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Embodied energy of pipe networks

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Abstract

Thousands of kilometres of pipes of different types and sizes are laid throughout the country, many in our urban residential environments for the delivery of water and disposal of sewage. Various piping materials are available and utilised at different stages of this whole process. In many situations, different piping materials and sizes can be interchanged to provide the same solution. Deciding upon which material should be utilised could involve many considerations.

To allow comparisons between materials, authorities are starting to embrace Whole Life Costing and Life Cycle Analysis concepts. An important aspect of these analysis processes is the inclusion of an Embodied Energy Analysis where the total energy used to manufacture and install different materials is compared. The manufacturing of various pipes involves different processes and materials and consequently the amount of energy required to manufacture each pipe type is also different. Determining how much energy is required is a complicated process as it should account for not only the direct energy input at the actual manufacturing stage, but also the indirect energy that comes from all the associated processes that go towards creating a pipe. This energy is known as ‘embodied energy’ and can be used to determine the overall energy impact of a particular piping solution.

This paper looks at a range of pipe types and determines their individual embodied energy coefficients. In order to assess practical comparisons of pipe systems a series of scenarios are developed to test the embodied energy implications of using different piping solutions to achieve a similar hydraulic performance for a simple simulated pipeline. The results show that there is significant embodied energy differences between the solutions modelled and highlights the possible embodied energy implications of using different materials for piping systems.

Introduction

Thousands of kilometres of pipes of different types and sizes are laid throughout the country, many in our urban residential environments for the delivery of water and disposal of sewage. Various piping materials are available and utilised at different stages of this whole process. In many situations, different piping materials and sizes can be interchanged to provide the same solution. Factors which need to be considered include the cost of the material, installation issues, the hydraulic performance characteristics and lifetime of the pipe material.

Originally, water authorities focused on the immediate cost and installation issues when determining which pipe materials they would use. Those pipes that were cheap to buy and/or were easy and cheap to install were often selected over more expensive alternatives. However, this was often found to lead to long-term problems with increasing failure rates leading to increasing maintenance bills and assets that did not last as long as hoped. This problem lead to the concepts of life cycle costing being adopted by many authorities who began to look at the long term performance of the pipe materials and their estimated maintenance requirements. Consequently, authorities began selecting pipe materials based on a long-term life cycle basis rather than a short-term capital cost basis.

Life cycle costing of pipe networks has usually focused solely on the economic cost of the pipe networks taking into account the initial installation costs, maintenance costs and replacement costs over the expected life of the pipe material. However, authorities and pipe manufacturers are now looking at extending this economic view to also include the social and environmental costs associated with a pipe network. Concepts such as whole of life analysis and triple bottom line (TBL) reporting are examples of this growing trend. TBL reporting has become increasingly popular amongst many organisations to provide what many consider is a more balanced assessment of a company's performance, rather than focusing purely on financial aspects. It is based on the premise that monitoring and reporting social, economic and environmental performance can better prepare organisations for future challenges and opportunities (Environment Australia, 2003). TBL reporting is generally focused at the organisational level but can extend to all aspects of an organisation's operation. For water authorities, this should include the materials they use in their daily work including the pipe materials.

Determining the social and environmental benefits of alternative pipe materials is a complex problem and it is not the intent of this paper to deal with all the issues which merit consideration. This paper will focus on the use of an Embodied Energy Analysis to determine the environmental consequence of various pipe materials which has gained increasing interest amongst many manufacturers as a way of determining their product's impact.

Embodied energy

Energy consumption (primarily electricity) is often used as a simple indicator for environmental impact. In countries such as Australia where electricity generation is mainly from coal fired power stations, the electricity consumption can be converted to greenhouse gas emissions via the power stations carbon dioxide output for every kilowatt hour of electricity they produce.

