thickness between two sensors, generally spaced between 150ft (45m) and 500ft (150m). The acoustic velocity varies along the length as a function of the structural thickness. The measured 'structural' wall thickness data is very useful for valuation, as it can be used to determine the amount of time that a specific pipe segment will likely remain structurally fit for service. See Figure 2.

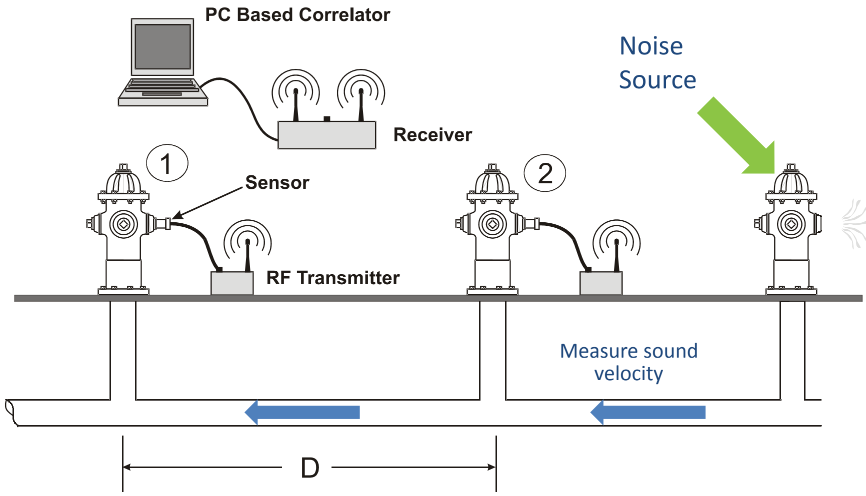

Figure 2: Acoustic Velocity Testing (Condition Assessment)

Once physical deterioration is determined via an AV study or using other data metrics, adjustments are made for any forms of functional and/or economic obsolescence that are identifiable and measurable. For example, forms of functional obsolescence attributable to the loss in value due to internal issues for water utility assets may include distribution bottlenecks or poor functionality issues where the capacity needs of the system are not met (i.e. – pumps operating at 50% capacity).

In many cases with machinery and equipment, and even in water systems, economic obsolescence is measured in the form of inutility where the "boilerplate" production capacity is compared to actual capacity. For instance if a well system is designed to draw 8,000 gallons of water a day but can only do 5,000 gallons, and current (as well as forecasted) demand only requires 5,000 gallons, an adjustment would be made to reflect the excess capacity cost of that system. It is also important to note though that if as the system acts in concert within a business enterprise, and the financial valuation determined that the fair value of the business cannot support the value of the system after physical deterioration and functional obsolescence adjustments, a further reduction in the value of the system should be made.

7. APPLICATION OF THE MARKET APPROACH

The market approach is conducted by researching sales of comparable assets in the used marketplace. In applying the market approach, the appraiser researches sales of the same or similar assets in published sources or through discussions with used equipment dealers, and then equates these comparable sales to the subject asset by making adjustments. These adjustments to the comparable assets' selling prices can be made for factors such as size, capacity, date of sale, and effective age. Typically, a used market comparable takes into consideration all forms of deterioration and obsolescence; thus, no further adjustments are made such as those in a cost approach.

Across most industries, there are many equipment categories that have a known, active used market whose comparable sales activities are tracked and documented. These categories include laboratory analytical and testing equipment, desktop and laptop computers, automobiles and trucks, and forklifts. Not every asset has a used market that tracks comparable sales; some assets are unique or custom configured, and their appraisal should then rely on other methods of valuation including the cost approach. This would include water system assets where the majority of the dollars would have its value developed via the cost and income approach, but smaller, “one-off” assets may have their value determined via the market approach.

8. APPLICATION OF THE INCOME APPROACH

The income approach determines the value of an asset, by discounting to a present value, the future cash flows that an asset is expected to generate over its remaining life, using an appropriate discount rate at a required rate of return. For water revenue, these forecasts would be discounted back, and then compared to, the results of the aforementioned cost approach. The income approach would be utilized for the entire business enterprise, along with components of the business such as the customer base, royalties, etc.

