PVCO SUPPLEMENT
For
Life Cycle Assessment of PVC Water and Sewer Pipe and Comparative Sustainability Analysis of Pipe Materials

June 1, 2017

The *Life Cycle Assessment of PVC Water and Sewer Pipe and Comparative Sustainability Analysis of Pipe Materials*[1] (LCA) and the *Environmental Product Declaration*[2] (EPD) for PVC pipe prepared by Sustainable Solutions Corporation include an environmental declaration based on quantified data and additional information, a life cycle assessment of environmental impacts of PVC pipe and a detailed comparative review of corresponding competing pipe products. Both reports were critically reviewed by experts in the environmental field and prepared in accordance with ISO 14044 and 14025 standards. The LCA and EPD reports did not contain PVCO pipe in their analysis, assessment and comparisons.

Comparisons and analysis of PVCO have been included in other LCA studies. The Uni-Bell PVC Pipe Association has prepared this supplement as a life cycle assessment and comparison of the environmental assets of PVCO using the same methodology and parameters as used for PVC and the competing pipe products in the LCA. The following information includes environmental product information and life cycle assessment data for PVCO pressure pipes that match the three sizes and pressure class alternatives included in the LCA. The approach of this document is to closely match the areas of the LCA where PVCO could be inserted and to supply additional text and replacement tables and figures that include PVCO for relative comparison. Where specific data is used in tables and figures the companion table or figure in the LCA will be listed in parenthesis ().

Much of the data used for comparison purposes of PVCO pipe came from *Estimation of CO_2 Emissions from the Life Cycle of a Potable Water Pipeline Project* by Kalyan R. Piratla, Samuel T. Ariaratnam and Aaron Cohen (Piratla) published by the American Society of Civil Engineers.[3]

Section 3.0: Introduction to Life Cycle Assessment (LCA)

Table 1(3.1) lists the pipe materials compared in the LCA including PVCO pipe products.

TABLE 1(3.1): PVC PIPE PRODUCTS UNDER THE SCOPE OF THE LCA

Application	Standard	Nominal Diameter	Dimension Ratio/ Pipe Stiffness	Average Weight* (lb./ft.)
Potable Water	AWWA C900	8”	DR18	9.1
	AWWA C909	8”	PC235	5.5
	AWWA C900	8”	DR25	6.7
	AWWA C909	8”	PC165	4.0
	AWWA C905**	24”	DR25	55.9
	AWWA C909	24”	PC165	31.5
Storm Water	ASTM F794 AASHTO M304	24” Profile Wall	PS46	19.2
Sanitary Sewer	ASTM F794	8” Profile Wall	PS46	2.5
	ASTM D3034	8” Solid Wall	PS46	4.3
	ASTM F679	24” Solid Wall	PS46	38.7

**Weights based on manufacturers' literature and pipe standards.*

***Effective August 2016 the provisions of the AWWA C905 standard have been replaced and included in the AWWA C900 standard.*

Section 3.6: Industry Coverage

The information on PVCO pipe used in this supplement was taken from the data in Piratla. Piratla's data on PVCO, PVC and HDPE was supplied by JM Eagle, a Uni-Bell PVC Pipe Association member company.

Section 8.0: Review of Alternative Pipe Materials

PVCO can easily be included in the comparisons with PVC and comparable pressure pipe products in Table 2(8.1).

TABLE 2(8.1): COMPARABLE PRESSURE PIPE PRODUCTS

PVC Size and Product	Comparable Products	Standard
8" PVC DR18 PC235 C900	8" PVC DR18	AWWA C900
	8" DI CL51	AWWA C151
	8" HDPE 4710 DR9	AWWA C906
	8" PVCO PC235	AWWA C909
8" PVC DR25 PC165 C900	8" PVC DR25	AWWA C900
	8" DI CL51	AWWA C151
	8" HDPE 4710 DR13.5	AWWA C906
	8" PVCO PC165	AWWA C909
24" PVC DR25 PC165 C905	24" PVC DR25	AWWA C905
	24" DI CL51	AWWA C151
	24" HDPE 4710 DR13.5	AWWA C906
	24" PCCP PC200	AWWA C301
	24" PVCO PC165	AWWA C909

Note: All ductile iron pressure pipes in this study are cement-lined per AWWA C104.

The service life of PVCO is consistent with the 100-year plus life of PVC pipes as shown in Table 3(8.3).

TABLE 3(8.3): SERVICE LIFE ASSUMPTIONS OF SELECED PIPES FOR COMPARISON

Pipe Lives Before Replacement for LCA		
Pipe Material	**Standard**	**Servie Life (Years)**
PVC	AWWA C900	100
PVC	AWWA C905	100
PVC	ASTM D3034	100
PVC	ASTM F679	100
PVC	ASTM F794	100
PVCO	AWWA C909	100
DI	AWWA C151	50
DI	AWWA A746	50
HDPE	AWWA C906	50
HDPE	ASTM F2306	50
PCCP	AWWA C301	75
PP	ASTM F2736	50
VCP	ASTM C700	50
NRCP	ASTM C14	50

Section 8.7.2: Pipe Friction Factors

PVCO's friction factors are identical to PVC's. Table 4(8.4) includes the listing of friction factors for PVCO.

TABLE 4(8.4): PIPE FRICTION FACTORS USED

Pipe Material	Standards	Hazen-Williams C	Manning's n
PVC	C900, C905, F794, D3034, F679	155 - 150	0.009
PVCO	C909	155 - 150	0.009
DI	C151, C104, A746	≤ 140	0.013
HDPE	C906, F2306	155 - 150	0.012
PP	F2736	N/A	0.012
PCCP/NRCP	C301, C14	≤ 140	0.013
VCP	C700	N/A	0.013

Section 9: Environmental and Performance Attributes of Alternative Piping Materials

The following description and information for PVCO pipe is comparable to similar descriptions of the alternate pipe materials included in Section 9 of the LCA.

Molecularly Oriented PVC (PVCO) Pipes

PVCO is molecularly oriented for a wall that is four times stronger than conventional PVC at half the thickness with a larger interior diameter for improved performance. Also called PVC-O, it has a very similar composition as typical PVC pipe except additional mechanical forces are applied during production to stretch the pipe such that the polymer molecules are oriented in the hoop direction around the diameter of the pipe. PVCO can also be stretched longitudinally. In addition to the typical PVC benefits of corrosion resistance and durability, this orientation process provides the resulting PVCO pipe with several improved performance attributes compared to typical PVC pipe. They include a larger internal diameter, higher strength, and greater impact resistance, fatigue resistance and resistance to longitudinal failure. Because of these attributes, PVCO pipe can achieve the same or higher pressure ratings as regular PVC pipe by using less material. This in turn reduces the environmental impact of PVCO even further than regular PVC.

Molecularly Oriented PVC (PVCO) Pipe Service Life

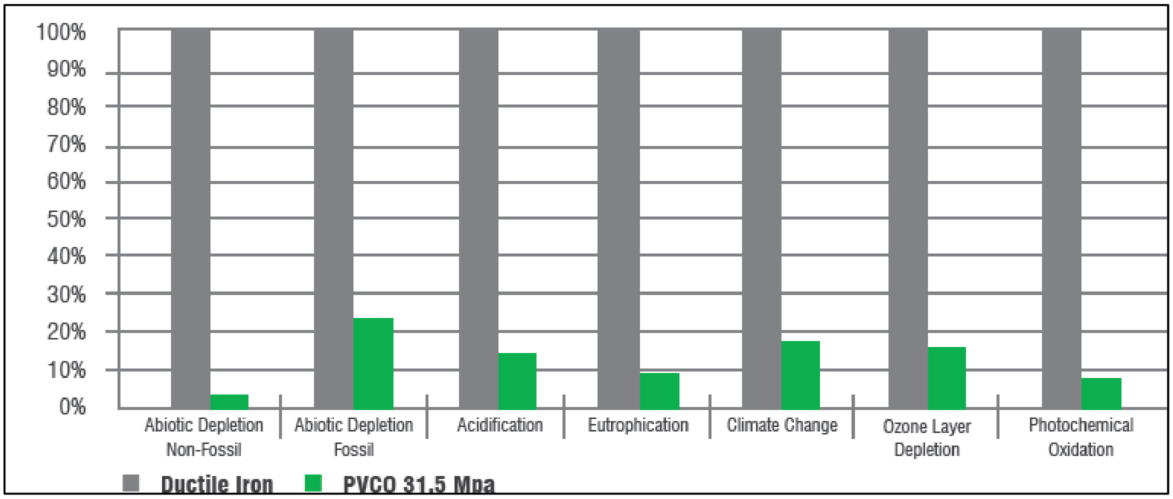
PVCO pipe is made from typical PVC pressure pipe material, but the pipe is expanded after extrusion to enhance its properties. Like PVC, PVCO has a service life of 100 plus years. Note that PVCO was not included in the original industry-wide LCA study conducted for the PVC pipe industry, but discussion has been added qualitatively to this report through review of LCA studies of PVCO. PVCO has been used in the U.S. as a pressure water pipe since the 1980s.

Molecularly Oriented PVC (PVCO) Pipe LCA

The scope of the LCA study did not include PVCO products; however, the European Plastic Pipes and Fittings Association (TEPPFA) undertook an LCA for PVCO pipe.[4] European water infrastructure meets different standards and the functional units are not quite comparable; however, these studies provide insight on the relative impacts. The results show that the raw materials and installation impacts are the main drivers in PVCO pipe. TEPPFA carried out several LCA studies from cradle-to-grave through a project with the Flemish Institute for Technological Research (VITO). The results of VITO's research closely agree with the results provided herein.

The TEPPFA study shows that PVCO pipe has fewer environmental impacts in all reported categories compared to ductile iron (DI) pipe. As shown in Figure 1, DI pipe impacts are significantly higher in all seven reported categories on a per 100 meter per year basis.

FIGURE 1: TEPPFA LCA COMPARISON OF PVCO (31,5 MPA) VS DUCTILE IRON PIPING SYSTEMS



Embodied Energy Calculations

The LCA did not include the cradle-to-gate embodied energy values for PVCO pipes. Table 5(9.1) lists the cradle-to-gate embodied energy values for PVC pipe comparisons used in the LCA with the addition of the PVCO values for pressure pipes.

TABLE 5(9.1): SUMMARY OF CRADLE-TO-GATE EMBODIED ENERGY FOR PVC AND ALTERNATIVE PIPE MATERIALS

PVC Size and Product	Comparable Products	Standard	Embodied Energy (MJ/100 ft.)
8" PVC DR18 PC235 C900	8" PVC DR18	AWWA C900	23,300
	8" PVCO PC235	AWWA C909	22,000
	8" HDPE 4710 DR9	AWWA C906	42,600
	8" DI CL51	AWWA C151	50,900
8" PVC DR25 PC165 C900	8" PVC DR25	AWWA C900	15,900
	8" PVCO PC165	AWWA C909	15,800
	8" HDPE 4710 DR13.5	AWWA C906	29,600
	8" DI CL51	AWWA C151	50,900
24" PVC DR25 PC165 C905	24" PVC DR25	AWWA C905	137,900
	24" PVCO PC165	AWWA C909	125,600
	24" HDPE 4710 DR13.5	AWWA C906	240,800
	24" DI CL51	AWWA C151 AWWA C104	206,600
	24" PCCP PC200	AWWA C301	53,500
24" PVC PS46 F794 Profile Wall	24" PVC PS46	ASTM F794 AASHTO M304	49,700
	24" PP PS46	ASTM F2736	43,700
	24" HDPE PS34	ASTM F2306	42,900
8" PVC PS46 F794 Profile Wall	8" PVC PS46	ASTM F794 AASHTO M304	5,900
	8" DI	ASTM A746	46,500
8" PVC PS46 SDR35 D3034 Solid Wall	8" PVC PS46	ASTM D3034	10,000
	8" DI	ASTM A746	46,500
	8" VCP	ASTM C700	10,800
24" PVC PS46 F679 Solid Wall	24" PVC PS46	ASTM F679	98,600
	24" DI	ASTM A746	176,600
	24” VCP	ASTM C700	82,400
	24" NRCP	ASTM C14	21,300

Note: All ductile iron pressure pipe in this study are cement-lined per AWWA C104.
All ductile iron sewer pipes in this study are double cement-lined per AWWA C104.

