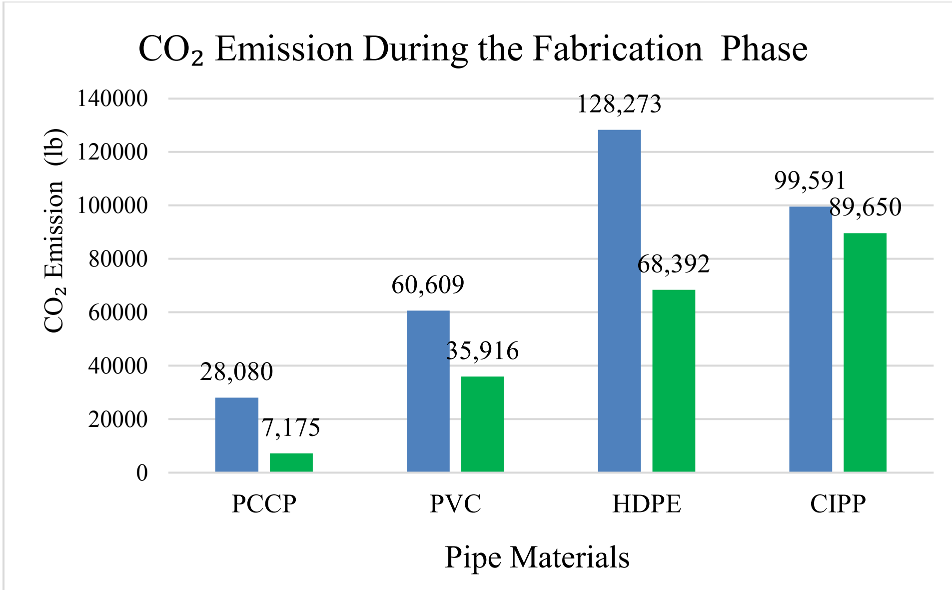


Figure 6-5 Shown the Difference Between the Pipeline Materials During the Fabrication Phase Before and After the Optimizing

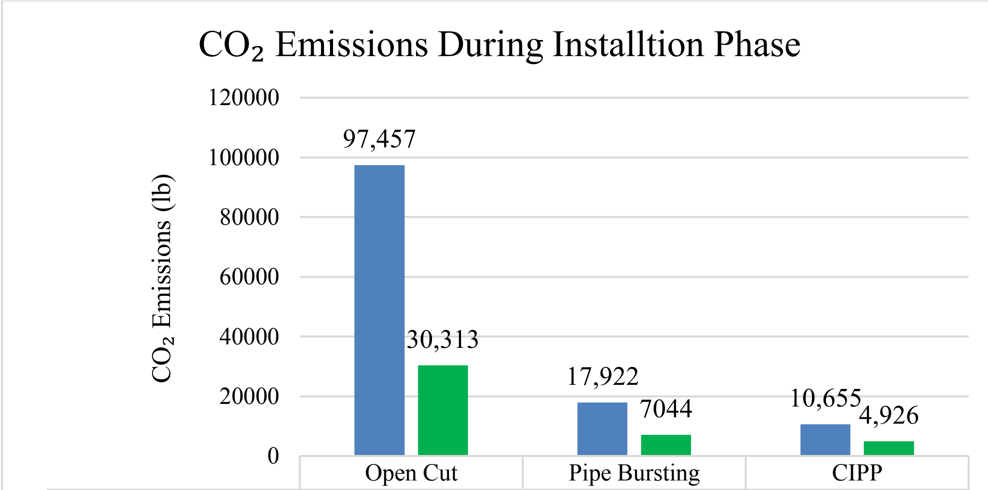
6.2 Installation Phase Optimization

In the installation phase, the open cut installation method has higher CO_2 emissions and the CIPP method has lower CO_2 emissions. In this phase, most of the energy consumption comes from the production and transport of backfill materials. For example, 75% of carbon emissions in the open cut construction method comes from the production and transport of backfill materials, and the pipe bursting and the CIPP methods are 68% and 61%, respectively. In case of using the same backfill materials, instead of new backfill, additional savings can be had.

There are two options evaluated for repaving the road surface: asphalt or concrete. Most of the project owners and decision makers look only at the direct cost and go with the asphalt option because it is cheaper than concrete. Asphalt pavement is cheaper compared to concrete pavement, but the asphalt has higher carbon emissions. The open cut construction method needs a big trench to install the pipeline. That means that the open cut method consumes more energy in repaving than other methods.

In this study, asphalt is used to repave the surface. Asphalt has higher embodied energy (0.63 kWh/lb.) compared to reinforced concrete (0.0945 kWh/lb.) (ICE database). For the open-cut method, when using concrete pavement, the CO_2 emissions are 6,826 pounds, but when using asphalt for repaving the surface, the CO_2 emissions are 52,784 pounds. For the pipe bursting method when using asphalt, the CO_2 emissions are 8,797 pounds, whereas they are 1,365 pounds when using reinforced concrete. In the CIPP method, when asphalt is used for repaving, CO_2 emissions are 4,692 pounds and when concrete is used, emissions are 728 pounds. Choosing concrete will result in a significant reduction in carbon use, which will help to mitigate greenhouse gas emissions.

In the installation phase, large reductions in CO_2 emissions are made by using the same backfill materials and concrete pavement instead of new backfill materials and asphalt pavement, as shown in Figure 6-6. The CO_2 emissions are reduced to almost 70% in the open-cut method, 60% in the pipe bursting method and 50% in the cured-in-place method.



	Open Cut	Pipe Bursting	CIPP
New backfill/asphalt	97457	17922	10655
Same backfill/concrete	30313	7044	4926

Figure 6-6 Comparing the CO_2 Emissions Between New Backfill Materials/Asphalt Pavement and Same Backfill Materials/ Concrete Pavement During the Installation Phase

6.3 Operation Phase Optimization

The two largest factors in the operation phase are the size of the pump force main and the roughness of the pipeline. The size of the pump depends on the inside diameter and the roughness of the interior pipe face (Hazen-Williams coefficient (C)). For the same outside pipe diameter with same flow rate; bigger inside diameter with smaller wall thickness needs smaller pump size and is the opposite for smaller inside pipe diameter with thicker wall thickness. Thus, a reduction in wall thickness results in a smaller pump size, which will help to reduce the CO_2 emissions during the operation phase. As shown in Figure 5-2, for a 36-inch pipe diameter with a 100-foot-long section under 100 psi pressure, PVC pipe emits the least carbon compared to HDPE, and that is due to the smaller wall thickness of PVC pipe for the same diameters.

PCCP pipe has the lowest C value (meaning it is rougher) compared to the PVC, HDPE, and CIPP pipe materials. To reduce the roughness of the interior surface of the PCCP pipe, an epoxy coating can be applied to the pipe to make it smoother as shown in Figure 6-7. A 0.13-inch (3.5mm) thickness is the minimum (industry recommended thickness), for an epoxy coating (Matthews, 2012). The coating will increase the Hazen Williams coefficient and reduce energy costs and CO_2 emissions (Assard, UCT 2017). Table 6-3 is showing the calculation of CO_2 emissions during the operation phase (pumping wastewater) of PCCP Pipe after the epoxy coating is applied.