The manufacturing of various pipes involves different processes and materials and consequently the amount of energy required to manufacture each pipe type is also different. This energy is known as 'embodied energy' and can be used to determine the overall energy impact of a particular piping solution. Embodied Energy Analysis determines the total energy used to manufacture and install different materials and allows comparison between materials.

The concept of embodied energy is a relatively new measure in the area of environmental assessment that has started to be included in life cycle energy calculations of buildings. Embodied energy is defined as: *"the quantity of energy required by all of the activities associated with a production process, including the relative proportions consumed in all activities upstream to the acquisition of natural resources and the share of energy used in making equipment and in other supporting functions i.e. direct energy plus indirect energy."* (Treloar, 1994), see Figure 1.

Thus the primary aim of any embodied energy analysis is to quantify the amount of energy used to manufacture a material. Consequently, from the material level an embodied energy value can then be calculated for a product, component, element or whole system. This involves the assessment of the overall expenditure of energy required to extract the raw material, manufacture products and components, build, and maintain the component, element or whole system whichever is being assessed. A secondary aim is to establish the embodied energy required to construct and maintain the item, component or system over the whole life cycle. For product manufacturers, embodied energy analysis is usually only carried out to the completion of the manufacturing process. This paper reports on the embodied energy intensities on that basis.

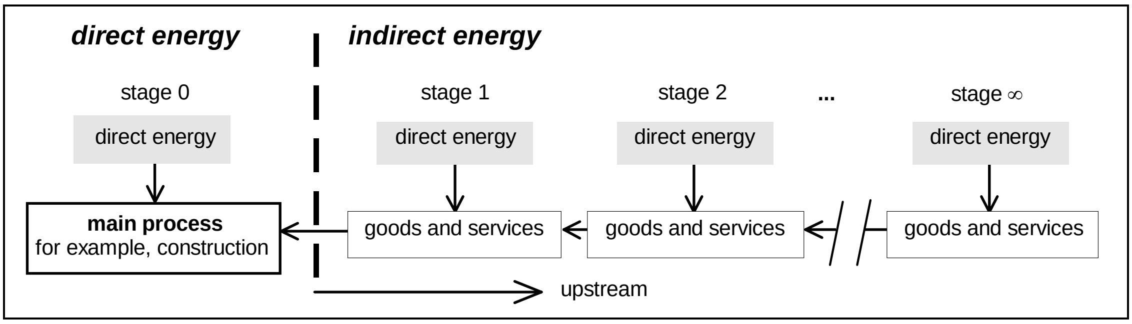

Figure 1 ‘Systems’ view of embodied energy, by upstream stage

Embodied energy analysis involves identifying energy consuming processes and calculating their contribution within the total product creation process. This usually involves several individual actions.

To be able to quantify the energy embodied in various pipe types, the quantities of individual materials must first be estimated through a process of disaggregation and decomposition to a level of detail which allows for the separation of components into their principal materials. Energy intensities of each material can then be multiplied by the quantities of individual materials and the products aggregated to obtain the total for the final pipe type.

Embodied energy coefficients

Embodied energy coefficients are derived from energy analysis studies from various national and international sources. Among the difficulties encountered in using a wide variety of sources to verify values is the need to clarify definitions of system boundaries or whether the values are in terms of primary energy or delivered energy. To obtain an accurate and reliable database of embodied energy coefficients for all materials used in water assets is an enormous task in itself and is a necessity for detailed comparisons of materials. The main requirement of embodied energy calculations at the design stage is obtaining accurate and useable material quantities and then combining them with currently available embodied energy intensity values. There are several methods used to carry out an energy analysis including:

- Process analysis - a commonly used procedure, which involves identifying a system boundary around a particular process and determining the requirements for direct energy and indirect energy. The critical aspect of a process analysis is the definition of the system boundary. Results can vary significantly depending on the selection of different system boundaries.
- Input-output analysis - developed for economic analysis in the 1940s and used by government economists who have collected data for the compilation of input-output matrices, which trace economic flows of goods and services between sectors of an economy. The energy intensity of a sector is expressed in gigajoules

(10^9 Joules) of energy per $100 of sector output (GJ/$100), and can be derived by dividing purchases from individual energy supply sectors by the appropriate tariffs. This is a fairly course methodology.