Section 10: PVC Pipe Pumping Energy Savings

PVCO can be compared on an equal basis to PVC and the alternate pipe materials in the pressure pipe scenarios in Section 10. The results of the three pipe scenarios for the 100-year pumping energy per 100 feet are shown in Figure 2(10.1). Using the same pipe analysis comparisons used in Section 10 yields exceptional results for PVCO pipes. The pumping energy use for 8-inch PVCO PC235 is 41% less than the equivalent DI pipe while 8-inch PVCO PC165 uses 46% less pumping energy than the equivalent DI pipe. Assuming 1.2 million miles of water supply pipes in the United States and 66% of those are 8 inches and smaller, the energy savings over a 100-year period by using PVCO instead of DI pipe and using the energy usage from these examples is up to 393 billion kWh. At an electrical power cost of $0.07 per kWh this would represent a savings of up to $27 billion by using PVCO instead of DI pipe.

The pumping energy required for 8-inch PVCO PC235 is 62% less than the equivalent HDPE pipe, while 8-inch PVCO PC165 uses 44% less pumping energy. Stated another way, for equivalent 8-inch pipes the primary pumping energy demand is as much as 162% greater for HDPE than for PVCO. In these comparisons, 8-inch HDPE uses over 2.6 times the pumping energy compared to PVCO PC235 pipe and 1.8 times the pumping energy of PVCO PC165. The energy savings over a 100-year period by using PVCO rather than HDPE and using the energy usage from these examples is up to 656 billion kWh. At an electrical power cost of $0.07 per kWh this would represent a savings of up to $46 billion by using PVCO instead of HDPE pipe.

Section 10.1: PVC Pipe Pumping Energy Cost Savings

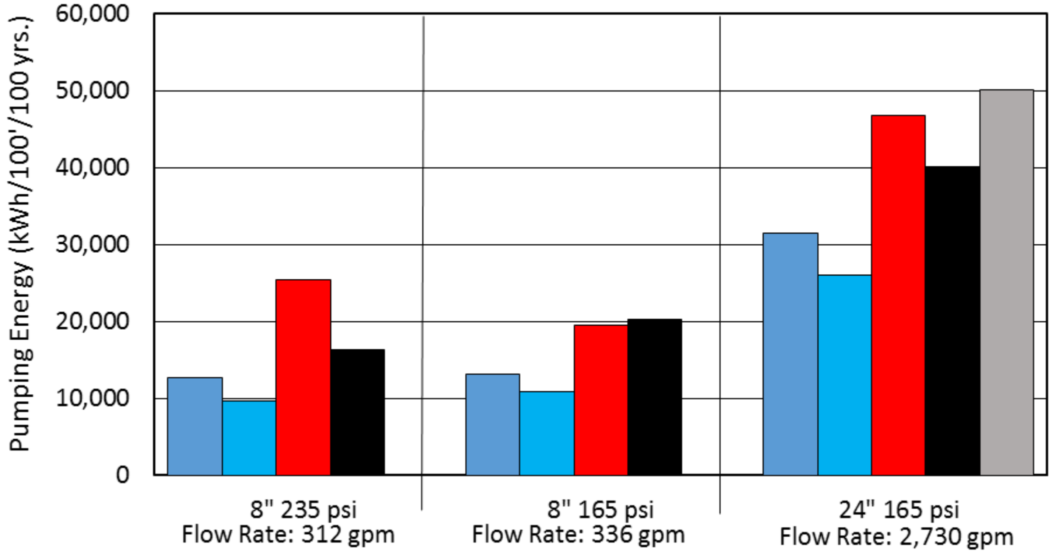
The results of the three pipe scenarios for the 100-year pumping energy costs per 100 feet are shown in Figure 3(10.2). Medium to large utilities typically have 1,000 miles of pipe so the potential savings of using PVCO pipe can be significant. This study used a common flow generated by an equivalent 2 feet per second velocity in a PVC pipe for analysis of various pipe material options including PVCO. Based on this, the 100-year average annual pumping cost savings were calculated. The savings for a utility using 8-inch PVCO compared to equivalent DI pipe are up to $580,000 annually. Savings for 8-inch PVCO pipe versus HDPE are up to $950,000 annually. Power costs for these 8-inch, 1,000-mile pipe networks are shown in Figure 4(10.3).

Comparisons are also provided for 24-inch water transmission mains to demonstrate the potential savings for large diameter piping. Alternative pipe materials are shown to have higher operating costs than PVCO pipe: PCCP has a 93% higher operating cost; HDPE is 80% higher; and DI is 55% more expensive to operate than PVCO pipe.

Based on average per capita water distribution system demand in the U.S., the average velocity for 8-inch pipes is between 0.3 and 0.5 fps. A velocity of 0.4 fps was used to provide a realistic comparison flow rate for all 8-inch pipe materials. The pumping costs for each alternative pipe material were computed using that flow rate. Power costs for these 8-inch, 1,000-mile pipe networks with an average velocity of 0.4 fps are shown in Figure 5(10.4).

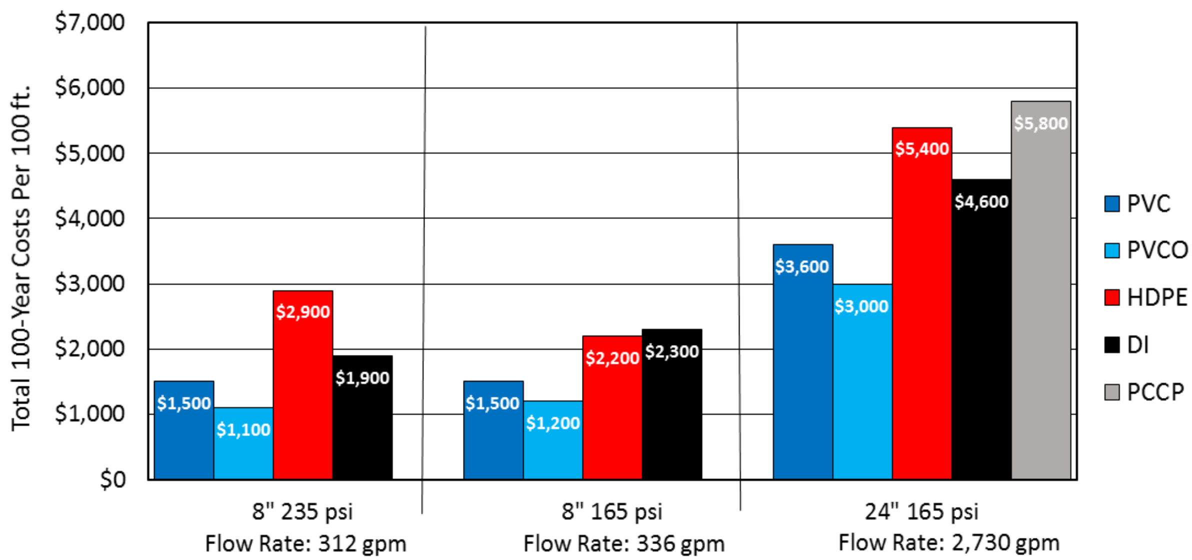
The difference in electrical power consumption between PVCO and DI pipe in a 1,000-mile network could power almost 5 homes annually. Savings in electricity achieved by PVCO compared to HDPE pipe would power almost 8 homes every year based on an average U.S. household using 10,812 kWh/year.

FIGURE 2(10.1): COMPARISON OF TOTAL 100-YEAR PUMPING ENERGY USE PER 100 FEET OF PIPE



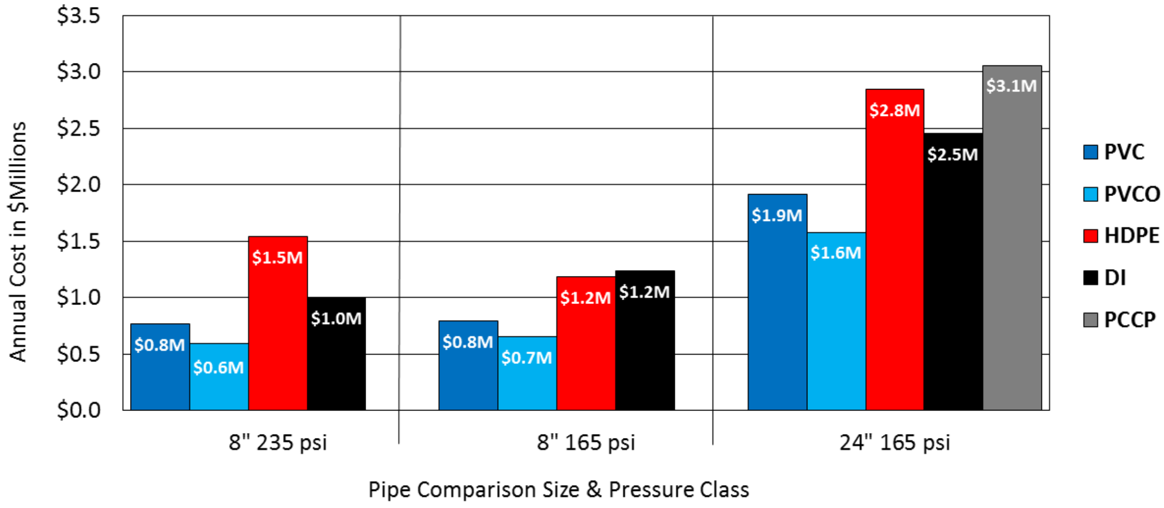
Note: Graph assumes replacement of HDPE pipe at 50 years, DI pipe at 50 years and PCCP at 75 years.

FIGURE 3(10.2): COMPARISON OF TOTAL 100-YEAR PUMPING ENERGY COSTS PER 100 FEET OF PIPE



Note: Graph assumes replacement of HDPE pipe at 50 years, DI pipe at 50 years and PCCP at 75 years.