Figure 6-7 Epoxy Coating for the PCCP pipe (ESCS Pipe Coating, 2018)

Table 6-3 CO_2 Emissions During the Operation Phase (Pumping Wastewater) of PCCP Pipe After Epoxy Coating

Description	Unit	Quantity	Reference/remark
Epoxy coating thickness	in	0.13	EPA 2012
PCCP pipe inside diameter after coating	in	29.74	30 in- (0.13×2)
Hazen Williams coefficient (C)		140	Gupta 2008
Cross section Area (A)	ft^2	4.9	
Flow rate	ft^3/sec	20	
Velocity of flow	ft/sec	4.08	$V = \frac{Q}{A}$
Equivalent roughness of PCCP after coating (ε)		$5 * 10^{-6}$	Gupta 2008
Kinematic Viscosity (v)	ft^2/sec	$0.93 * 10^{-5}$	Gupta 2008
R_e		1,095,860	$R_e = \frac{Vd}{v}$
Fraction factor (f)		0.0115	From moody diagram for frication factor for pipes
Friction head lose	ft	0.119	$h_f = \frac{fL}{d}\frac{V^2}{2g}$
Pump head Hp	ft	1.119	$\mathrm{Hp} = \Delta Z + h_{loss}$ ΔZ= 1 ft.
Pump Efficiency (η)		70%	
Specific weight (γ)	lb/ ft^3	62.418	
Pump break power	hp	3.63	$BHP = \frac{\gamma Q \mathrm{Hp}}{550\eta}$
Working hours per day	6	hours	Assumption
Energy consumed per one year	kWh	5,930	1 hp = 0.746 kw
CO_2 emissions rate	lb/kWh	1.2038	eGRID2014
CO_2 emissions for 100 years	lb	713,853	Total energy for 100 years × CO_2 emissions rate

After the coating, the PCCP interior surface is smoother than before the coating, which means less water is needed for pipeline cleaning. Table 6-4 shows the energy consumption and carbon emissions for PCCP pipes after the coating is applied.

Table 6-4 CO_2 Emissions During the Cleaning of PCCP Pipes After Epoxy Coating

Description	Unit	Quantity
Inside diameter	in	29.74
Volume of pipeline	gal	3,609
Number of trucks for each time to clean the pipeline		1
distance between the job-site and truck storage	mil	20
CO_2 emissions from trucks in ten times of cleaning	lb	1,505
Amount of water for ten times of cleaning	gal	36,090
Energy consumed in water treatment	kWh	90.3
CO_2 emissions from water treatment	lb	108.7
Total CO_2 emissions	lb	1,614

It is important to calculate the energy required for the epoxy coating and add it to the total energy consumption for the operation phase of the PCCP pipe. If the total energy with epoxy coating is less than the total energy without coating for the operation phase, then carbon emissions can be reduced by applying the epoxy coating. Table 6-5 shows the CO_2 emissions from applying the epoxy coating. The CO_2 emissions during applying the epoxy coating is estimated to be 120 lb for a 100-foot section (Matthews, 2012).

Table 6-5 Total CO_2 Emissions for the Epoxy Coating

Description	Unit	Quantity	Reference/remark
Epoxy coating thickness	in	0.13	EPA 2012
Weight of the epoxy coating	lb	799	Volume × density
Epoxy coating embodied energy	kWh/lb	17.26	ICE version 2.0
Energy consumed from producing the epoxy coting	kWh	13,791	Embodied energy × weight
CO_2 emissions rate	lb/kWh	1.2038	eGRID2014
CO_2 emissions from producing the epoxy coating	lb	16,602	Energy consumed from epoxy coating × CO_2 emissions rate
CO_2 emissions from applying the epoxy coating	lb	120	EPA 2012
Total CO_2 emissions	lb	16,722	

The pumping energy, cleaning energy, and epoxy coating manufacturing's energy can be added together in the operation phase for a PCCP pipe to compare the pipeline with and without epoxy coating. The result found that 56,127 lb of carbon dioxide can be saved by using the epoxy coating for PCCP pipe during the operation of 100 years, which means 7% saving on CO_2 emissions as shown in Figure 6-8.

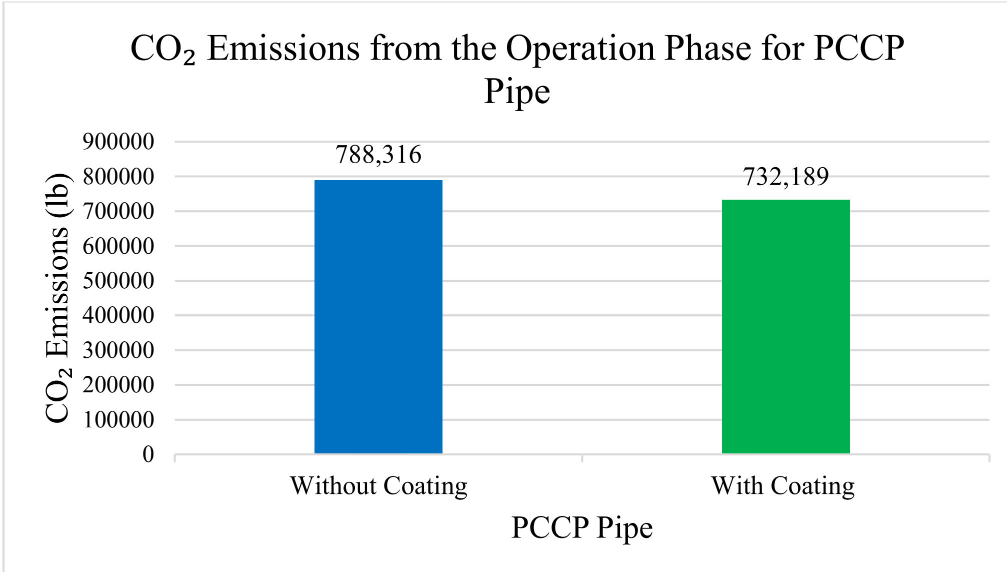


Figure 6-8 CO_2 Emissions During the Operation Phase of PCCP Pipe Before and After Coating

In this study, the operation life is assumed to be 100 years. The life expectancy for PCCP, PVC, and HDPE pipes are 100 years (Bueno, 2010). CIPP pipe has been in service for more than 40 years, and the life design for CIPP pipe is 50 years, but the actual is perhaps well beyond (Allouche, 2011). If we assume that CIPP pipes will last for 100 years, Figure 6-9 shows the CO_2 emission during the life-cycle of CIPP pipes with epoxy resin used in the fabrication phase with different lifespans (50 and 100 years).