- Hybrid analysis - direct energy and quantities of goods and services are obtained for critical aspects of the process under consideration by process analysis and the energy intensities of goods and services further upstream are then obtained using input-output analysis. This helps remove errors associated with input-output analysis from a large proportion of the result.

Traditionally, input-output analyses have been used to derive the embodied energy coefficients, as the resultant energy coefficients were more complete than those derived from process analysis. However, this study uses a hybrid analysis which greatly reduces the errors associated with input-output analysis and is now considered the preferred method for embodied energy studies. The embodied energy coefficients were established using a combination of published data and calculations based on actual factory manufacturing data. They include transport energy of raw materials to the factory, but not transport energy to site or direct on site energy for installation. The values also include the pipe manufacturing process. Embodied energy coefficients are usually expressed in gigajoules (or megajoules) per unit, with mass being the most common unit. Table 1 lists the various embodied energy coefficients that were used for the pipe materials in this study.

Table 1 Embodied energy coefficients for pipe types

Pipe Type	Embodied Energy (MJ/kg)
Ductile Iron Cement Lined (DICL)	40.2
Polyvinylchloride – Unplasticised (PVC-U)	74.9
Polyvinylchloride – Modified (PVC-M)	76.6
Polyvinylchloride – Orientated (PVC-O)	87.9
Polyethylene 80B (PE80B)	75.2
Polyethylene 100 (PE100)	75.2

The DICL pipes combine different materials and so it was important to consider whether their embodied energy coefficient would change as the pipe size changed. However, investigation showed that the ratio of ductile iron to concrete remains fairly constant for the DICL pipes considered in this study and so no adjustment was required.

For PVC-O and PVC-M no published data was available. However, through consultation with the pipe manufacturers it was possible to develop embodied energy coefficients for these products. The major difference in the pipes is in the actual manufacturing/extrusion process, that is, the raw materials are essentially the same. For PVC-U the embodied energy of the manufacturing/extrusion phase is around 12MJ/kg. A local pipe manufacturing plant was studied and its operating energy and output rate for the various pipe types was compared against its values for standard PVC-U pipes. It was discovered that the pipe manufacturing process for PVC-O required 20% more energy than standard PVC-U and had a 40% lower output rate. This equates to a doubling of the embodied energy component within the manufacturing/extrusion phase that is 24MJ/kg, giving a total embodied energy coefficient of 87.9MJ/kg. The pipe manufacturing process for PVC-M was found to require 3% more energy than standard PVC-U production and an output rate 10% lower. This equates to an estimated total embodied energy coefficient of 76.6MJ/kg.

PVC-M also has about 5% of the PVC content replaced by a modifier, typically chlorinated polyethylene. No values could be located for this modifier, but given the small amount it was not expected to have a major effect on the final value.

Choosing a pipe material on the basis of the above coefficients can be misleading however, since similarly sized pipes will have different mass depending on the material. Consequently, for pipes it is better to consider values based on a lineal metre per pipe for various materials. When this approach is taken a different picture emerges. For example, the embodied energy coefficients for PVC-U and PVC-O are 74.9MJ/kg and 87.9MJ/kg respectively perhaps leading to the misconception that a PVC-O network would have a higher embodied energy total than a PVC-U network. However, on a lineal metre basis the embodied energy coefficients for 100mm PVC-U PN12 pipe and 100mm PVC-O PN12 pipe are 280.8MJ/m and 175.8MJ/m respectively. The PVC-O pipe has a significantly lower coefficient due to the thinner wall of the PVC-O pipe which translates into a lighter pipe than its PVC-U counterpart.