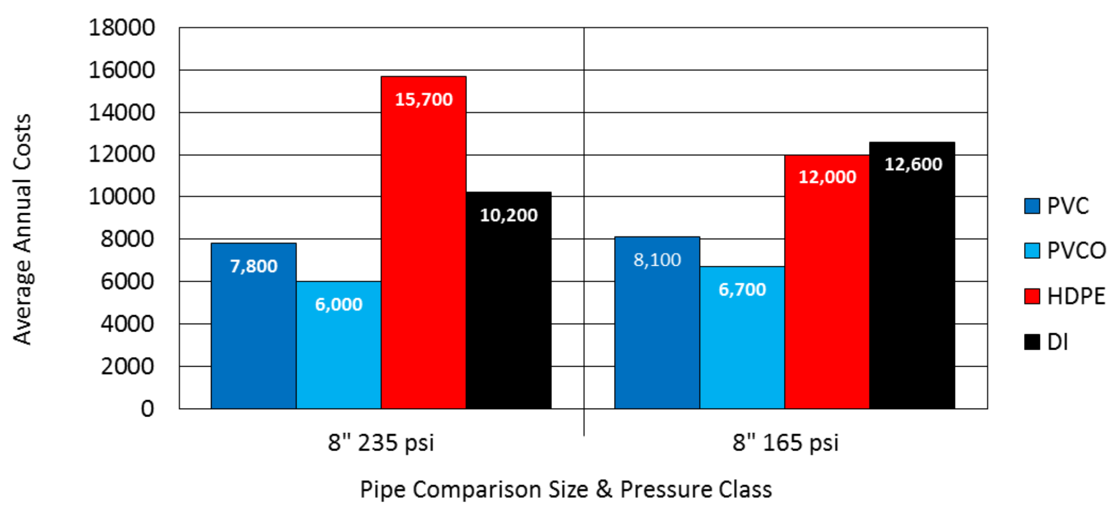
FIGURE 4(10.3): COMPARISON OF AVERAGE ANNUAL PUMPING ENERGY COSTS PER 1,000 MILES OF PIPE BASED ON 2 FPS VELOCITY



The average annual pumping cost savings for 8-inch pipe using PVC instead of DI can be up to $440,000, and the savings using PVC instead of HDPE can be up to $770,000.
The average annual pumping cost savings for 8-inch pipe using PVCO instead of DI can be up to $580,000, and the savings using PVCO instead of HDPE can be up to $950,000.

Note: Graph assumes replacement of HDPE pipe at 50 years, DI pipe at 50 years and PCCP at 75 years.

FIGURE 5(10.4): COMPARISON OF AVERAGE ANNUAL 100-YEAR PUMPING ENERGY COSTS PER 1,000 MILES OF PIPE BASED ON 0.4 FPS VELOCITY

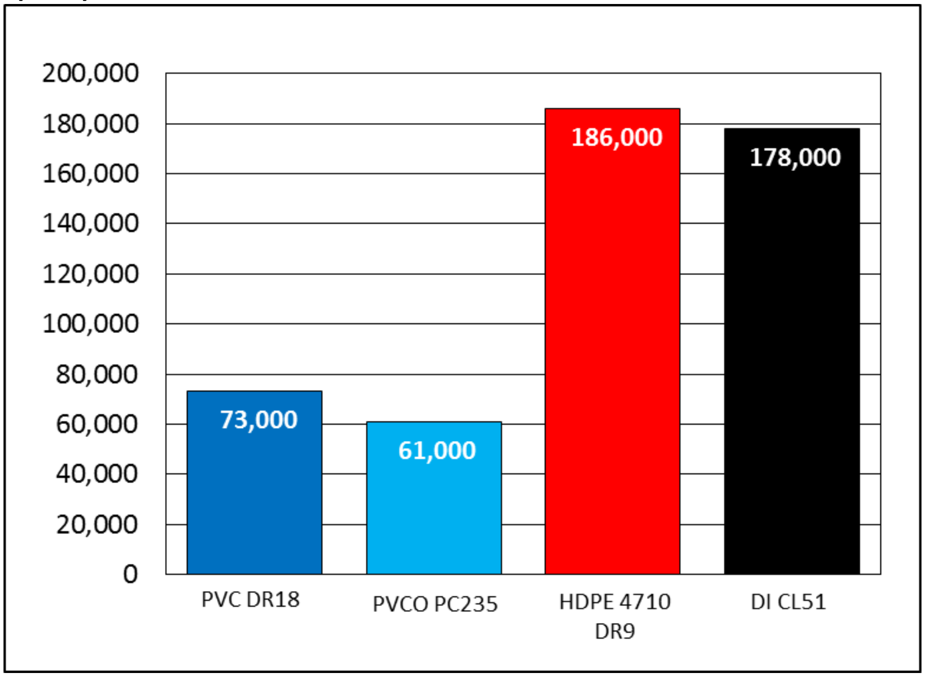


Note: Graph assumes replacement of HDPE and DI pipe at 50 years.

Section 10.2: PVC Pipe Low Monetized Carbon Footprint

As shown in Figure 6(10.5), 8-inch PVCO pipe has a much lower total life cycle energy usage compared to equivalent HDPE and DI products. HDPE has the greatest total energy consumption over a 100-year design life at over 3 times that of PVCO pipe while DI pipe's is just under 3 times that of PVCO.

FIGURE 6(10.5): 8" PVC DR18 EQUIVALENT PIPES 100-YEAR TOTAL EMBODIED ENERGY



Section 12: Summary Findings – Embodied Energy and Sustainability

Section 12.1.1: Pressure Pipe Total Embodied Energy Calculations

Direct PVCO comparisons to the information presented in Chapter 12 include the following figures and discussion. The inclusion of PVCO in Figures 7(12.1), 8(12.2) and 9(12.3) provides a direct comparison to figures in the LCA. The lower use-phase energy of PVCO pipes contribute to its overall lower total 100-year embodied energy. Figure 7(12.1) compares 8-inch PVC, PVCO, HDPE and DI pipes with a pressure class at or equivalent to PVC DR18 PC235. Figure 8(12.2) compares compares 8-inch PVC, PVCO, HDPE and DI pipes with a pressure class at or equivalent to PVC DR25 PC165. Figure 9(12.3) compares compares 24-inch PVC, PVCO, HDPE and DI pipes with a pressure class at or equivalent to PVC DR25 PC165.

FIGURE 7(12.1): TOTAL 100-YEAR EMBODIED ENERGY FOR 8" PVC DR18 EQUIVALENT PRESSURE PIPES

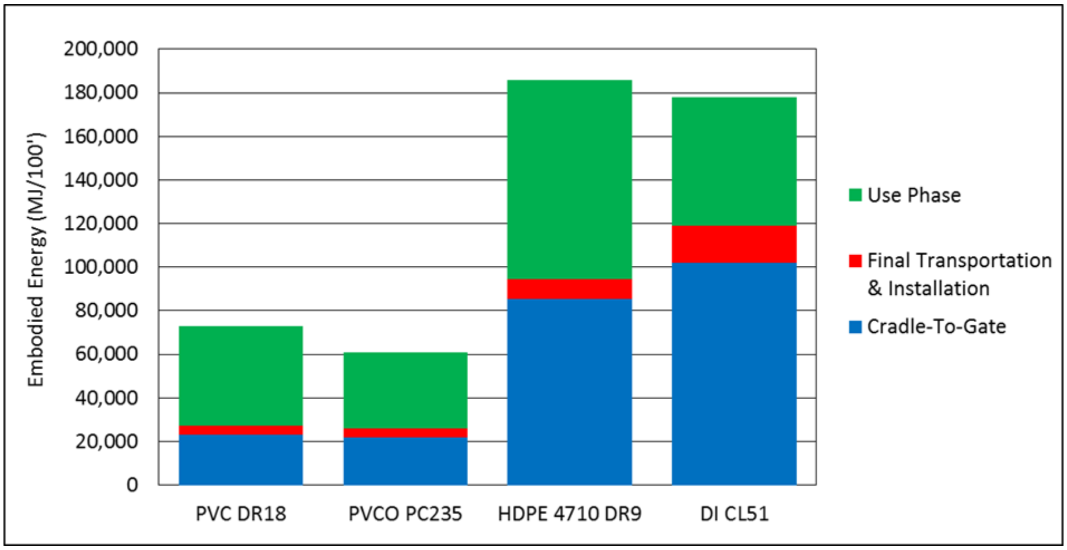


FIGURE 8(12.2): TOTAL 100-YEAR EMBODIED ENERGY FOR 8" PVC DR25 EQUIVALENT PRESSURE PIPES

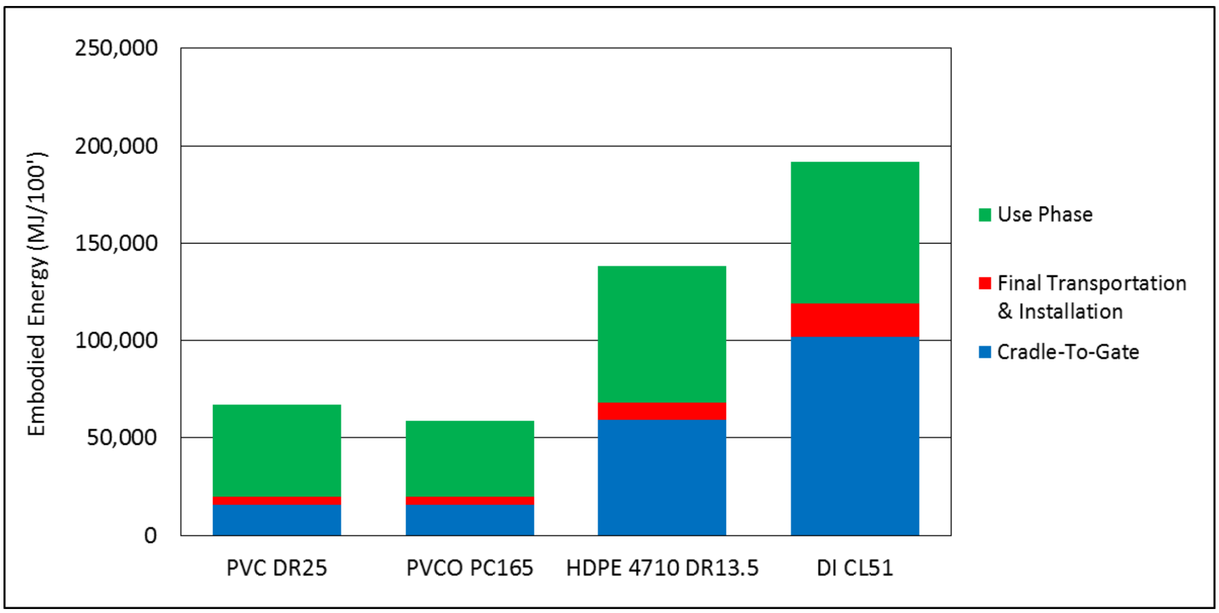
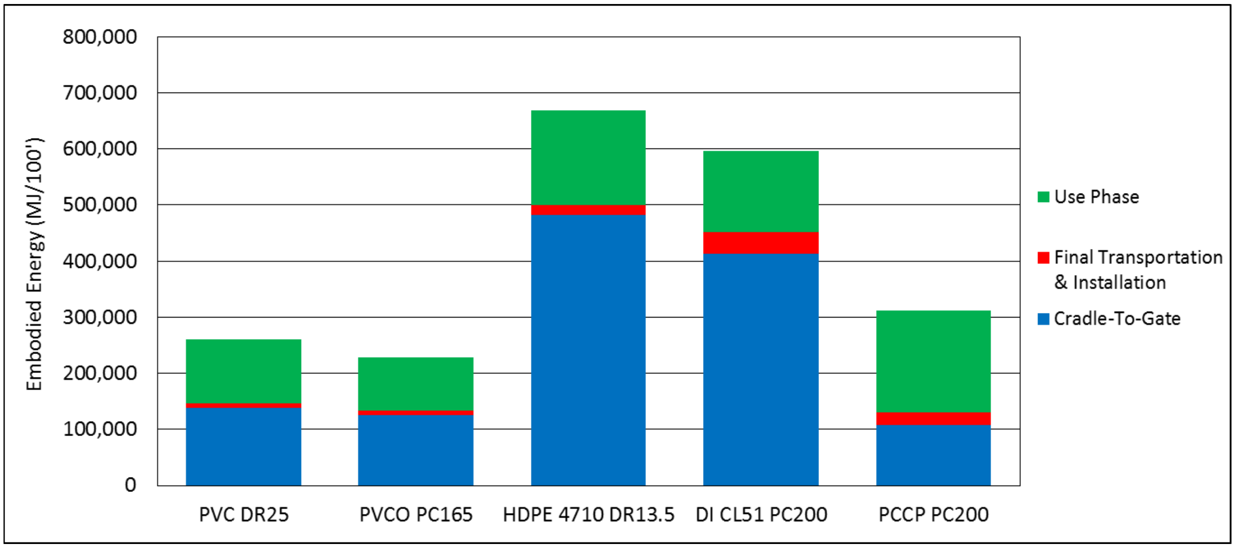


FIGURE 9(12.3): TOTAL 100-YEAR EMBODIED ENERGY FOR 24" PVC DR25 EQUIVALENT PRESSURE PIPES



When the embodied energy values for the replacement of HDPE, DI and PCCP are not included in the total 100-year embodied energy for 24-inch pipes, PVC and PVCO pipes have less total embodied energy as shown in Figure 10(12.4).