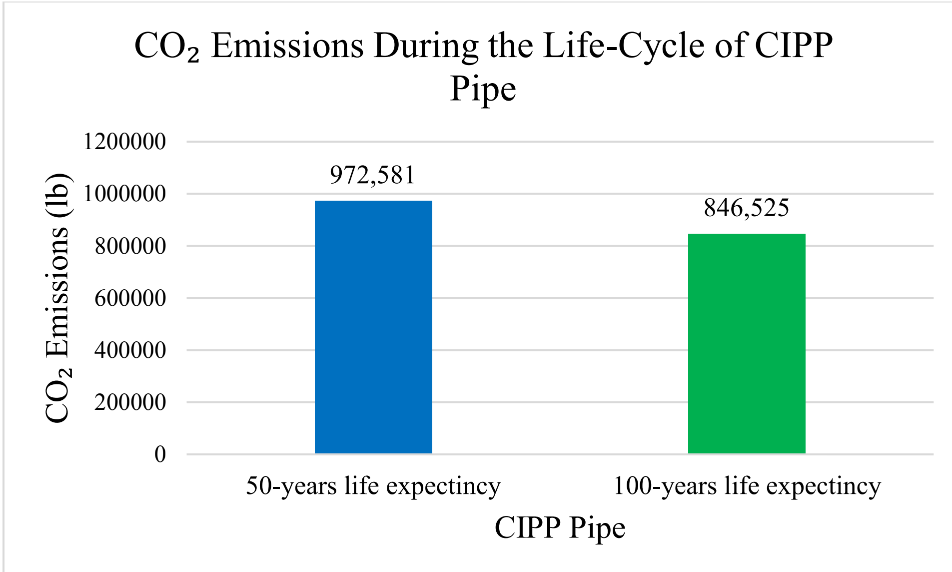


Figure 6-9 CO_2 Emissions During the 100 Years of Life-Cycle of CIPP Pipe

6.4 Disposal Phase Optimization

In the disposal phase, decreasing the CO_2 emissions can be done by increasing the percentage of recycled materials at the end of their service life and decreases the amount of disposal materials at the end of the service life of the pipeline. Figure 6-10 shows an example of how the percentage of recycling materials affects the CO_2 emissions. The example is showing the difference between the recycling percentage in PCCP (steel cylinder, pre-stressing wire 80% to 90% and concrete from 20% to 50%), and for PVC and HDPE increasing the percentage of recycling from 50% to 80%.

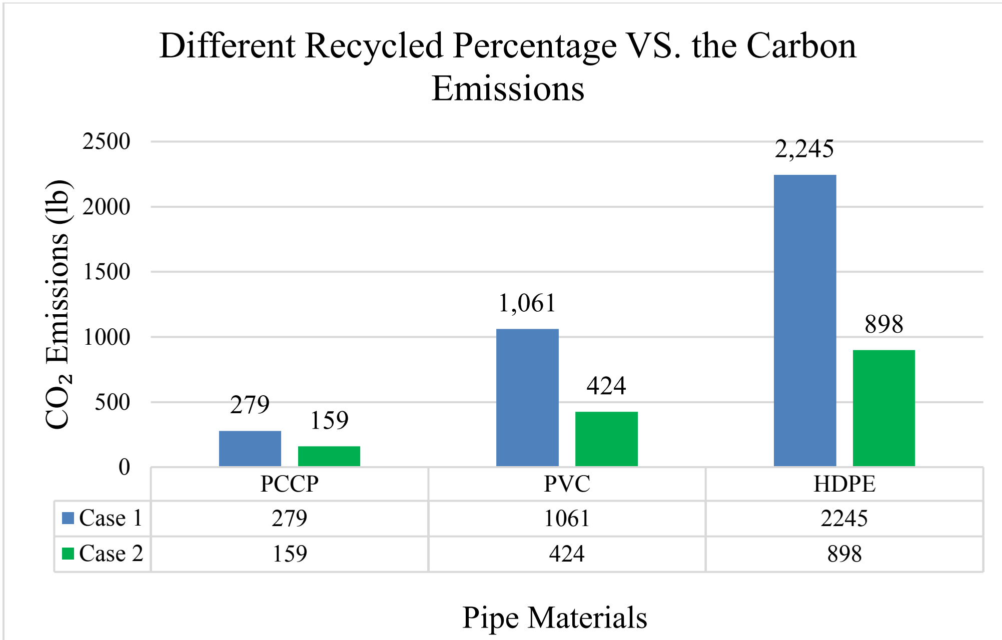


Figure 6-10 Different Recycled Percentage VS. the Carbon Emissions

6.5 Chapter Conclusion

As I discussed at the beginning of this Chapter, a small change in materials can make a big difference in carbon emissions. This chapter presents recommendations to reduce the carbon emissions and to help the engineers and decision-makers to choose the most environmentally friendly pipe materials, installation method, and methods for reducing the carbon emissions during the life-cycle of the pipeline. Figure 6-11 compares the life-cycle of pipeline materials before and after Chapter 6 and shows that a significant savings in carbon emissions during the life-cycle phases is possible.

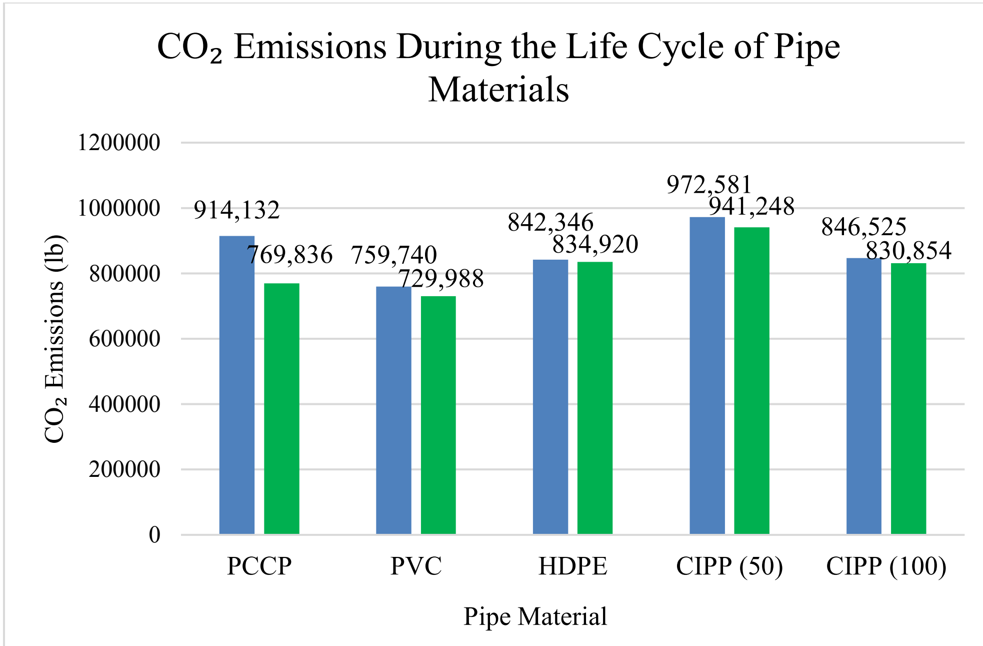


Figure 6-11 The Difference Between the Carbon Emissions During the Life-Cycle of Pipeline Materials Before and After Optimization, CIPP the First Two Columns are Presenting a 50-Years Life Expectancy, While the Last Two Columns are Presenting a 100-Years Life Expectancy

As shown in Figure 6-11, PVC pipe is the most environmentally friendly pipe among all the other pipe materials evaluated due to the smaller wall thickness and the smoother interior surface. Smaller wall thickness will help to save the carbon emissions during the fabrication, and the smoother interior surface will help saving energy during the operation phase. PCCP pipe had less carbon emits to the environment during the life-cycle compared to HDPE and CIPP because of the significant saving on the carbon emissions during the installation when the same backfill materials are used and coating the interior surface of the pipe will help to make the pipe smooth and reduce the C value, which will help to save consuming energy during the operation phase. HDPE pipe has the highest carbon emissions among the other pipe materials due to the wall thickness of the pipe. Thicker wall thickness increases the carbon emissions during fabrication and operation in case of pressure pipeline. In the case of 100 years' life expectancy, CIPP is the better option compared to HDPE regarding the environmental impact. And in the case of 50 years' life expectancy, CIPP pipe has the highest carbon emits compared to other pipes.