9. FINAL OPINION OF VALUE AND DELIVERABLE

At the end of an appraisal, when the applied methods have been conducted and reconciled to one another, the opinions of value are compiled into an appraisal report. The report thoroughly discusses the purpose of the appraisal, definition of value and valuation premise, effective date of the appraisal, scope of the engagement, methods and procedures used, assumptions made, and opinions reached. The body of the appraisal is organized in such a way that it clearly and cohesively shows a determination of the value opinions in a manner that is not misleading. Also included in an appraisal report would be exhibits such as a summary of values (by asset category or class; sometimes by location if there are multiple sites) and a detailed inventory of the assets or model of the system showing values my major component.

10. AVOIDING VALUATION MYTHS

A growing list of municipal water utilities are exploring options for long-term sustainability of their systems including asset sales, contract operations, and public-private partnerships. As utilities look to map their future plans, they should avoid 3 major myths:

1. **Myth #1: Net book value is a good proxy for fair market value!**
   Reality: Net book value is an accounting exercise to recapture costs over time and runs to zero after a set amount of years. Assets in operation whose costs are written off may (and are) still operating, thus adding value and are worth more than zero!
2. **Myth #2: Utilizing the cost basis on the books to “desktop” the system is sufficient**
   Reality: Depending on the passage of time, indices may not truly capture the true cost today of a system, not to mention the fact that if certain items of a system were no capitalized but expensed, all parties may not have a complete picture of “what’s out there,” thus understating value!
3. **Myth #3: “My system is old…it’s worthless! I’ll sell it for the value in the customer base!”**
   Reality: Utilizing certain technologies, the remaining service life (RSL) of a system can

be determined. The RSL can be compared to the design life, and applied against the current cost of the system to determine a true estimate of value!

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Evaluation of the Environmental Sustainability during Fabrication of Commonly Used Pipe Materials

Alhossin Alsadi[1]; John Matthews[2]; and Elizabeth Matthews[3]

[1]Ph.D. Student and Graduate Research and Teaching Assistant, Louisiana Tech Univ. E-mail: aaa022@latech.edu
[2]Associate Professor and Director of Trenchless Technology Center, Louisiana Tech Univ. E-mail: matthews@latech.edu
[3]Assistant Professor, Louisiana Tech Univ. E-mail: ematt@latech.edu

ABSTRACT

With the consistent increase in global population, environmental sustainability of construction has become a larger issue due to the increasing concerns about global climate change and carbon emissions. In the pipeline industry, carbon footprint analyses have been performed regularly to identify fewer carbon intensive materials and methods used during construction. The pipeline industry, however, has yet to evaluate the environmental sustainability of pipe materials during the fabrication stages. The objective of this paper is to calculate and analyze the environmental sustainability, as determined by carbon footprint and embodied energy, of 100 feet of pipe during the fabrication stages (material extraction, material production, and pipe manufacturing) made from three different types of pipe: pre-stressed concrete cylinder pipe (PCCP), polyvinyl chloride (PVC), and cured-in-place pipe (CIPP). This paper focuses on a large-diameter, 36 inches' sewer pressure pipe operating at 100 psi internal pressure. Initial results show the environmental sustainability of PCCP to be lower than PVC and CIPP. The second phase of this project will focus on the environmental impact for each during construction, operation, and end of life to determine the overall life-cycle environmental sustainability of each material.

KEYWORDS: life cycle analysis; carbon footprint; embodied energy; fabrication stage; trenchless technology

INTRODUCTION

Globally, increasing population and industrial growth is putting increased pressure on existing water transmission pipelines. A major portion of the existing water and wastewater pipelines are rapidly approaching the end of their useful service life and will need to undergo rehabilitation or replacement. Typically, a new pipeline is installed using open cut technology or trenchless technology (i.e., pipe bursting, pipe jacking, horizontal directional drilling, horizontal auger boring, etc.) or rehabilitated using trenchless methods such as cured-in-place pipe (CIPP), sliplining, or pipe bursting.

The objective of this paper 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 (material extraction, material production, and pipe manufacturing) as shown in Figure 1. The fabrication stage is the most energy consuming stage when compared to the construction stage and operation stage. This 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 study is to analyze and compare carbon (CO_2) emissions during the fabrication phase associated with the three types of pipe: pre-stressed concrete cylinder pipe (PCCP), polyvinylchloride (PVC), and CIPP, used for large diameter 36 inches pressure sewer pipelines.