FIGURE 10(12.4): TOTAL 100-YEAR EMBODIED ENERGY FOR 24" PVC DR25 EQUIVALENT PRESSURE PIPES (HYDRAULIC ENERGY WITHOUT REPLACEMENT)

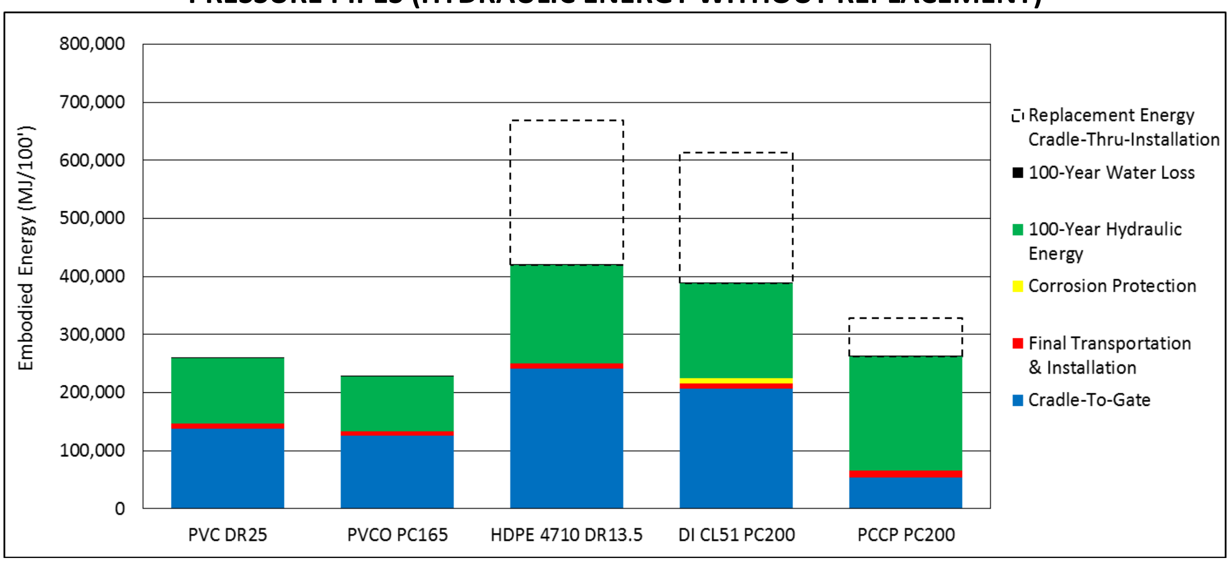


Figure 10(12.4) highlights the differences in the 100-year embodied energy among the 24-inch pressure pipes excluding the cradle-through-installation energy needed for replacements of HDPE, DI and PCCP (dashed gray area) during the 100-year life cycle. Figure 10(12.4) demonstrates that without replacements, HDPE, DI and PCCP would have greater total 100-year embodied energies than PVC and PVCO. Without their needed replacements during the life cycle, HDPE would have 38 percent greater embodied energy than PVC pipes and 46 percent greater embodied energy than PVCO pipes. DI would have 33 percent greater embodied energy than PVC pipes and 41 percent greater embodied energy than PVCO pipes. PCCP would have 1 percent greater embodied energy than PVC pipes and 13 percent greater embodied energy than PVCO pipes.

Section 13: Conclusions

The conclusions in Section 13 would not change other than to state that for pressure pipe applications, PVCO has the lowest pumping energy, lowest total 100-year embodied energy and the lowest costs among the comparison pipes.

Appendix

Pressure Pipe Water Loss

For pressure pipe water loss rates for PVCO, the same water main break rate as PVC was used. The PVCO rates can be seen in Table 6(A.2) below.

TABLE 6(A.2): WATER LOSS VOLUME PER YEAR AND 100-YEAR WATER LOSS EMBODIED ENERGY

Pipe Material	PVC Size/DR/PC	Flow Rate (gpm)	Break Time (min)	Failure Rate (#/100'/yr)	Annual Loss Volume (gal/100'/yr)	Treated Water Embodied Energy (kWh/Mgal)	100-Year Water Loss Embodied Energy (kWh/100')
PVC	8"/18/235	312	240	0.000492	36.9	1410	**5.2**
	24"/25/165	2730	240	0.000492	322.6	1410	**45.5**
PVCO	8"/-/235	312	240	0.000492	36.9	1410	**5.2**
	24"/-/165	2730	240	0.000492	322.6	1410	**45.5**
DI	8"/-/350	312	240	0.000928	69.5	1410	**9.8**
	24"/-/200	2730	240	0.000928	608.0	1410	**85.7**
HDPE	8"/9.0/250	312	240	0.000492	36.9	1410	**5.2**
	24"/13.5/160	2730	240	0.000492	322.6	1410	**45.5**
PCCP	24"/-/200	2730	240	0.001023	670.0	1410	**94.5**

Pressure Pipe: Hydraulic Energy Calculations

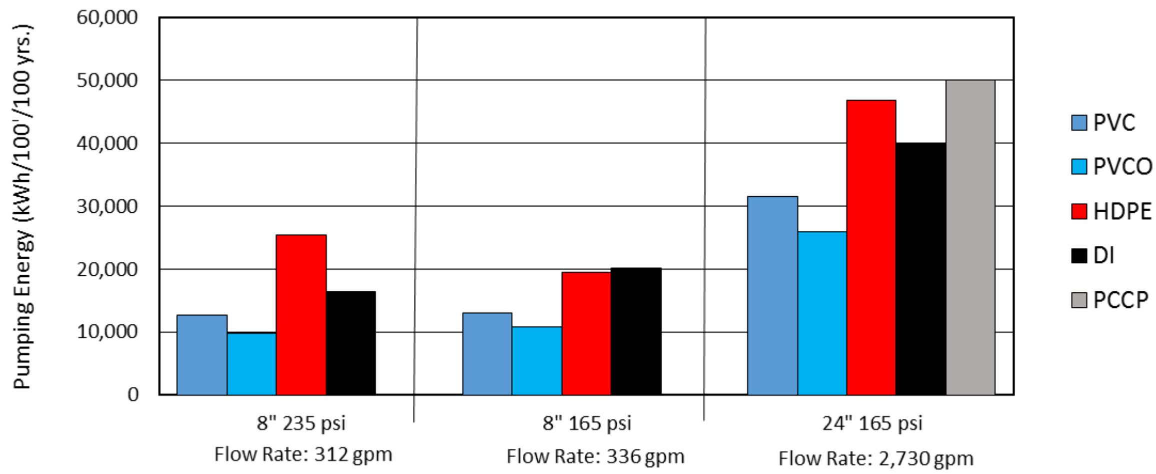
The calculations of hydraulic energy and hydraulic energy costs for PVCO were performed with the same assumptions and methods as were used for other pipe products. The results for the pumping energy and pumping energy costs calculations are summarized in the following tables and graphs. The data provided in the Table 7(A.3) and Figures 11(A.3) and 12(A.4) subtly demonstrate PVC and PVCO pressure pipes' energy use and cost advantages per 100 feet of pipe. If this same data is considered on a practical water system basis, the environmental and economic advantages of PVC and PVCO are more obvious. If a utility had a 24-inch, 10-mile long water transmission main with a flow rate of 2,730 gallons per minute, then the difference in 100-year average annual power usage and cost would be 81,700 kWh and $9,400 more for HDPE than PVC pipe and 110,600 kWh and $12,700 more for HDPE than PVCO pipe. For that same pipeline, the difference in 100-year average annual power usage and cost would be 71,900 kWh and $9,100 more for DI than PVC pipe and 100,800 kWh and $12,500 more for DI than PVCO pipe. This example pipeline would produce a difference in 100-year average annual power usage and cost of 123,000 kWh and $15,200 more for PCCP than PVC pipe and 151,900 kWh and $18,500 more for PCCP than PVCO pipe.

TABLE 7(A.3): 100-YEAR PUMPING ENERGY PER 100 FEET AND 100-YEAR PUMPING COST PER 100 FEET OF PIPE

Pipe Material	Comparable PVC Size and Pressure Class					
	8" 235 psi		8" 165 psi		24" 165 psi	
	kWh/100'/100 yrs.	$/100'/100 yrs.	kWh/100'/100 yrs.	$/100'/100 yrs.	kWh/100'/100 yrs.	$/100'/100 yrs.
PVC	12,700	$1,500	13,100	$1,500	31,500	$3,600
PVCO	9,700	$1,100	10,800	$1,200	26,000	$3,000
HDPE	25,400	$2,900	19,400	$2,200	46,800	$5,400
DI	16,400	$1,900	20,200	$2,300	40,000	$4,600
PCCP	N/A	N/A	N/A	N/A	50,100	$5,800

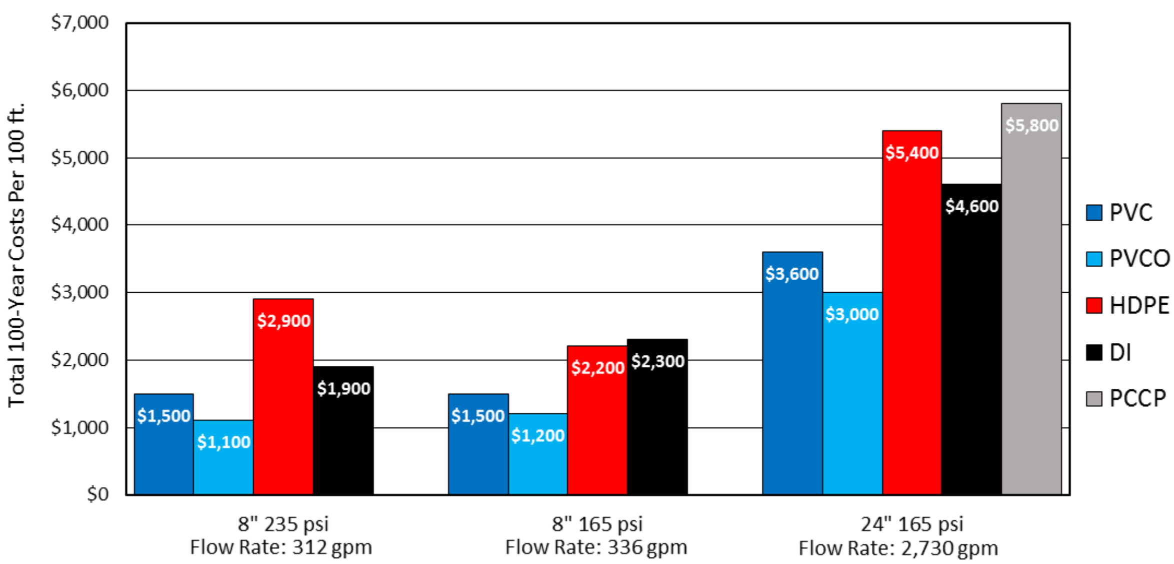
Note: Table assumes replacement of HDPE pipe at 50 years, DI pipe at 50 years and PCCP at 75 years.