CHAPTER 7

CONCLUSION AND RECOMMENDATION FOR FUTURE STUDY

7.1 Conclusion

Selection of the most feasible construction pipeline materials and installation method is becoming increasingly more important due to design requirements, site restrictions, existing infrastructure, above ground structures, soil conditions, required accuracy, as well as costs. Choosing the proper pipeline material and the installation method will result in a significant reduction in CO_2 emissions, which will help to mitigate greenhouse gas emissions. The problem is that most decision-makers are considering primarily the direct cost before starting a project, and they typically ignore the social cost and the environmental impact because it is practically challenging to quantify the impact when considering that many factors are unknown or not available. However, with an increase in public concerns, other factors should be taken into account while choosing the pipeline material and installation method. Three factors should be considered before starting installation on a new pipeline project or rehabilitating existing pipeline: the direct cost, the social cost, and the environmental impact.

Carbon footprint analysis is becoming more popular in every industry due to the increasing concern about global warming. The construction industry needs to quantify the carbon footprint for every project to select the method that is most environmentally friendly. This study focused on CO_2 emissions during the fabrication, installation, operation, and disposal phases of the pipeline life-cycle. The fabrication phase includes all the energy from the cradle to the factory gate to produce the pipe. The installation phase includes transporting the pipeline and construction equipment to the job-site, pipeline installation, backfilling, and repaving. The operation phase includes pumping energy and pipeline cleaning, and the disposal phase includes the energy for disposal of the non-recyclable materials of the pipeline material. The life-cycle focus must help decision-making when selecting the best technology available and minimizing the environmental impact of the constructions through their design or refurbishing (Bribian, 2011).

This study focused on a large diameter-36-inch, 100-foot section long sewer pressure pipe operating at 100 psi internal pressure, and the life of the pipeline is 100 years. Four pipeline materials are used in this study: PCCP, PVC, HDPE, and CIPP. Three installation methods are used for installing the pipeline: the open-cut method is used to install PCCP, the pipe bursting method is used to install PVC and HDPE, and the CIPP method.

For the fabrication phase of the pipe life-cycle, the results found that CIPP lining has the highest CO_2 emissions during the fabrication phase. CIPP pipe has higher carbon emissions during the fabrication phase, because of the high embodied energy for the epoxy resin. HDPE pipe is the second higher carbon emissions after the CIPP lining due to the thickness of the wall and the higher embodied energy compared to PCV resin. For a 100-years life-cycle, CIPP pipe would require relining of the pipeline after 50-years of operation (in case of the life expectancy is 50-years) which means CIPP will emit twice the amount of CO_2 emissions during the 100 years of service for the fabrication phase. PCCP has the lowest CO_2 emissions in the fabrication phase due to the basic materials for PCCP (concrete and steel). Besides minimizing embodied energy, it is equally important to produce pipeline with high recycling potential materials to reduce the use of energy and resources over an extended length of time.

Chapter 6 gives some recommendations to help the engineers and decision-makers optimize the CO_2 emissions during the fabrication phase in PCCP pipe that can be done by using recycled steel and geopolymer concrete. For PVC and HDPE, the CO_2 emissions can be reduced in the fabrication phase by using the recycled materials. Finally, for CIPP, CO_2 emissions can be reduced by using other resin instead of epoxy resin. The results found that the reduction in carbon emissions during the fabrication phase after the optimizing are 75% in PCCP pipe, 41% in PVC pipe, 47% in HDPE pipe, and 12% in CIPP pipe as shown in Figure 6.5.

The three methods used to install the pipeline in this study are open-cut, pipe bursting, and CIPP. The installation phase was divided into three categories: energy consumed during transporting pipes and equipment to the job-site, energy consumed from equipment activities to install the pipeline, and energy consumed from backfill material production and transport of the materials to the job-site. The open-cut method requires more construction equipment to dig the trench and more backfill material to fill up the trench compared with pipe bursting and CIPP. Open-cut has the highest energy consumption during the installation phase, while the CIPP method is the most environmentally friendly construction method because it needs less construction equipment, and smaller entry and exit pits. Pipe bursting creates more carbon emissions compared to the CIPP method due to the need for more construction equipment, the larger entry and exit pits, and the requirement to transport the pipe to the job-site. To install a 100-foot pipeline section with a 36-inch diameter, open-cut requires an excavation trench 120 feet long with a 12-foot width. For the pipe bursting method, the dimension of the entry and exit pits are 12 foot ×10 foot, and for CIPP method the size of the two pits are 10 foot × 8 foot.

To optimize the CO_2 emissions during the installation phase, Chapter 6 recommended using the same backfill materials, which will make a significant reduction on CO_2 emissions especially for open-cut construction method because of the big trench required to install the pipeline. In Chapter 4, asphalt was used to repave the surface. Asphalt has higher embodied energy (0.63 kWh/lb.) compared to reinforced concrete (0.0945 kWh/lb.) (ICE database). For the open-cut method, when using the concrete pavement, the CO_2 emissions were 6,826 pounds, but when using asphalt for repaving the surface, the CO_2 emissions are 52,784 pounds. For the pipe bursting method when using asphalt, the CO_2 emissions are 8797 pounds, whereas they are 1365 pounds when using reinforced concrete. In the CIPP method, when asphalt is used for repaving CO_2 emissions are 4,692 pounds and 728 pounds for concrete pavement (as shown in Chapter 6).

The result of optimizing the CO_2 emissions during the installation phase found that a significant reduction on CO_2 emissions is made by using the same backfill materials and concrete pavement instead of new backfill materials and asphalt pavement, as shown in Figure 6.6 (Chapter 6). The reduction of the CO_2 emissions are almost 70%

in the open-cut method, 60% in the pipe bursting method and 44% in the cured-in-place method after same backfill materials and concrete pavement are used.

For the operation phase, PCCP has the highest energy consumption compared to CIPP, PVC, and HDPE due to the inside pipe diameter and the roughness of the pipe interior surface. A smoother interior pipe surface requires less pump energy compared to a rougher interior pipe. To reduce the CO_2 emissions for the PCCP pipe, Chapter 6 recommended applying an epoxy coating to the interior surface of PCCP pipe to reduce the C value which will help to decrease the CO_2 emissions during the operation phase. The result found that 56,127 lb of CO_2 can be reduced during the operation of 100 years by coating the interior surface of PCCP pipe, 7% reduction on CO_2 emissions are made it after applying the epoxy coating as shown in Figure 6.8.

Finally, for the disposal phase, this phase focuses on the energy consumed to dispose of the pipe materials that cannot be recycled, and in this study 3.5% of the fabrication energy estimated to be required energy for disposal of the non-recyclable pipe materials. Because CIPP lining cannot be recycled, the result found that CIPP lining has the highest CO_2 emissions during the disposal phase compared to the other pipe materials. PCCP pipe is the most environmentally friendly in this phase due to the basic materials for PCCP, and these materials can be recycled. To reduce the CO_2 emissions during the disposal phase: that can be done by increasing the percentage of recycled materials at the end of their service life and decrease the amount of disposal materials at the end of the service life of the pipeline.