Scenarios

In order to assess practical comparisons of pipe systems a series of scenarios were developed to test the embodied energy implications of using different piping solutions to achieve a similar hydraulic performance over a fixed length. Three scenarios were decided upon that used different sized pipes and hydraulic performance criteria. PVC–O (AS 4441) Series 2, PN12 pipes were used to establish a baseline for each scenario because for each nominal size group they represent the largest internal diameter and thus produce the best hydraulic performance. Three different pipe sizes were selected with nominal diameters of 100mm, 250mm and 375mm. For each pipe size their velocity (V) was set at 1 metre per second for a length of 1000 metres. This resulted in values for flow rate (Q) and head loss (H) which were then set as the benchmark performance. The three resulting scenarios for 1000m of pipes were:

- Scenario 1 – 100mm pipes, V = 1m/s, Q = 10.4l/s and H = 7.82m
- Scenario 2 – 250mm pipes, V = 1m/s, Q = 54.4l/s and H = 2.8m
- Scenario 3 – 375mm pipes, V = 1m/s, Q = 128l/s and H = 1.76m

Using these baselines, different piping solutions were developed to maintain the same basic hydraulic performance using different piping materials. Alternative solutions were restricted to a maximum of two different pipe sizes of the same material. In order to achieve the optimum solution a simple spreadsheet was created which allows the baseline case to be set and then the alternative solutions created to match the same result. Apart from the baseline case all other systems needed to utilise two different sized pipes to achieve the same result. The spreadsheet program utilised the Hazen-Williams Formula and performed a simple simultaneous equation to equate the pipe lengths required. Once the lengths were established the values were multiplied by their respective embodied energy coefficients to produce the embodied energy total for each piping solution.

Scenario 1

Table 2 list the results for the scenario 1 and shows that the baseline case is the best performer in embodied energy terms. The next lowest embodied energy total for this scenario is achieved by the PVC-O Series 1 piping system which utilises 666m of DN100mm PVC-O pipe and 334m of DN150mm PVC-O pipe to achieve a total embodied energy of 204GJ which is 16% higher than the baseline case. The worst embodied energy result is achieved by the DICL piping solution, which has a total embodied energy of 1099GJ or 625% higher than the baseline case. The results are summarised in Figure 2 which shows the breakdown in embodied energy for each pipe length that goes to make up the piping system. In each case *Pipe 1* represents the smaller diameter pipe in the system, so for the PVC-U piping systems *Pipe 1* is the DN100mm pipe and *Pipe 2* is the DN150mm pipe.

Table 2 Scenario 1 results

	DN100		DN150			
Pipe	Length (m)	Head Loss (m)	Length (m)	Head Loss (m)	Total H (m)	Total EE (GJ)
PVC-O AS 4441 Series 2 PN12	**1000**	**7.84**	**NA**	**NA**	**7.84**	**176**
PVC-O AS 4441 Series 1 PN12	666	7.15	334	0.69	7.84	204
PVC-U AS/NZS 1477 S1 PN12	440	6.30	560	1.54	7.84	375
PVC-U AS/NZS 1477 S2 PN12	702	7.34	298	0.50	7.84	290
DICL AS/NZS 2280	387	6.64	613	1.20	7.84	1099
PVC-M AS/NZS 4765 S1 PN 12	529	6.70	471	1.14	7.84	231
PVC-M AS/NZS 4765 S2 PN 12	816	7.56	184	0.27	7.83	205
	DN125		**DN180**			
PE80B AS/NZS 4130 PN12.5	428	6.40	572	1.44	7.84	502
PE100 AS/NZS 4130 PN12.5	580	6.98	420	0.85	7.83	375