FIGURE 11(A.3): TOTAL 100-YEAR PUMPING ENERGY USE PER 100 FEET OF PIPE



Note: Graph assumes replacement of HDPE pipe at 50 years, DI pipe at 50 years and PCCP at 75 years.

FIGURE 12(A.4): TOTAL 100-YEAR PUMPING ENERGY COSTS PER 100 FEET OF PIPE



Note: Graph assumes replacement of HDPE pipe at 50 years, DI pipe at 50 years and PCCP at 75 years.

Pressure Pipe: Total Embodied Energy Calculations

TABLE 8(A.4): 100-YEAR TOTAL EMBODIED ENERGY (MJ/100') FOR 8" PVC DR18 PC235 C900 COMPARISON

100-Year Life Cycle Activity	8" PVC DR18 Comparison			
	PVC DR18 PC235	PVCO PC235	HDPE 4710 DR9 PC250	DI CL51 PC350
Cradle-to-Gate	23,300	22,000	42,600	50,900
Final Transportation & Installation	4,100	4,000	4,700	5,300
Corrosion Protection	N/A	N/A	N/A	3,300
Total Cradle-Through-Installation	27,400	26,000	47,300	59,500
Replacement	N/A	N/A	47,300	59,500
100-Year Hydraulic Energy	45,700	34,900	91,400	59,000
Water Loss/100 Years	19	19	19	35
Total 100-Year Embodied Energy	73,100	60,900	186,000	178,000

FIGURE 13(A.5): 8" PVC DR18 EQUIVALENT PIPES: 100-YEAR TOTAL EMBODIED ENERGY

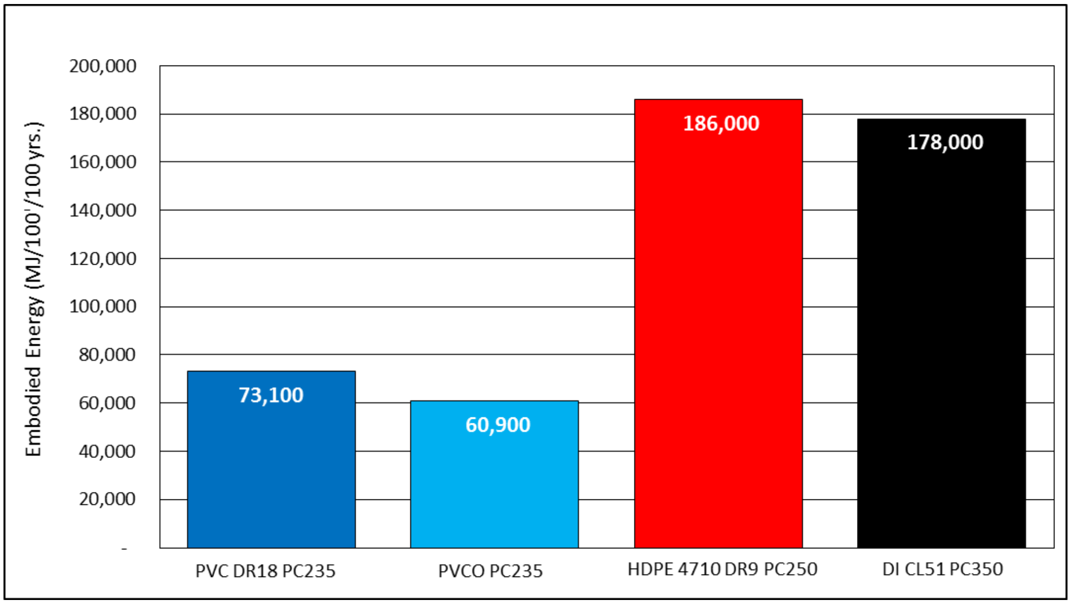


TABLE 9(A.5): 100-YEAR TOTAL EMBODIED ENERGY (MJ/100') FOR 8" PVC DR25 PC165 C900 COMPARISON

100-Year Life Cycle Activity	8" PVC DR25 Comparison			
	PVC DR25 PC165	PVCO PC165	HDPE 4710 DR13.5 PC160	DI CL51 PC350
Cradle-to-Gate	15,900	15,800	29,600	50,900
Final Transportation & Installation	4,000	3,900	4,400	5,300
Corrosion Protection	N/A	N/A	N/A	3,300
Total Cradle-Through-Installation	19,900	19,700	34,000	59,500
Replacement	N/A	N/A	34,000	59,500
100-Year Hydraulic Energy	47,000	38,900	70,000	72,700
Water Loss/100 Years	19	19	19	35
Total 100-Year Embodied Energy	66,900	58,700	138,000	191,700

FIGURE 14(A.6): 8" PVC DR25 EQUIVALENT PIPES: 100-YEAR TOTAL EMBODIED ENERGY

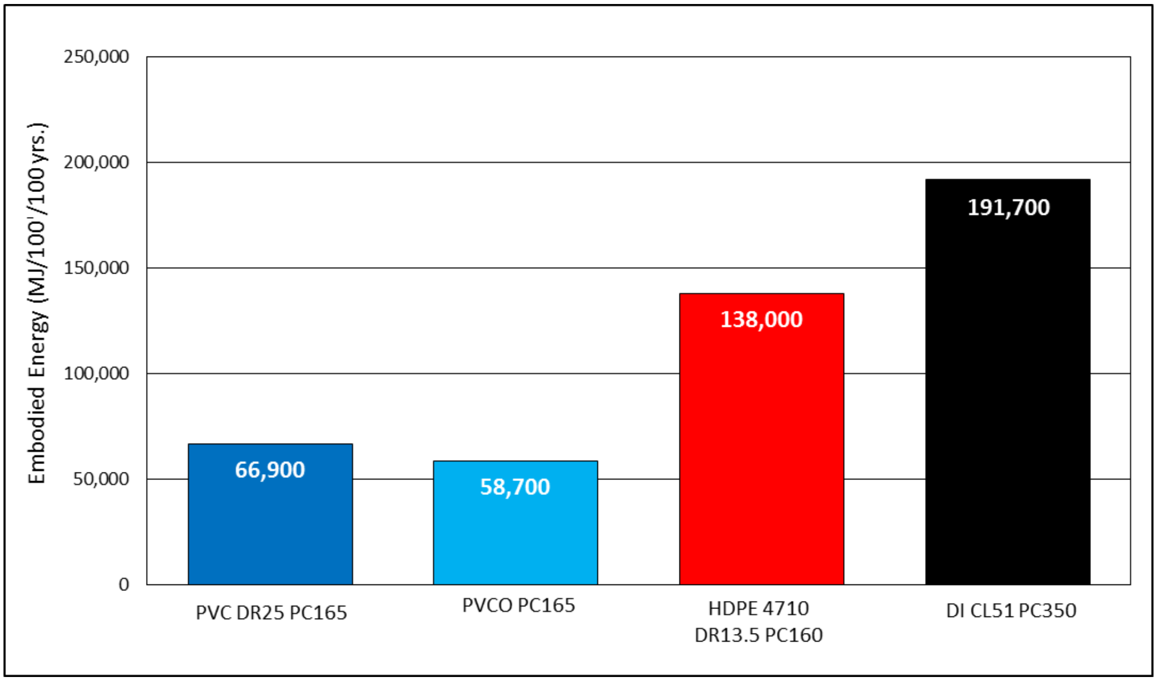
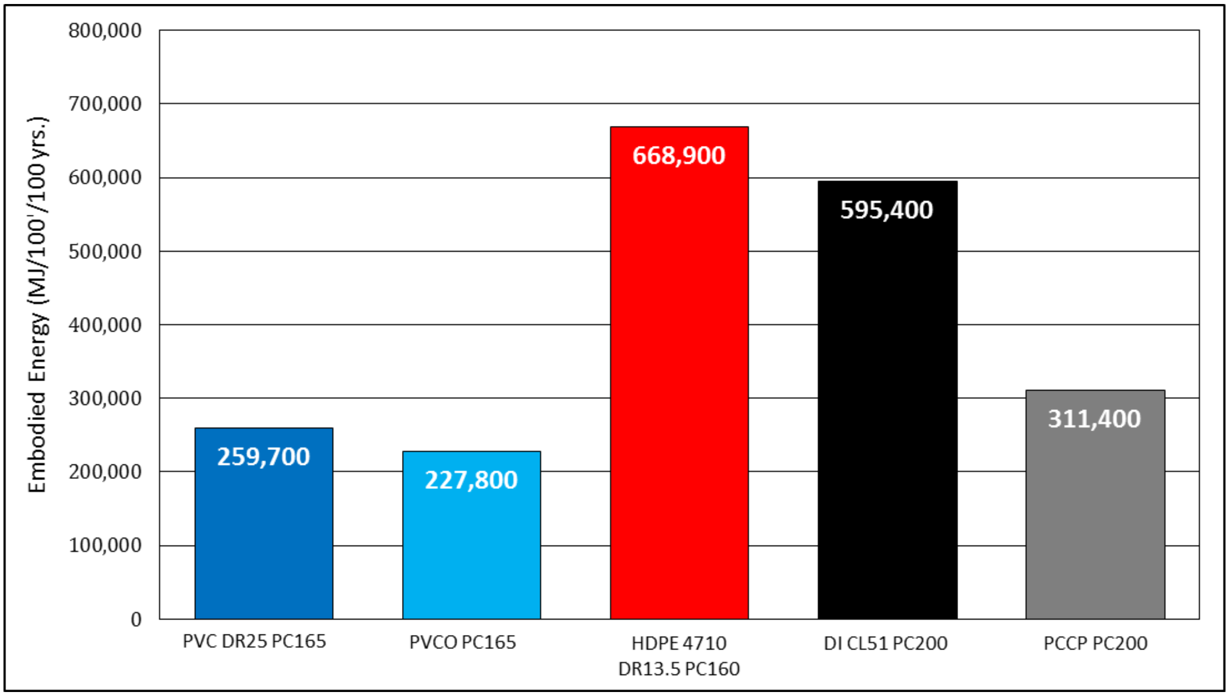


TABLE 10(A.6): 100-YEAR TOTAL EMBODIED ENERGY (MJ/100') 24" PVC DR25 PC165 C905 COMPARISON

100-Year Life Cycle Activity	24" PVC DR25 Comparison				
	PVC DR25 PC165	PVCO PC165	HDPE 4710 DR13.5 PC160	DI CL51 PC200	PCCP PC200
Cradle-to-Gate	137,900	125,600	240,800	206,600	53,500
Final Transportation & Installation	8,300	8,400	9,300	10,000	11,900
Corrosion Protection	N/A	N/A	N/A	8,900	N/A
Total Cradle-Through-Installation	146,200	134,000	250,100	225,500	65,400
Replacement	N/A	N/A	250,100	225,500	65,400
100-Year Hydraulic Energy	113,300	93,600	168,500	144,100	180,300
Water Loss/100 Years	160	160	160	310	340
Total 100-Year Embodied Energy	259,700	227,800	668,900	595,400	311,400

FIGURE 15(A.7): 24" PVC DR25 EQUIVALENT PIPES: 100-YEAR TOTAL EMBODIED ENERGY



PIPE MATERIAL EMBODIED ENERGY SUMMARY

Table 11(A.9) includes the cradle-to-gate embodied energy for PVCO pressure pipes and comparable products in the applicable sections included in the LCA.