The overall goal of the study was to look at the CO_2 emissions during the entire life-cycle of the pipeline materials, to determine which material generates the lowest amount of CO_2. This study found that PVC pipe using the pipe bursting method has the smallest carbon footprints as compared to PCCP, HDPE, and CIPP. In case of the life expectancy for CIPP lining is 50-years, the CIPP method has the higher environmental impact compared to the other pipe materials, and in the case of 100-years-life expectancy for CIPP lining, the results indicate that HDPE emitted the highest carbon footprint to the environment. It is recommended to include all the three impact factors together (direct cost, social cost, and environmental impact), that will help the decision-maker to select the pipeline material and installation method. This study can be used for any length, diameter, pipe material, and installation method. Table 7-1 and Figure 7-1 shows the result of CO_2 emissions through the entire life-cycle of PCCP, PVC, HDPE, and CIPP pipes.

Table 7-1 CO_2 Emissions During the Pipeline Life-Cycle Phases

	Stage	PCCP	PVC	HDPE	CIPP	Unit	Remark
Phase 1	Fabrication/ Original	28,080	60,609	128,273	99591	lb	From cradle to factory gate
	Fabrication/ Optimization	7,175	35,916	68,392	89,650		
	Reduction	75%	41%	47%	10%		
Phase 2	Installation/ Original	97,457	17,922	17,922	21,310	lb	Transportation + Construction+ Backfill+ Repaving
	Installation/ Optimization	30,313	7,044	7,044	4,926		
	Reduction	69%	61%	61%	77%		
Phase 3	Operation/ Original	788,316	680,148	693,906	738,146	lb	Pumping + Pipe cleaning
	Operation/ Optimization	732,189	680,148	693,906	738,146		
	Reduction	7%	0	0	0		
Phase 4	Disposal/ Original	279	1,061	2,245	6,971	lb	CIPP cannot be recycled
	Disposal/ Optimization	159	424	898	6,971		
	Reduction	43%	60%	60%	0		

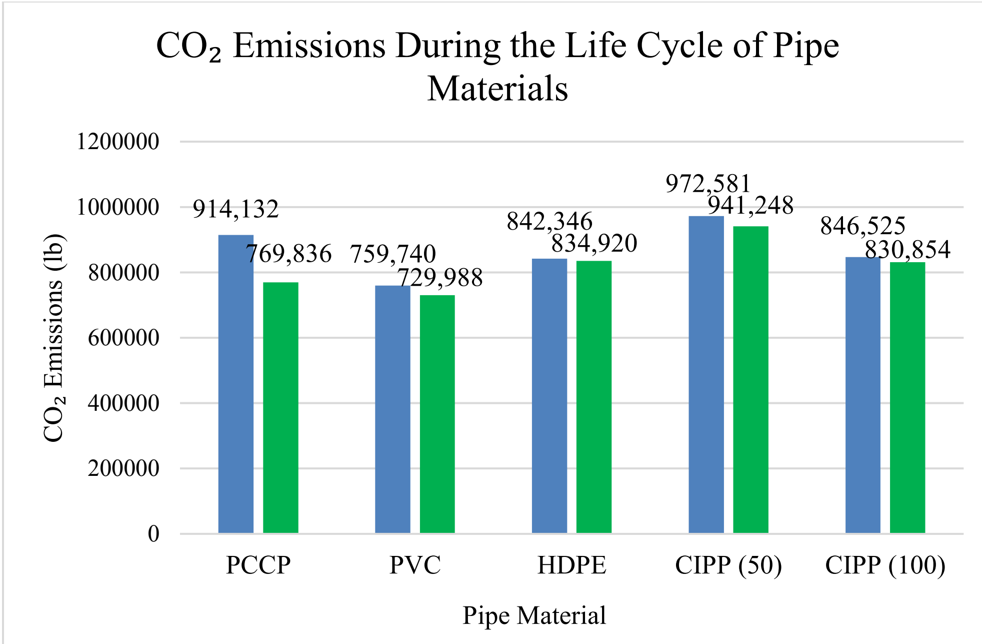


Figure 7-1 CO_2 Emissions During the Life-Cycle of Pipe Materials

7.2 Limitations

- There are three factors that should be considered during the planning of installation of a new pipeline project: direct cost, social cost, and environmental impact. This study focuses only on the environmental impact (carbon footprint) of the pipeline materials during the pipeline life-cycle phases. Matthews in 2015 estimated and evaluated the social and direct cost (social cost impact of pipeline infrastructure projects). This study could be used as an example to evaluate the social and direct costs.
- The embodied energy database which is used in this study represents the UK average and may vary from location to location.
- The CO_2 emissions from human consumption were not considered in this study due to the lack of information.

- In the fabrication phase, the boundary conditions are assumed to be from cradle to the factory gate.
- The waste materials during the fabrication are assumed to be negligible and are not accounted for. Also, the PCCP joint used in this study is assumed to be a rubber O-ring bell and spigot joint.
- This study does not include the energy consumed to manufacture the PCCP pipe inside the factory. The fabrication stage of PCCP pipe in this study is assumed to be negligible due to the lack of the manufacture data.
- All the construction equipment is assumed to be 2010 models years, and the size of the dump truck is medium size (15 cubic yard).
- Maintenance and repair for the pipeline during the operation phase are not included in the study because of the lack of data and information. The energy needed for maintenance and repair is assumed to be negligible in this study except the energy used to reline new CIPP pipe after 50 years of operation.

7.3 Recommended Future Study

For future research, it is recommended that field studies should be conducted to obtain necessary data to overcome dependence on assumptions made in this study. In the fabrication phase, it is recommended in a future study to include the energy consumed in the waste materials. Moreover, for the operation phase it is recommended to include the energy for maintenance and repair. It is recommended to apply this method for a longer section and to apply the method for both pressure pipeline and gravity pipeline. For embodied energy, it is recommended in future studies to use the database present in the location where the study is done because the embodied energy varies from one location to another.

REFERENCES

Achilias, D. S., Roupakias, C., Megalokonomos, P., Lappas, A. A., & Antonakou, E. V. (2007). Chemical recycling of plastic wastes made from polyethylene (LDPE and HDPE) and polypropylene (PP). Journal of Hazardous Materials, 149(3), 536-542.

Agency, E.P. (2009). Standard Practice for Rehabilitation of Existing Pipelines and Conduits by the Inversion and Curing of a Resin-Impregnated Tube 12. Water 1–9.

Akbari, H., Heller, T., Shin, S., Yang, X., Kolay, P., Kumar, S., Mohanty, M., (2013). Geopolymer-Based Concrete to Reduce Carbon Footprint of the Construction Industry. Mining Engineering, 2013, Vol. 65, No. 12, pp. 57-62.

Alimi, L., Azzouz, S., Chaoui, K., & Amirat, A. (2017). Reliability Index of HDPE Pipe Based on Fracture Toughness. Mechanika, 23(6), 820-825.