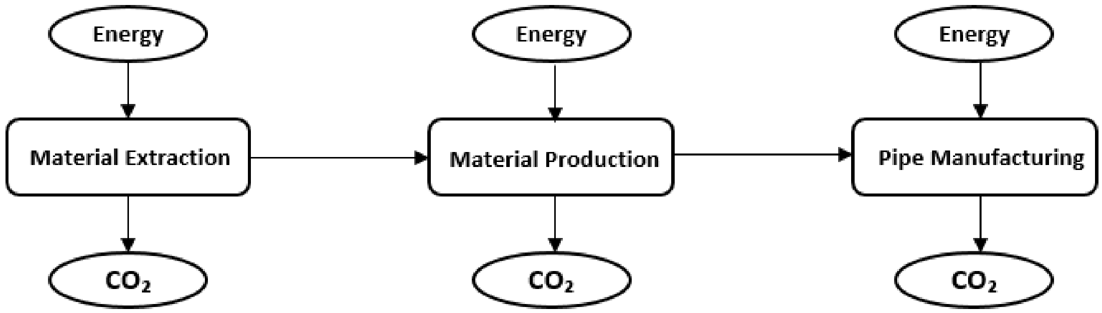

Figure 1: Schematic Shows the Energy Consumption During the Fabrication Activities

The Inventory of Carbon and Energy (ICE) database version 2.0 (2011) used for this study was published by the University of Bath in the United Kingdom. The ICE data provides an embodied energy for each material of the pipe. The ICE database contains both embodied energy and embodied carbon, but the embodied energy coefficients are more accurate (Hammond and Jones 2011). 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.

Most carbon emissions studies are about buildings. There are a few studies on pipeline carbon emission, but none compare CIPP with other pipe materials. Chilana analyzed the carbon footprints for 150 miles of pipeline of different large diameters (66, 72, 84 and 108 inches). The pipe materials were pre-stressed concrete cylinder pipe and steel pipe (Chilana 2011). Chilana found that PCCP pipe was better in terms of ecological impacts since it has a smaller carbon footprint than steel pipe Khan and Tee analyzed the life cycle assessment between steel, ductile iron (DI) and polyvinylchloride pipe, for a 5000 feet long pipeline with a 15.7 inches diameter. The results indicate that PVC emitted less carbon compared to the steel and ductile iron pipe materials. (Khan and Tee 2015). Kyung's estimated the total greenhouse gas (GHG) emissions for the complete life cycle stages of a sewer pipeline system for the following pipeline materials: polyvinylchloride, polyethylene, concrete, and cast iron. The results showed that concrete pipe generated a lower amount of GHG than pipes made from other materials (Kyung 2017). Du performed a life cycle analysis (LCA) study for six different pipe materials: polyvinylchloride (PVC), cast iron, high-density polyethylene (HDPE), ductile iron, concrete, and reinforced concrete (Du 2013). The objectives were to compare the six pipe materials regarding global warming potential through the four life cycle phases. The pipe diameter ranged 4 to 48 inches for this study. The results for CO_2 emissions during the fabrication phase showed that for pipe diameters less than or equal to 24 inches, the ductile iron pipe was the largest emitter among the six pipe types. For pipe diameters larger than or equal to 30 inches, PVC had the highest CO_2 emissions. For all pipe sizes, the concrete pipe had the lowest CO_2 emissions.

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

PRE-STRESSED CONCRETE CYLINDER PIPE (PCCP)

Pre-stressed concrete cylinder pipes (PCCP) have been manufactured and in use since 1942. PCCP is the most widely used type of concrete pressure pipe. PCCP is designed for operating pressures greater than 400 psi and underground covers of 100 feet. There are two types of PCCP. The first one is Lined Cylinder Pipe (LC-PCCP), this pipe 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. This type has been in use in the U.S. since 1942. The second type is Embedded Cylinder Pipe (EC-PCCP), this pipe 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. This type was developed later and was first installed in 1953. For both types of pipes, the lengths in general are between 16 to 24 feet. (AWWA M9) (AWWA C 301). Key differences are highlighted in Figure 2.