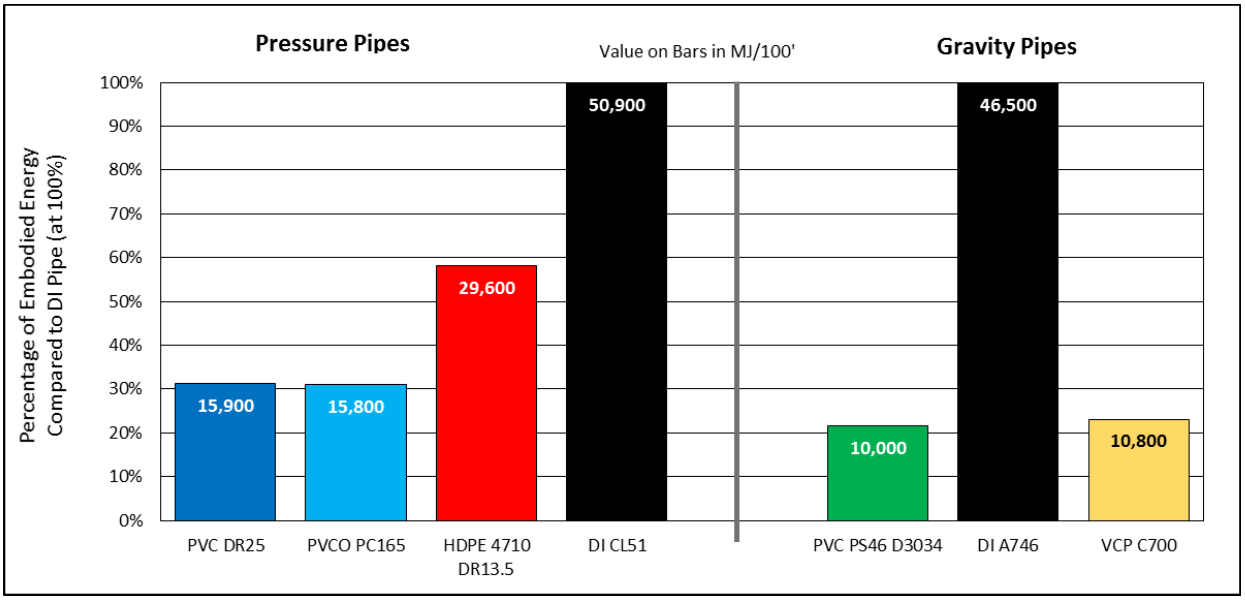
TABLE 11(A.9): SUMMARY OF CRADLE-TO-GATE EMBODIED ENERGY FOR PVC AND ALTERNATIVE PIPE MATERIALS

PVC Size and Product	Comparable Products	Standard	Embodied Energy (MJ/100 ft.)
8" PVC DR18 PC235 C900	8" PVC DR18	AWWA C900	23,300
	8" PVCO PC235	AWWA C909	22,000
	8" HDPE 4710 DR9	AWWA C906	42,600
	8" DI CL51	AWWA C151	50,900
8" PVC DR25 PC165 C900	8" PVC DR25	AWWA C900	15,900
	8" PVCO PC165	AWWA C909	15,800
	8" HDPE 4710 DR13.5	AWWA C906	29,600
	8" DI CL51	AWWA C151	50,900
24" PVC DR25 PC165 C905	24" PVC DR25	AWWA C905	137,900
	24" PVCO PC165	AWWA C909	125,600
	24" HDPE 4710 DR13.5	AWWA C906	240,800
	24" DI CL51	AWWA C151 AWWA C104	206,600
	24" PCCP PC200	AWWA C301	53,500
24" PVC PS46 F794 Profile Wall	24" PVC PS46	ASTM F794 AASHTO M304	49,700
	24" PP PS46	ASTM F2736	43,700
	24" HDPE PS34	ASTM F2306	42,900
8" PVC PS46 F794 Profile Wall	8" PVC PS46	ASTM F794 AASHTO M304	5,900
	8" DI	ASTM A746	46,500
8" PVC PS46 SDR35 D3034 Solid Wall	8" PVC PS46	ASTM D3034	10,000
	8" DI	ASTM A746	46,500
	8" VCP	ASTM C700	10,800
24" PVCPS 46 F679 Solid Wall	24" PVC PS46	ASTM F679	98,600
	24" DI	ASTM A746	176,600
	24” VCP	ASTM C700	82,400
	24" NRCP	ASTM C14	21,300

Note: All ductile iron pressure pipes in this study are cement-lined per AWWA C104.
All ductile iron sewer pipes in this study are double cement-lined per AWWA C104.

Figure 16(A.14) contains the same 8-inch pressure and gravity comparison pipes as shown in LCA Figure A.14 with the addition of PVCO pressure pipe.

FIGURE 16(A.14): CRADLE-TO-GATE EMBODIED ENERGY COMPARISONS FOR EQUIVALENT 8" PIPES (MJ/100')



Note: Total 100-year embodied energy includes cradle-through-installation, required replacements and corrosion protection.

PUMPING ENERGY COMPARISONS OVER A 100-YEAR LIFE CYCLE

Figure 17(A.15) contains the same comparisons to 8-inch PVC DR25 water pipe as shown in Figure A.15 of the LCA with the addition of PVCO. If Figure 17(A.15) were labeled for the percentages of increased pumping costs relative to the life cycle pumping cost for PVCO, the percentages would be a 21 percent increase for PVC, an 80 percent increase for HDPE and an 88 percent increase for DI.

Loss of carrying capacity and higher pumping costs are due much more to the effects of iron pipe corrosion, leaks and tuberculation rather than minor internal diameter differences between iron and PVC pipes. The same deterioration conditions for iron pipes apply to the comparison to PVCO pipes; however, PVCO pipes have a larger internal diameter than iron pipes which further increases the PVCO life cycle pumping energy and cost advantages. HDPE pipe, on the other hand, has a much smaller internal diameter than DI, PVC or PVCO pipe, significantly impacting its pumping energy requirements over time. PVCO, with thinner walls and a larger internal diameter than both PVC and DI, has lower embodied energy and energy use.

Figures 17(A.15), 18(A.16), 19(A.17) and 20(A.18) compare PVC and PVCO pipes with similar pressure classes of DI, HDPE and PCCP piping. When the diameter and deterioration of friction factor of all pipe materials are considered, 24-inch PVC and PVCO pipes are the clear, sustainable choices for efficiency in pumping energy and lower life cycle costs.