Allouche, E., Alam, S., Simicevic, J., Sterling, R., Condit, W., Headington, B., ... & Downey, D. (2011). A retrospective evaluation of cured-in-place pipe (CIPP) used in municipal gravity sewers. Edison, NJ.

Alsadi, A., Matthews, J., Matthews, E. (2018). Evaluation of the Environmental Sustainability During Fabrication of Commonly Used Pipe Materials. Pipelines 2018.

Alsadi, A., Matthews, J., Matthews, E. (2019). Environmental Impact Assessment of the Fabrication of Pipe Rehabilitation. ASCE Journal of Pipeline System-Engineering and Practice, Accepted for Publication.

American Water Works Association (2002). AWWA M23, Design and Installation of Polyvinyl Chloride Pipe, 2nd ed. Denver, CO: American Water Works Association

American Water Works Association (2008). AWWA M9, Concrete Pressure Pipe, 3rd ed Denver, CO: American Water Works Association

American Water Works Association (2014). Design Prestressed Concrete Pressure Pipe, Steel Cylinder Type. ANSI/ AWWA C301 -14. Denver, CO: American Water

Works Association.

American Water Works Association (2014). Design Prestressed Concrete Cylinder Pipe. ANSI/ AWWA C304 -14. Denver, CO: American Water Works Association.

American Water Works Association (2014). Standard for Design Polyvinyl Chloride (PVC) Pressure Pipe and Fabricated Fittings, 14In. Through 48 In. ANSI/AWWA C905 -10. Denver, CO: American Water Works Association.

American Water Works Association (2016). Polyvinyl Chloride (PVC) Pressure Pipe and Fabricated Fittings, 14In. Through 48 In. ANSI/AWWA C900-16.

Anspach, J. H. (2010). Collecting and Converting 2-D Utility Mapping to 3-D. In Pipelines 2010: Climbing New Peaks to Infrastructure Reliability: Renew, Rehab, and Reinvest (pp. 278-284).

Antaki, G. A. (2003). Piping and pipeline engineering: design, construction, maintenance, integrity, and repair. CRC Press.

Anthoff, D., Tol, R., (2013). The Uncertainty About the Social Cost of Carbon: A Decomposition Analysis Using Found. Springer 2013.

Ariaratnam, S. T., Piratla, K., Cohen, A., & Olson, M. (2013). Quantification of sustainability index for underground utility infrastructure projects. Journal of Construction Engineering and Management, 139(12), A4013002.

Ariaratnam, S., (2013). Sustainable Development through Innovative Underground Infrastructure Construction Practices. Arizona State University 2013.

Ariaratnam, S.T., and Sihabuddin, S.S. (2009). Comparison of Emitted Emissions Between Trenchless Pipe Replacement. Journal of Green Building 4, 126–14.

Ashby. Michael F. (2009). Materials and the Environment. Elsevier, London.

Assard L., Rosenberg, D., (2017). Epoxy Coating and Cement Mortar Lining. UCT Conference 2017.

ASTM Standard Specification (2007) for; Biodiesel (B100), Diesel, & Heating Oil ASTM D 6751-07 a Biodiesel Blend Stock Specification. azpilicueta/table/31/

ASTM. (2009). Standard practice for rehabilitation of existing pipelines and conduits by the inversion and curing of a resin-impregnated tube.

Bartlett, S., Cisneros, H., Decker, P., Heartwell, G., Warnock, A., Nellenbach, M., ... & Campanelli, B. (2017). Executive Council on Infrastructure Water Task Force.

BC' Magazine for Trenchless Construction, (2018). https://www.nastt.org/wp-content/uploads/2018/05/BC118-WEB.pdf.

Beale, D.J., Marlow, D.R., and Cook, S. (2013). Estimating the Cost and Carbon Impact of a Long Term Water Main Rehabilitation Strategy. Water Resources Management 27, 3899–3910.

Bourbour Ajdari, E. (2016). Volatile Organic Compound (VOC) Emission during Cured-in-Place-Pipe (CIPP) Sewer Pipe Rehabilitation.

Bribián, I. Z., Capilla, A. V., & Usón, A. A. (2011). Life cycle assessment of building materials: Comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential. Building and environment, 46(5), 1133-1140.

Bueno. Sharon M. (2010). Choosing Your Pipe. Trenchless Technology Pipe Selection Guide.

Burian, S. J., Nix, S. J., Pitt, R. E., & Durrans, S. R. (2000). Urban wastewater management in the United States: Past, present, and future. Journal of Urban Technology, 7(3), 33-62.

Chilana, L. (2011). Carbon Footprint Analysis of a large diameter water transmission pipeline installation.

Chilana, L., A. H. Bhatt, M. Najafi, and M. Sattler (2016). "Comparison of carbon footprints of steel versus concrete pipelines for water transmission," Journal of the Air & Waste Management Association, vol. 66, no. 5, pp. 518–527, May 016.

Connell, D. (2001). Hazen-Williams C-factor Assessment in an Operational Irrigation Pipeline (Doctoral dissertation, McGill University Libraries).

Conshohocken, W. (2004). Standard Specification for Cured-In-Place Thermosetting Resin Sewer Pipe 1. Test 07, 5–8.

Davidovits, J. (2015). False values on CO2 emission for geopolymer cement/concrete published in scientific papers. Technical Paper, 24.

Davis, S. C., Diegel, S. W., & Boundy, R. G. (2015). Transportation energy data book (No. ORNL-5198). Oak Ridge National Laboratory.

De Feo, G., Antoniou, G., Fardin, H., El-Gohary, F., Zheng, X., Reklaityte, I., ... & Angelakis, A. (2014). The historical development of sewers worldwide. Sustainability, 6(6), 3936-3974.

Deshmukh, P. P. (2014). Performance of Large Diameter Polyvinyl Chloride (PVC) Pipes in Water Applications.

Development of an LCA-Toll for the Composites-Industry, EuCIA Eco Calculator: Cradle to Gate LCA for Composite Parts (2016). http://www.teknologidager.no/uploads/2/6/2/1/26210140/eco_calculator_jaap_van_de_woude.pdf.

Du F., Woods G. J., Kang D., Lansey K. E., and Arnold R. G., (2013). "Life Cycle Analysis for Water and Wastewater Pipe Materials," Journal of Environmental Engineering, vol. 139, no. 5, pp. 703–711, May 2013.

EFFICIENCY, E. EPA's, (2013). Local Government Climate and Energy Strategy Series.

Ellison, D. (2003). Investigation of pipe cleaning methods. American Water Works Association.

Environmental Protection Agency EPA (2000). Wastewater technology fact sheet pipe construction and materials.

Environmental Protection Agency EPA (2014). eGRID2014 US grid intensity.

Environmental Protection Agency EPA (2016). Climate change indicators in the United States.

Facts, E. (2005). Average Carbon Dioxide Emissions Resulting from Gasoline and Diesel Fuel. US EPA, February.

Filion, Y. R., MacLean, H. L., & Karney, B. W. (2004). Life-cycle energy analysis of a water distribution system. Journal of Infrastructure systems, 10(3), 120-130.

Fletcher, S. R., & Resources, Science, and Industry Division. (2005). Global climate change: The Kyoto Protocol, Library of Congress.