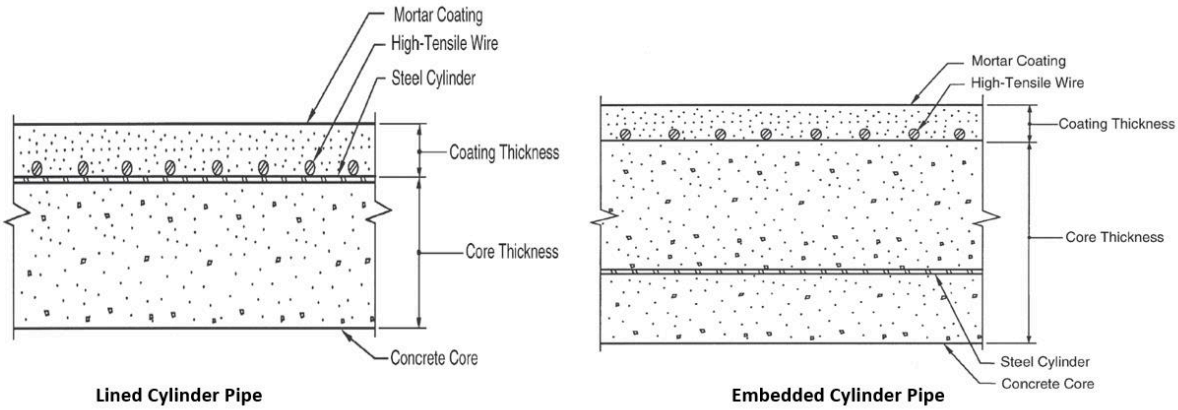

Figure 2: Schematic Shows the Different in Wall Cross Sections Between LCP and ECP Pipe (AWWA C304-14)

DESIGN CONSIDERATIONS

- Assumption
  1. The outside diameter of PCCP is 36 inches
  2. The pipe internal pressure is 100 psi
  3. The total length of PCCP section is 100 feet.
- Thickness measurement
  1. In this study we used Lined Cylinder Pre-Stressed Concrete Cylinder Pipe (LC-PCCP).
  2. The minimum design thickness of the core including the thickness of the steel cylinder, should be $\frac{1}{16}$ of the design pipe diameter (AWWA C301-14). So, the core thickness:

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

  3. The thickness of the steel cylinder is 16 gauge (0.0598 in). (AWWA C301-14)

4. The size of pre-stressing wire is 6 gauge (0.192 in). (AWWA C301-14)
5. The design spacing between pre-stressing wire is 2.75 wire diameter (AWWA C301-14).

So, the space between wires is:

$$2.75 \times 0.192 = 0.528\ in$$

6. The mortar coating thickness is 0.75 in. (AWWA C301-14)

- The materials density:

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 lb./ in³ (1170 Kg/ m³)

- Calculations

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

$$\text{Total Energy }(\text{PCCP}) = \text{Embodied Energy }(\text{concrete}) \times \text{Weight }(\text{concrete}) + \text{Embodied Energy }(\text{steel cylinder}) \times \text{ Weight }(\text{steel cylinder}) + \text{Embodied Energy }(\text{Mortar coating}) \times \text{Weight }(\text{Mortar coating}) + \text{Embodied Energy }(\text{pre-stressing wire}) \times \text{Weight }(\text{pre-stressing wire})$$

2. Total CO_2 emissions = Total Energy consumption × CO_2 Emission Rate

Table 1: Energy consumption and CO_2 Emission for PCCP

Description	Unit	Quantity	Reference
Outside diameter	in	36	Assumption
Length of pipe section	ft.	20	Assumption
Pipe weight	lb.	6729.17	Weight of steel cylinder+ weight of concrete core + weight of mortar coating+ weight of pre-stressing wire
Total energy consumption	kWh	23326	ICE version 2.0
CO_2 Emission Rate	lb./kWh	1.2038	eGRID2014
Total CO_2 Emission	lb.	28080	Total energy × CO_2 Emission Rate

POLYVINYLCHLORIDE (PVC) PIPE

PVC was first invented in the late nineteenth century. In the 1920s, scientists brought PVC to the public attention again. In the 1930s, the engineers and scientists in Germany developed and produced limited quantities of PVC pipe. The fundamental raw materials for PVC pipe resin are derived from ethylene (mostly natural gas or petroleum), and chlorine (mostly salt). The PVC pipe is manufactured by mixing the PVC resin with heat stabilizers, lubrication materials, and filler. The purpose of adding heat stabilizer 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).