FIGURE 17(A.15): PUMPING ENERGY COST OF 8" PVC DR25 EQUIVALENT PIPES OVER A 100-YEAR LIFE CYCLE

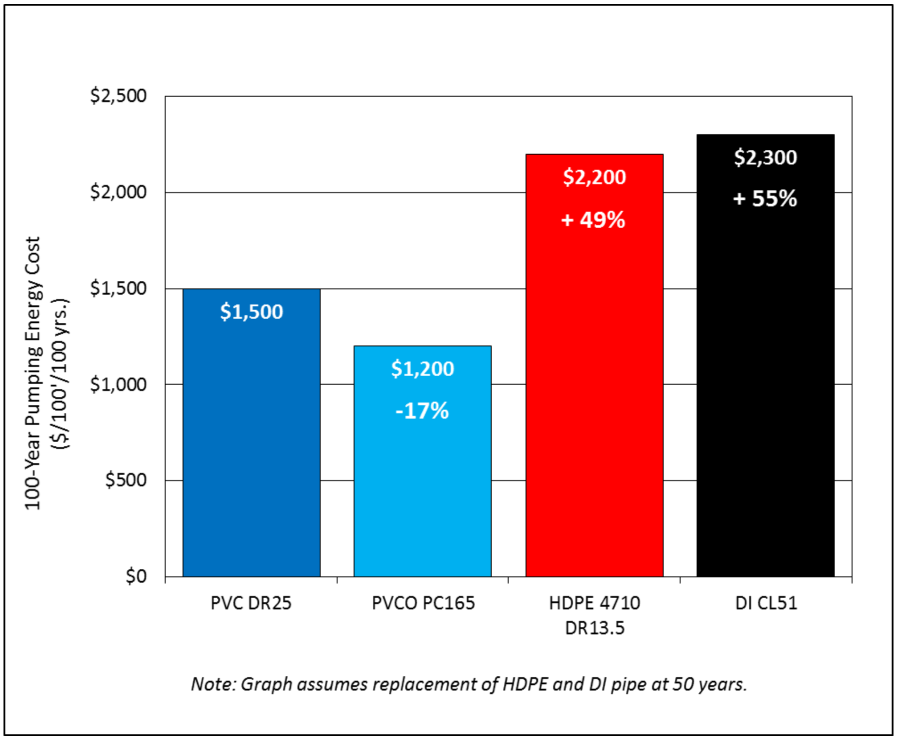


FIGURE 18(A.16): 8" PVC DR18 EQUIVALENT PIPES 100-YEAR PUMPING ENERGY

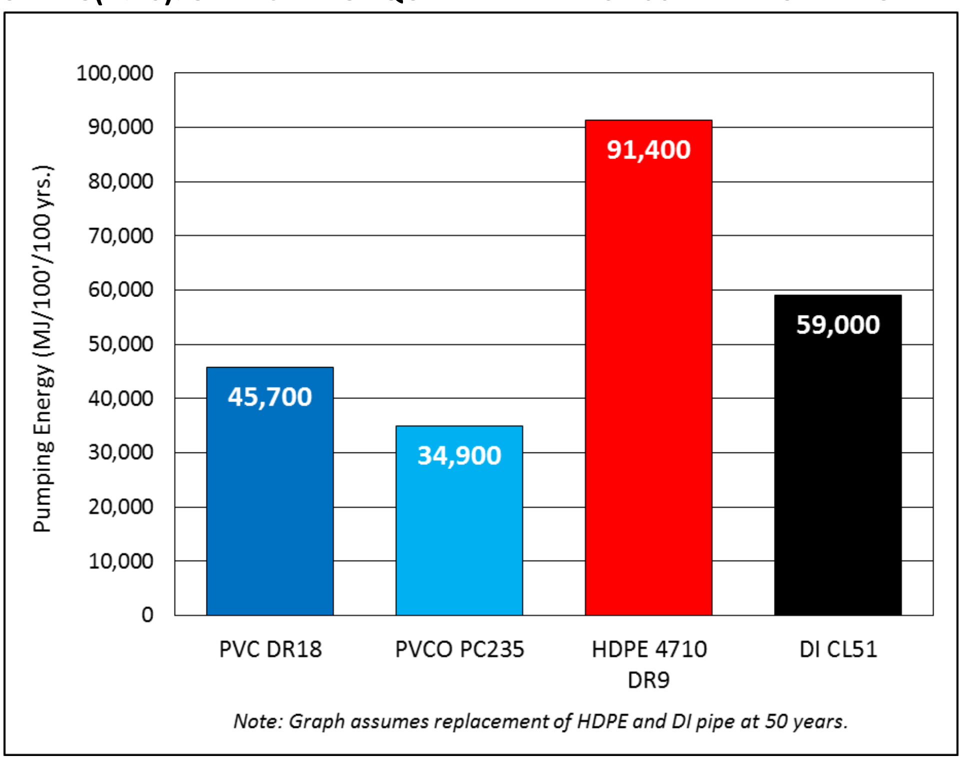


FIGURE 19(A.17): 8” PVC DR25 EQUIVALENT PIPES 100-YEAR PUMPING ENERGY

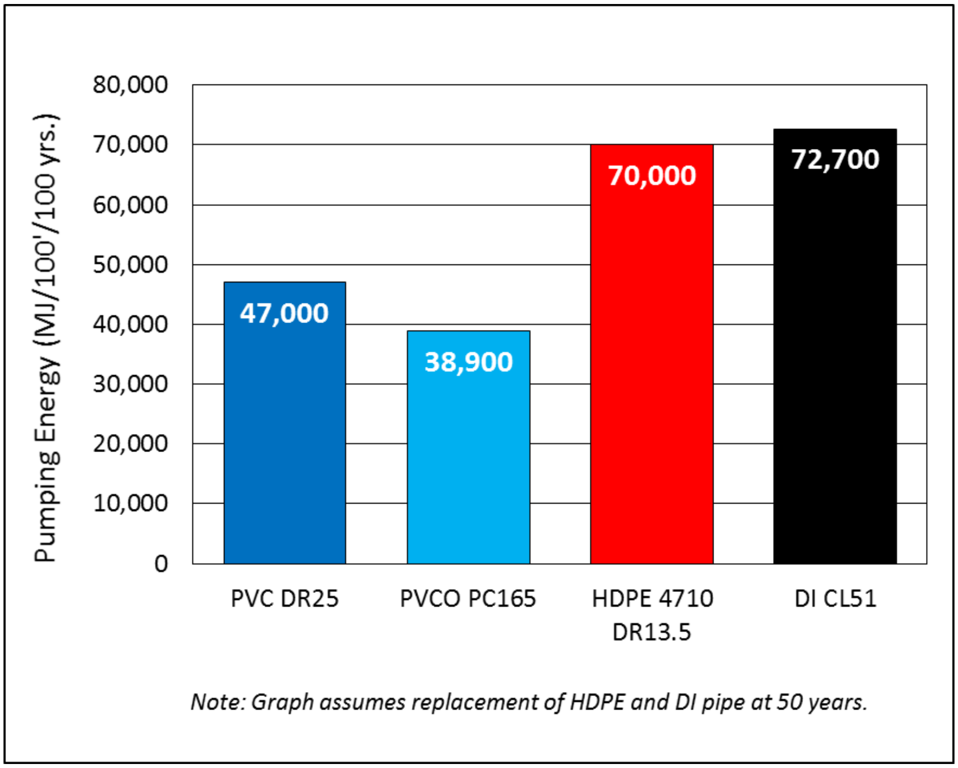
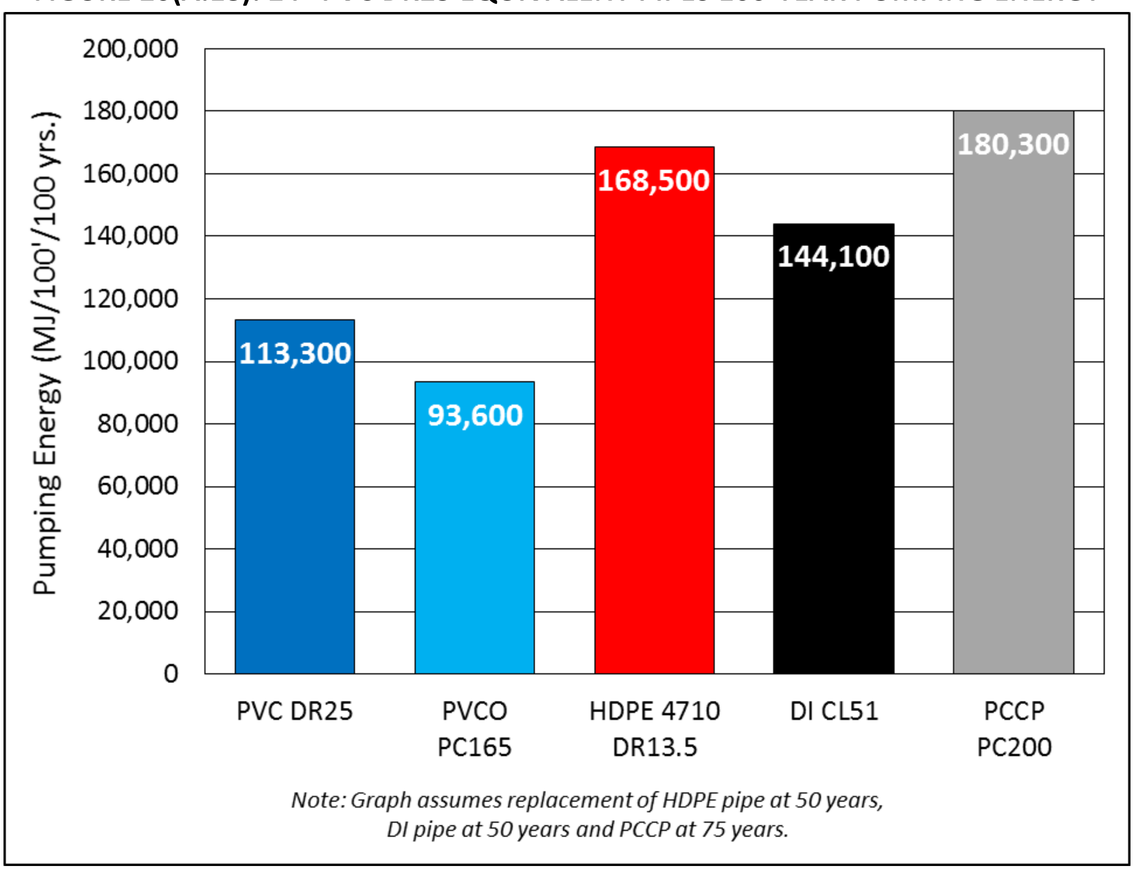


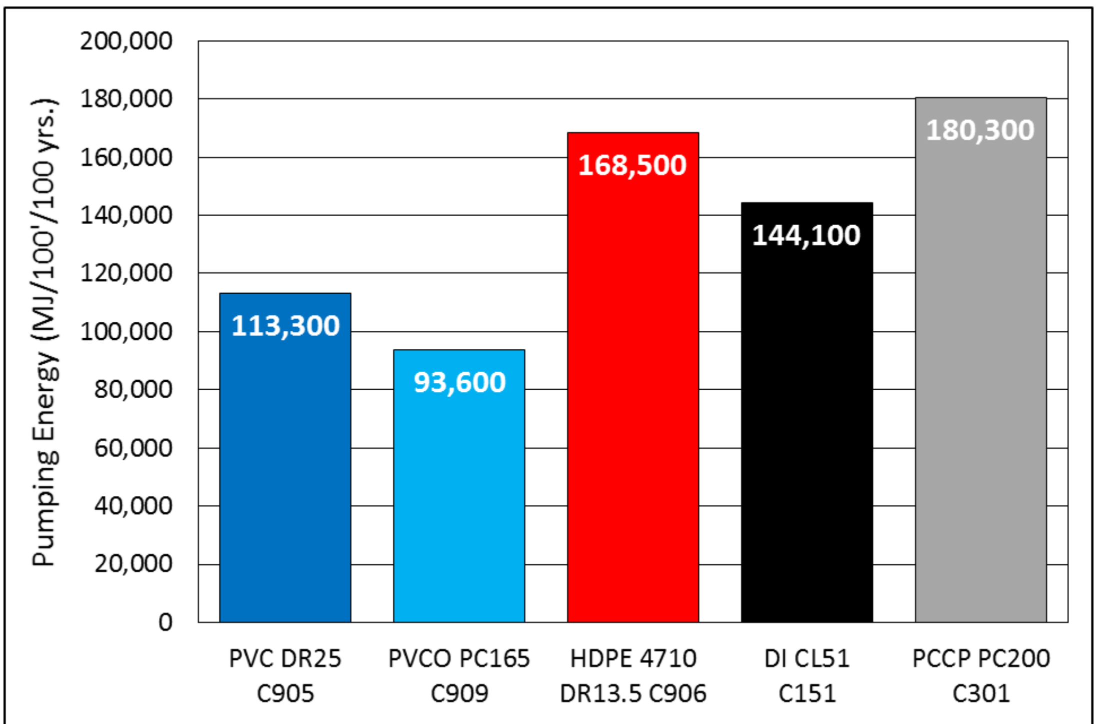
FIGURE 20(A.18): 24” PVC DR25 EQUIVALENT PIPES 100-YEAR PUMPING ENERGY



Total 100-Year Pumping Energy: Costs Over Time Using Differing Pipe Service Lives

Pumping costs can be the largest budget item for utilities. Energy for pumping can be 70-90 percent of the total energy use for a utility. PVC and PVCO offer significant savings in energy use and energy costs. Energy savings for a utility equate to sustainable practices and reduction in greenhouse gases. Utilities that judge replacement of water pipelines solely on main break records should also consider loss of flow capacity due to degradation of the interior surface of pipe over time. Leaving pipes in service beyond an efficient service life can increase the pumping energy use for a utility over time. Figure 21(A.19) shows the differences in 100-year pumping energy use per 100 feet of pipe based on reasonable life expectances of the comparison 24-inch pipes. Figure 22(A.20) shows the same data with the addition of the pumping energy required if the competitive pipes are not replaced at the end of their service life. Figure 22(A.20) exposes the fact that leaving pipe in service after its useful service life increases the pumping energy over time due to increased degradation of the pipe walls. Figure 24(A.22) reveals that with the increase in pumping energy use, a utility pays a penalty in increased electrical costs for leaving degrading pipe in the service beyond a reasonable life.

FIGURE 21(A.19): 24” PVC DR25 EQUIVALENT PIPES 100-YEAR PUMPING ENERGY



Note: Graph assumes replacement of HDPE pipe at 50 years, DI pipe at 50 years and PCCP at 75 years.

FIGURE 22(A.20): 24" PVC DR25 EQUIVALENT PIPES TOTAL 100-YEAR PUMPING ENERGY USING DIFFERING PIPE LIVES

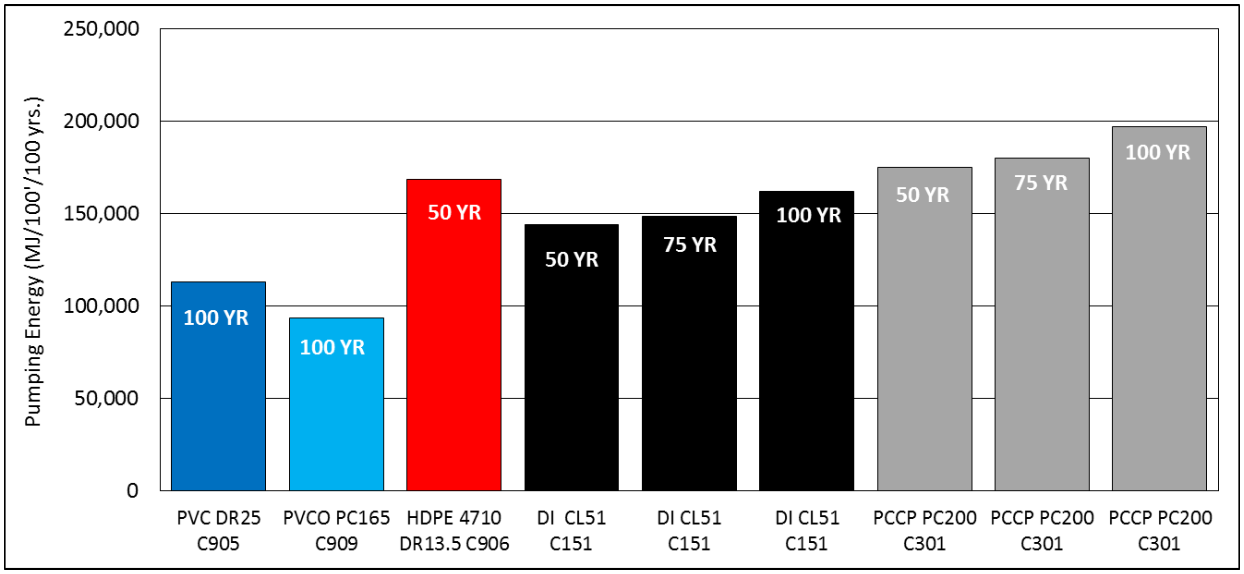


FIGURE 23(A.21): 8" PVC DR18 EQUIVALENT PIPES TOTAL 100-YEAR PUMPING COSTS USING DIFFERING PIPE LIVES ($/100'/100 YRS.)