Fu, F., Luo, H., Zhong, H., & Hill, A. (2014). Development of a carbon emission calculations system for optimizing building plan based on the LCA framework. Mathematical Problems in Engineering, 2014.

Gao, W., Ariyama, T., Ojima, T., & Meier, A. (2001). Energy impacts of recycling disassembly material in residential buildings. Energy and Buildings, 33(6), 553-562.

Gilchrist, A., & Allouche, E. N. (2005). Quantification of social costs associated with construction projects: state-of-the-art review. Tunnelling and underground space technology, 20(1), 89-104.

González, M. J., & Navarro, J. G. (2006). Assessment of the decrease of CO2 emissions in the construction field through the selection of materials: Practical case study of three houses of low environmental impact. Building and environment, 41(7), 902-909.

Gupta, Ram S. (2008). Hydrology and Hydraulic Systems. Waveland Press, Illinois.

Hammond, G., and C. Jones. (2011). Inventory of Carbon and Energy (ICE), Version 2.0. Sustainable Energy Research Team. Department of Mechanical Engineering, University of Bath.

Hammond, G., Jones, C., Lowrie, F., & Tse, P. (2008). Inventory of carbon & energy: ICE (Vol. 5). Bath: Sustainable Energy Research Team, Department of Mechanical Engineering, University of Bath.

Hashemi, S. B. (2008, December). Construction cost of underground infrastructure renewal: a comparison of traditional open-cut and pipe bursting technology. In Masters Abstracts International (Vol. 47, No. 03).

Herstein, L. M., Filion, Y. R., & Hall, K. R. (2010). Evaluating the environmental impacts of water distribution systems by using EIO-LCA-based multiobjective optimization. Journal of Water Resources Planning and Management, 137(2), 162-172.

History of HDPE and HDPE pipe products. http://www.pes-tec.com/images/pestec-docs/technology-and-services/GI-080-History/TI-080-1-History-of-HDPE-and-HDPE-pipe-products.pdf.

Hong, J., Shen, G. Q., Feng, Y., Lau, W. S. T., & Mao, C. (2015). Greenhouse gas emissions during the construction phase of a building: a case study in China. Journal of cleaner production, 103, 249-259.

Howarth, J., Mareddy, S. S., & Mativenga, P. T. (2014). Energy intensity and environmental analysis of mechanical recycling of carbon fibre composite. Journal of Cleaner Production, 81, 46-50.

ImpEE, P. (2005). Recycling of plastics. project University of Cambridge.

Instrument, I., and Threads, L.P. (2002). Standard Practice for Determining Dimensions of “Fiberglass” (Glass-Fiber- Reinforced Thermosetting Resin) Pipe and Fittings 1. 97, 1–4.

Interagency Working Group. (2013). Technical update on the social cost of carbon for regulatory impact analysis-under executive order 12866. Interagency Working

Group on Social Cost of Carbon, United States Government.

International Society for Trenchless Technology http://www.istt.com

Jones, C. I. (2011). Life cycle energy consumption and environmental burdens associated with energy technologies and buildings (Doctoral dissertation, University of Bath).

Joshi, Akshay, (2012). "A Carbon Dioxide Comparison of Open Cut and Pipe Bursting". Master of Technology Management Plan II Graduate Projects. Paper 7.

Karl, T. R., Melillo, J. M., Peterson, T. C., & Hassol, S. J. (Eds.). (2009). Global climate change impacts in the United States. Cambridge University Press.

Khan, L. R., & Tee, K. F. (2015). Quantification and comparison of carbon emissions for flexible underground pipelines. Canadian Journal of Civil Engineering, 42(10), 728-736.

Khasreen, M., Banfill, P., Menzies, G., (2009). Life-Cycle Assessment and the Environmental Impact of Buildings: A Review. Sustainability 2009.

Kim, D., Yi, S., & Lee, W. (2012). Life cycle assessment of sewer system: Comparison of pipe materials. In The World Congress on Advances in Civil, Environmental, and Materials Research.

Kreiger, M. A., Mulder, M. L., Glover, A. G., & Pearce, J. M. (2014). Life cycle analysis of distributed recycling of post-consumer high density polyethylene for 3-D printing filament. Journal of Cleaner Production, 70, 90-96.

Krock, R., & Middleton, G. (2013). The Role of PVC Resins in Sustainable Design. The Vinyl Institute.

Kyung, D., Kim, D., Yi, S. et al., (2017). Estimation of greenhouse gas emissions from sewer pipeline system Int J Life Cycle Assess (March- 2017).

Latake, P. T., Pawar, P., & Ranveer, A. C. (2015). The greenhouse effect and its impacts on environment. International Journal of Innovative Research and Creative Technology, 1(3), 333-337.

Lawrence, M., (2015) Reducing the Environmental Impact of Construction by Using Renewable Materials. Scrivener Publishing LLC 2015.

Liu, H. (2003). Pipeline engineering. CRC Press.

Lloyd, N., & Rangan, V. (2009). Geopolymer concrete-sustainable cementless concrete. In Proceedings of Tenth ACI International Conference (pp. 33-53). American

Concrete Institute.

Loss, A., Toniolo, S., Mazzi, A., Manzardo, A., Scipioni, A., (2016). LCA comparison of traditional open cut and pipe bursting Systems for Relining Water Pipelines. Elsevire 2016.

MacLeod, S. P. (2010). Evaluating the Impact of Climate Change Mitigation Strategies on Water Distribution System Design and Optimization (Doctoral dissertation).

Manda, R. (2014). Performance of Prestressed Concrete Cylinder Pipe (PCCP) In Water Applilcations.

Martins, J., Freire, E., and Hemadipour, H. (2009). Applications and market of PVC for piping industry. Polímeros 19, 58–62.

Matthews J. (2014). Demonstration and evaluation of innovative wastewater main rehabilitation technologies (London: IWA Publishing: [distributor] Portland Customer Services: [distributor] CoInfo Book Services).

Matthews J., Allouche E., and Sterling R., (2015). Social cost impact assessment of pipeline infrastructure projects. Environmental Impact Assessment Review, 50(1), 196-202, Elsevier.

Matthews, J. C., Selvakumar, A., Sterling, R. L., & Condit, W. (2014). Innovative rehabilitation technology demonstration and evaluation program. Tunnelling and Underground Space Technology, 39, 73-81.

Matthews, J. C., Stowe, R. J., & Vaidya, S. (2017). Environmental impact of cured-in-place pipe renewal on an asbestos cement water main. Journal of Water Supply: Research and Technology-Aqua, 66(6), 361-366.

Matthews, J., Condit, W., Wensink, R., Lewis, G., & Sterling, R. (2012). Performance evaluation of innovative water main rehabilitation spray-on lining product in Somerville, NJ. US Environmental Protection Agency, Ofce. Res. & Development, National Risk Management Res. Laboratory.

McPherson, D. L. (2009). Choice of pipeline material: PVC or DI using a life cycle cost analysis. In Pipelines 2009: Infrastructure's Hidden Assets (pp. 1342-1354).

McPherson, D.L. (2009). Choice of Pipeline Material: PVC or Di Using a Life Cycle Cost Analysis. In Proceedings of the Pipelines 2009 Conference, ASCE Conf. Proc. Doi, p.36

Merah, N., Saghir, F., Khan, Z., & Bazoune, A. (2006). Effect of temperature on tensile properties of HDPE pipe material. Plastics, rubber and composites, 35(5), 226-

230.