DESIGN CONSIDERATIONS

- Assumption
  1. The PVC pipe outside diameter is 36 inches.
  2. The pipe internal pressure is 100 psi.
  3. The length of PVC pipe section is 100 feet.
- Thickness measurement
  1. The wall thickness is 0.878-inch (AWWA C 905)
  2. The pipe length is 20-feet (ASTM D 2665 Standard)
- Calculations
  1. The PVC pipe embodied energy is 67.5 Mj/ kg (ICV version 2.0)
  2. The total energy consumption for each pipe of PVC is calculate using the following equation:

$$\text{Total Energy} = \text{Embodied Energy}(\text{PVC}) \times \text{Weight }(\text{PVC})$$

  3. Total CO_2 emissions = Total Energy consumption × CO_2 Emission Rate

Table 2: Energy consumption and CO_2 Emission for PVC Pipe

Description	Unit	Quantity	Reference
Outside diameter	in	36	Assumption
Length of pipe section	ft.	20	Assumption
Pipe weight	lb.	1184	Weight = Volume × Density
Total energy consumption	kWh	50348	ICE version 2.0
CO_2 Emission Rate	lb./kWh	1.2038	eGRID2014
Total CO_2 Emission	lb.	60609	Total energy × CO_2 Emission Rate

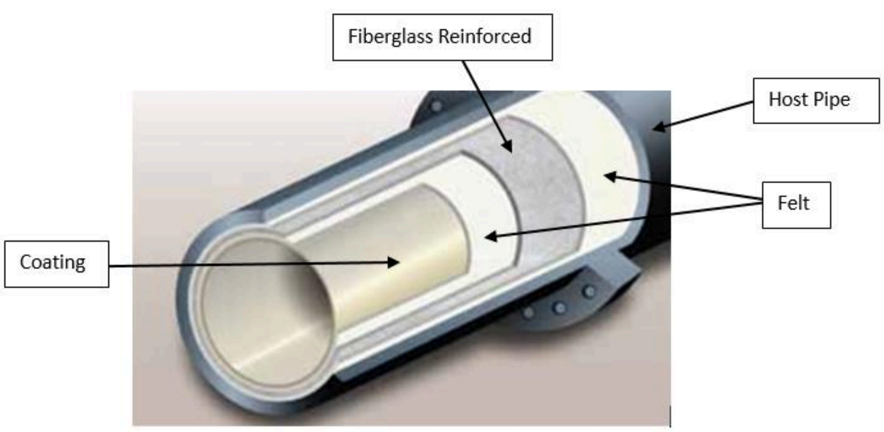

Figure 3: Schematic Pipe- Wall Cross Section for CIPP (adapted from http://www.premierpipeusa.com)

CURED-IN-PLACE PIPE (CIPP)

CIPP is the most widely used trenchless pipe repair technology for sewer pipelines. CIPP has been in use since the 1970s. CIPP liner typically consists of tube and resin. Tube contains one or more layers of flexible felt, and one or more layers of fiberglass-reinforced mesh. The outside layer should be plastic coated 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 cross section is shown in Figure 3.

DESIGN CONSIDERATIONS

- Assumption:
  1. The outside tube diameter is 36 inches
  2. The pipe internal pressure is 100 psi
  3. The total length of the CIPP section is 100 feet
- Thickness measurement: according to (F 1216- 09, D 5813 -4, and D 3567-97) designation standards, our design for CIPP tube will be:
  1. CIPP tube thickness is calculated from Equation 1,2 and 3 and the largest thickness is selected as shown in table 3.