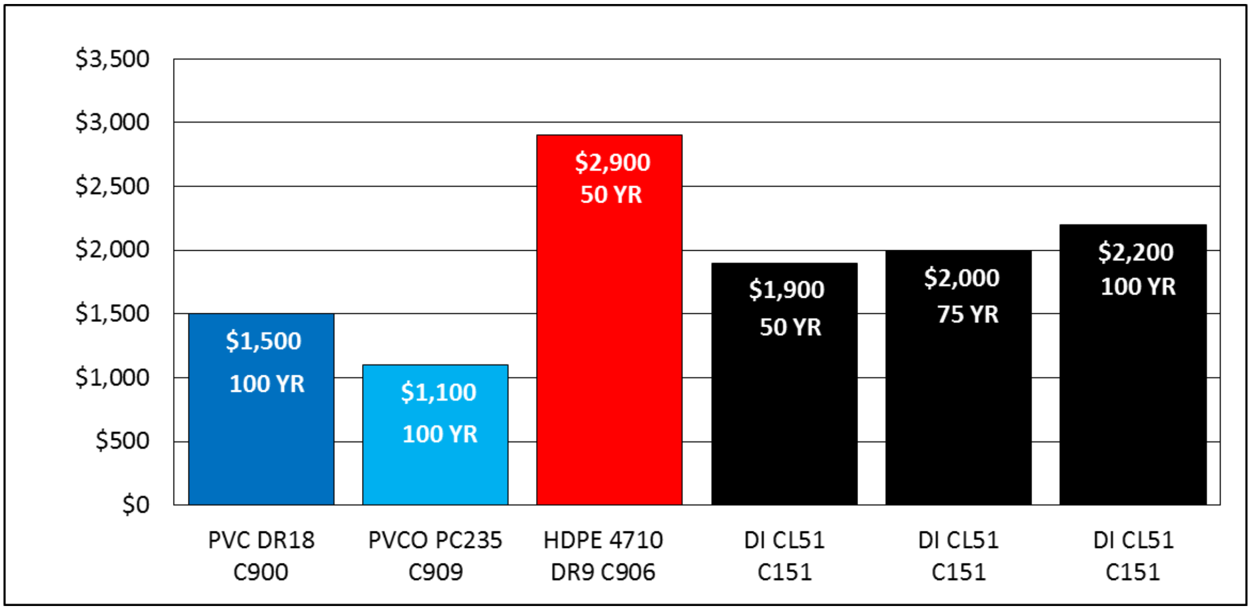
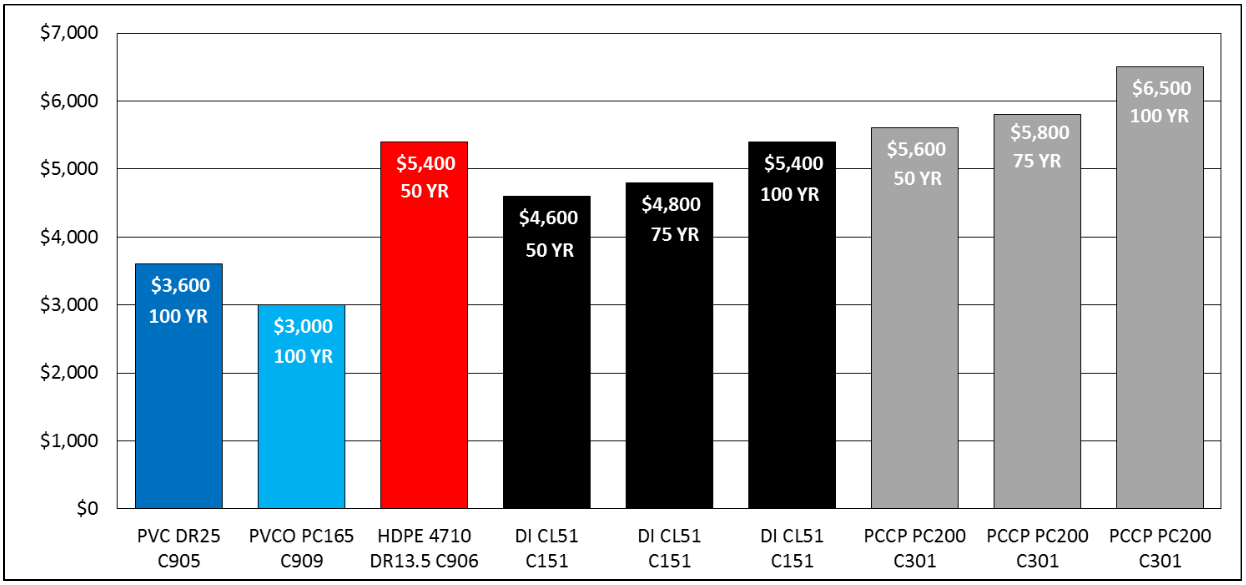


FIGURE 24(A.22): 24" PVC DR25 EQUIVALENT PIPES TOTAL 100-YEAR PUMPING COSTS USING DIFFERING PIPE LIVES ($/100'/100 YRS.)

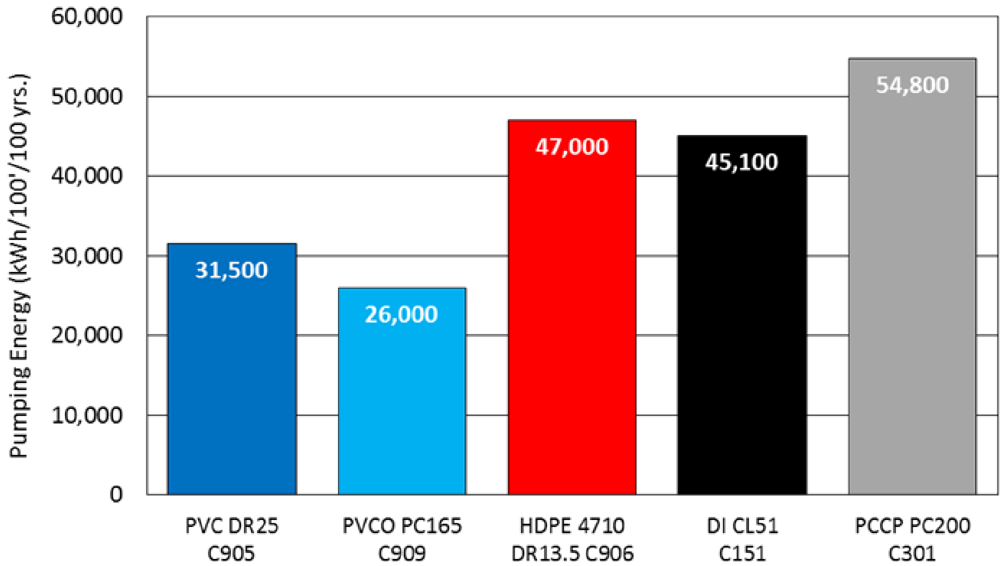


NOTE: PLEASE USE FIGURES 25 AND 26 WHEN COMPARING 100-YEAR PUMPING

All figures dealing with pumping costs in the LCA include resets at 50 years for DI and 75 years for PCCP. As a result we do not recommend using figures found in the LCA for 100-year pumping comparisons.

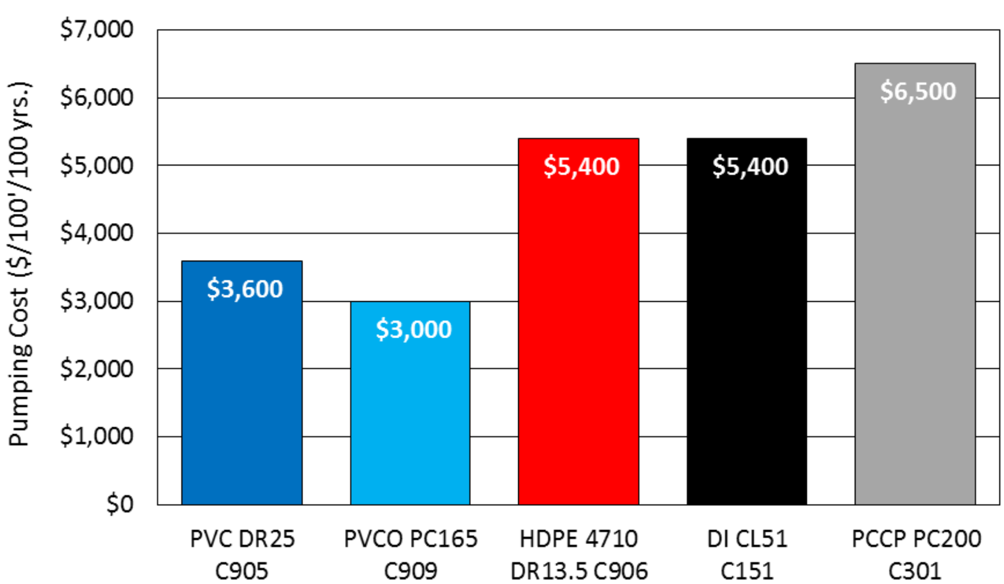
Figures 25 and 26 have been specially prepared to allow for 100-year pumping comparisons by not including the reset Hazen Williams that come from replacements for DI and PCCP during the 100-year life cycle. Instead, they show what the degradation would be if the pipes lasted 100 years even though this is unlikely in most cases. Wording has been provided below for each graph to help explain this.

FIGURE 25: 24" PVC DR25 EQUIVALENT PIPES 100-YEAR PUMPING ENERGY



Note: Assumes all pipes at 100 years of continuous service without replacement with average internal pipe wall degradation for DI and PCCP pipes. Graph allows for longer theoretical pipe lives for demonstration puposes for HDPE, DI and PCCP pressure pipes which need replacement before 100 years because of oxidation and strain creep for HDPE and corrosion and degradation for DI and PCCP.

FIGURE 26: 24" PVC DR25 EQUIVALENT PIPES 100-YEAR PUMPING ENERGY COSTS



Note: Assumes all pipes at 100 years of continuous service without replacement with average internal pipe wall degradation for DI and PCCP pipes. Graph allows for longer theoretical pipe lives for demonstration puposes for HDPE, DI and PCCP pressure pipes which need replacement before 100 years because of oxidation and strain creep for HDPE and corrosion and degradation for DI and PCCP.

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[1] Sustainable Solutions Corporation. "Life Cycle Assessment of PVC Water and Sewer Pipe and Comparative Sustainability Analysis of Pipe Materials." April 2017.

[2] NSF International. "Environmental Product Declaration." Accordance with ISO 14025. May 15, 2015.

[3] Piratla, K. R., Ariaratnam, S. T., and Cohen, A. "Estimation of CO_2 Emissions from the Life Cycle of a Potable Water Pipeline Project." *Journal of Management in Engineering*. American Society of Civil Engineers. (January 2012).

[4] The European Plastic Pipes and Fittings Association. "Environmental Product Declaration – Bi-oriented Polyvinylchloride (PVC-O), MRS 45 MPa Pipe System for Water Distribution." January 2012.