Michaels, P. J., & Paul, C. (2015). Office of Management and Budget's Request for Comments on the Technical Support Document Entitled Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866. Montana.

Mohit, S., Monfared, M. A. N., Kang, C., & Bayat, A. (2017). Comparative study of greenhouse gas emissions from hand tunneling and pilot tube method underground construction methods. Journal of Green Building, 12(4), 54-69.

Monfared, M. A. N. (2018). Comparison of Trenchless Technologies and Open Cut Methods in New Residential Land Development.

Moore, W., & Dig, N. N. (2011). Non-Styrene Options for Cured In Place Pipe. NASTT, No Dig February.

Morrison, R., & Wang, L. (2010). State of technology report for force main rehabilitation. US Environmental Protection Agency National Risk Management Research Laboratory Water Supply and Water Resources Division, Cincinnati.

Naganathan, H. (2017). Energy Analytics for Infrastructure: An Application to Institutional Buildings (Doctoral dissertation, Arizona State University).

Najafi, M., (2005). Trenchless Technology: Pipeline and Utility Design, Construction, and Renewal. MCGraw-Hill, New York.

Najafi, M., and Kim, K.O. (2004). Life-cycle-cost comparison of trenchless and conventional open-cut pipeline construction projects. Proceedings of the ASCE Pipeline Division Specialty Congress - Pipeline Engineering and Construction 635–640.

Nath, P., Sarker, P. K., & Biswas, W. K. (2018). Effect of fly ash on the service life, carbon footprint and embodied energy of high strength concrete in the marine environment. Energy and Buildings, 158, 1694-1702.

National Liner Specifications. https://www.nationalliner.com/Portals/0/PDF/national-liner-specifications.pdf

Ormsby, Charles, (2009). A Framework for Estimating the Total Cost of Buried Municipal Infrastructure Project Master of Engineering.

Parvez, J. (2018). Life Cycle Assessment of PVC Water and Sewer Pipe and Comparative Sustainability Analysis of Pipe Materials. Proceedings of the Water Environment Federation, 2018(7), 5493-5518.

Piehl, R. (2005). Summary of trenchless technology for use with USDA Forest Service culverts. US Department of Agriculture, Forest Service, San Dimas Technology and Development Center.

Piratla, K., Ariaratnam, S., Cohen, A., (2012). Estimation of CO2 Emissions from the Life Cycle of a Potable Water Pipeline Project. Journal of Management in Engineering.

PREMIER- PIPE USA Website http://www.premierpipeusa.com

Rehan, R., & Knight, M. (2007). Do Trenchless Pipeline Construction Methods Reduce Greenhouse Gas Emissions?.

Romer, A., Bell, G., and Ellison, R. (2007). Failure of Prestressed Concrete Cylinder Pipe. Pipelines 2007: Advances and Experiences with Trenchless Pipeline Projects 1–17.

Rose, S., (2014) Understanding the Social Cost of Carbon: A Technical Assessment. U.S. Energy Association 2014.

Rudolph, L & Harrison, C., (2016). A Physician's Guide to Climate Change, Health and Equity. Public Health Institute. Oakland, CA.

Rui, Z., Metz, P. A., Reynolds, D. B., Chen, G., & Zhou, X. (2011). Historical pipeline construction cost analysis. International Journal of Oil, Gas and Coal Technology, 4(3), 244-263.

Sangwan, K. S., & Bhakar, V. (2017). Life cycle analysis of HDPE pipe manufacturing–a case study from an Indian industry. Procedia CIRP, 61, 738-743.

Säynäjoki, A., Heinonen, J., & Junnila, S. (2012). A scenario analysis of the life cycle greenhouse gas emissions of a new residential area. Environmental Research Letters, 7(3), 034037.

Sendesi S. M. T., Ra K., Conkling E. N., Boor B. E., Nuruddin Md., Howarter J. A., Youngblood J. P., Kobos L. M., Shannahan J. H., Jafvert C. T., and Whelton A. J., (2017). "Worksite Chemical Air Emissions and Worker Exposure during Sanitary Sewer and Stormwater Pipe Rehabilitation Using Cured-in-Place-Pipe (CIPP), Environmental Science & Technology Letters, vol.4, no. 8, pp. 325-333, Aug.

Sewer pipe cleaning specification guideline (2014). NASSCO 2014.

Simicevic, J., & Sterling, R. L. (2001). Guidelines for pipe bursting. US Army Corps of Engineers, Vicksburg, Miss. TTC technical report, (2001.02).

Speight, V. L. (2014). Impact of pipe roughness on pumping energy in complex distribution systems. Procedia Engineering, 70, 1575-1581.

Tavakoli, R., Najafi, M., Tabesh, A., and Ashoori, T., (2017). Comparison of Carbon Footprint of Trenchless and Open-Cut Methods for Underground Freight Transportation. In Pipelines 2017, pp. 45-55

Thomas, A., Mantha, B. R., & Menassa, C. C. (2016). A framework to evaluate the life cycle costs and environmental impacts of water pipelines. In Pipelines 2016 (pp. 1152-1163).

Thormark, C. (2006). The effect of material choice on the total energy need and recycling potential of a building. Building and environment, 41(8), 1019-1026.

Turner, L. K., & Collins, F. G. (2013). Carbon dioxide equivalent (CO2-e) emissions: A comparison between geopolymer and OPC cement concrete. Construction and Building Materials, 43, 125-130.

Union of Concerned Scientists, (2009). Climate Change in the United States. https://www.ucsusa.org/sites/default/files/legacy/assets/documents/global_warming/climate-costs-of-inaction.pdf

US Environmental Protection Agency EPA (2016). Social Cost of Carbon.

Watson, N., (2015). Developing Material Selection Strategies to Improve the Embodied Impacts of Buildings. Doctor of Engineering (EngD), University of Bath.

Wibowo, M. A., & Uda, S. A. K. (2018). Reducing carbon emission in construction base on project life cycle (PLC). In MATEC Web of Conferences (Vol. 195, p. 06002). EDP Sciences.

Wiedmann, T., & Minx, J. (2008). A definition of 'carbon footprint'. Ecological economics research trends, 1, 1-11.

Williams, S.E., Davis, S.C., and Boundy, R.G. (2017). Transportation Energy Data Book: Edition- 36 (Oak Ridge National Lab. (ORNL), Oak Ridge, TN (United States)

Wu, W., Simpson, A. R., & Maier, H. R. (2009). Accounting for greenhouse gas emissions in multiobjective genetic algorithm optimization of water distribution systems. Journal of Water Resources Planning and Management, 136(2), 146-155.

Yan, H., Shen, Q., Fan, L. C., Wang, Y., & Zhang, L. (2010). Greenhouse gas emissions in building construction: A case study of One Peking in Hong Kong. Building and Environment, 45(4), 949-955.

Zhang, Y. R., Liu, M. H., Xie, H. B., & Wang, Y. F. (2015, February). Assessment of CO2 emissions and cost in fly ash concrete. In Environment, Energy and Applied Technology: Proceedings of the 2014 International Conference on Frontier of Energy and Environment Engineering (ICFEEE 2014), Taiwan, December 6-7, 2014 (p. 327). CRC Press.