Table 3: CIPP Tube Thickness Calculation

(1)	$t = \dfrac{D}{[\dfrac{2KElC}{PN(1-v)}]^{\frac{1}{3}}+1}$	$t = \dfrac{36}{[\dfrac{2\times 7\times 1.5\times 10^{6}\times 0.64}{3.464\times 2(1-0.27)}]^{\frac{1}{3}}+1} = 0.26$ in
(2)	$\dfrac{E}{12(DR)^{3}} \geq 0.093$	$t = \dfrac{D}{DR} = \dfrac{36}{66.94} = 0.537\ in$
(3)	$p = \dfrac{2\ Q_{TL}}{(DR-2)N}$	$t = \dfrac{D}{DR} = \dfrac{36}{62} = 0.58\ in$

Where,
t = thickness of the CIPP lining
D = mean inner pipe diameter (36in)
K = enhancement factor (typically 7)
E_L = Long term modulus of elasticity for the liner material $(E = 3\times 10^{6},\ E_L = 1.5\times 10^{6})$ (D 5813 Standard)

C = ovality reduction factor ($[\dfrac{1-\dfrac{\Delta}{100}}{[1+\dfrac{\Delta}{100}]^{2}}]^{3}$)

$\Delta = \%\ ovality \quad (5\%) \quad C = 0.64$

P = external pressure due to ground water ($P = 0.433\left(H_{w1} + \dfrac{D}{12}\right)$)

H_{w1} = height of ground water above pipe invert (5ft)
N = safety factor (typically 2)

v = Poisson's ratio (0.27)
p = internal pressure (100 psi)
Q_{TL} = long term tensile strength for CIPP (6000 psi)

From Equation 1,2 and 3, the CIPP tube thickness is 0.58 in (equation 3)

2. Two layers of felt with 6.125 mm thickness per layer.
3. Three layers of fiberglass reinforced with thickness of 0.75 mm per layer
4. The thickness of inside and outside tube liner is 0.10 mm per layer
5. The amount of resin should be sufficient to fill out all voids in the tube material with adding 5 - 10% extra amount of resin. It was assumed that the felt is 100% saturated with resin, which yields a thickness of resin equal to the thickness of the felt

- Calculations:

1. The total energy consumptions for CIPP is calculated using the follow equation:

$$\text{Total Energy} = \text{Embodied Energy}(\text{Felt}) \times \text{Weight}(\text{Felt}) + \text{Embodied Energy}(\text{Resin}) \times \text{Weight}(\text{Resin}) + \text{Embodied Energy}(\text{Fiberglass reinforced}) \times \text{Weight}(\text{Fiberglass reinforced}) + \text{Embodied Energy}(\text{Tube liner}) \times \text{Weight}(\text{Tube liner})$$

2. Total CO_2 emissions = Total Energy consumption × CO_2 Emission Rate. The inputs for the CIPP calculation are shown in Table 4.

Table 4: Energy consumption and CO_2 Emission for CIPP

Description	Unit	Quantity	Reference
Outside diameter	in	36	Assumption
Length of pipe section	ft.	100	Assumption
Total energy consumption	kWh	82731	ICE version 2.0
CO_2 Emission Rate	lb./kWh	1.2038	eGRID2014
Total CO_2 Emission	lb.	99591.5	Total energy × CO_2 Emission Rate

RESULTS AND DISCUSSION

The study focused on CO_2 emissions during the fabrication phase for the three most used pipe materials: PCCP, PVC, and CIPP. The three types of pipe all have a 36 inch diameter with a 100 feet length. CO_2 emissions for the fabrication phase for the three pipe types are provided in Figure 4. For the material production and pipe fabrication phase, the result was that PCCP pipe has less energy consumption as compared to PVC and CIPP pipe. CIPP has the highest energy consumption during the material production and fabrication phase. CIPP pipe CO_2 emissions were more than three times the amount of emissions from PCCP pipe; and PVC pipe CO_2 emissions were almost double the amount of carbon emissions from PCCP pipe during the fabrication phase. For a 100 feet section, PCCP pipe has a massive weight compared to PVC and CIPP pipe, yet 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 modeled to have a 74% concrete content and, due to the small concrete embodied energy (0.12 KWh/lb), PCCP has less carbon emissions during the fabrication stage. In this study, the CIPP liner consisted of a tube containing 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 (17.26 KWh/lb), CIPP