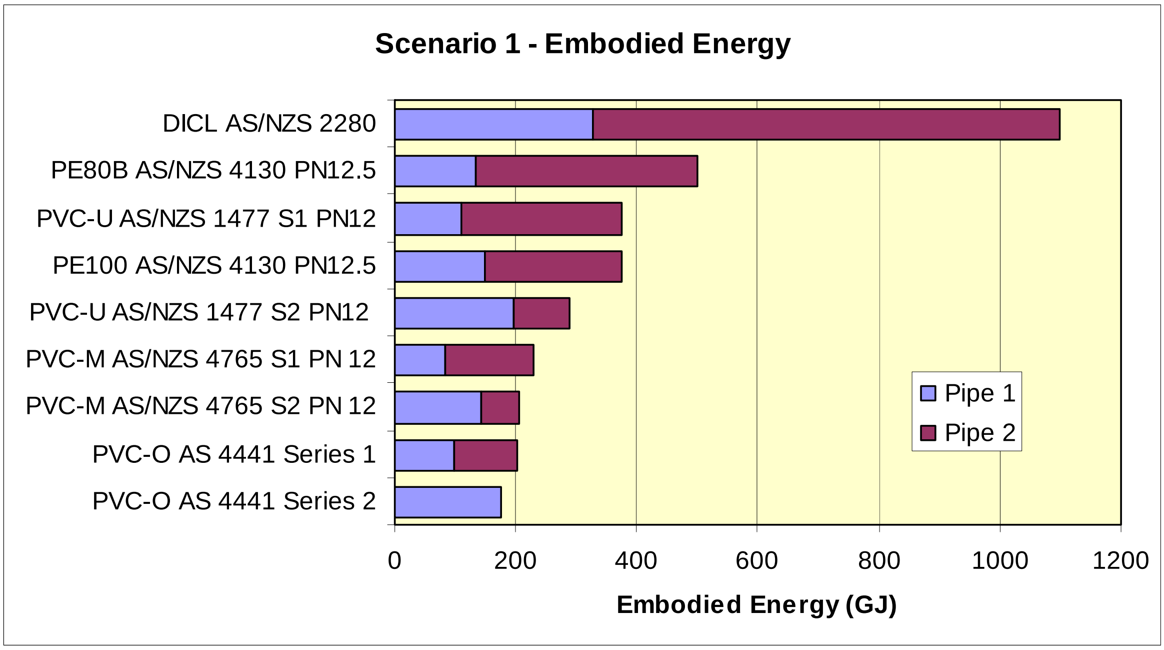

Figure 2 Scenario 1 embodied energy

Scenario 2

Table 3 lists the results from scenario 2 and shows that the baseline piping system has again performed well in terms of embodied energy, although it is not the best performing system. The best was the PVC-O S1 piping system, which had a total embodied energy of 912GJ which was 9% lower than the baseline systems total of 996GJ. As with scenario 1, the DICL piping system was the worst performer with a 267% increase in embodied energy over the baseline case. The embodied energy results are summarised in Figure 3.

Table 3 Scenario 2 results

Pipe	DN250 Length (m)	DN250 Head Loss (m)	DN300 Length (m)	DN300 Head Loss (m)	Total H (m)	Total EE (GJ)
PVC-O AS 4441 Series 2 PN12	**1000**	**2.81**			**2.81**	**996**
PVC-O AS 4441 Series 1 PN12	786	2.44	214	0.37	**2.81**	912
PVC-U AS/NZS 1477 S1 PN12	357	1.4	643	1.42	2.82	1531
PVC-U AS/NZS 1477 S2 PN12	657	2.33	343	0.48	2.81	1258
DICL AS/NZS 2280	621	2.29	379	0.52	2.81	2655
PVC-M AS/NZS 4765 S1 PN 12	480	1.74	520	1.07	2.81	1111
PVC-M AS/NZS 4765 S2 PN 12	757	2.49	243	0.32	2.81	1138
	DN315		**DN355**			
PE80B AS/NZS 4130 PN12.5	440	1.66	560	1.15	2.81	2263
PE100 AS/NZS 4130 PN12.5	826	2.52	174	0.29	2.81	1713

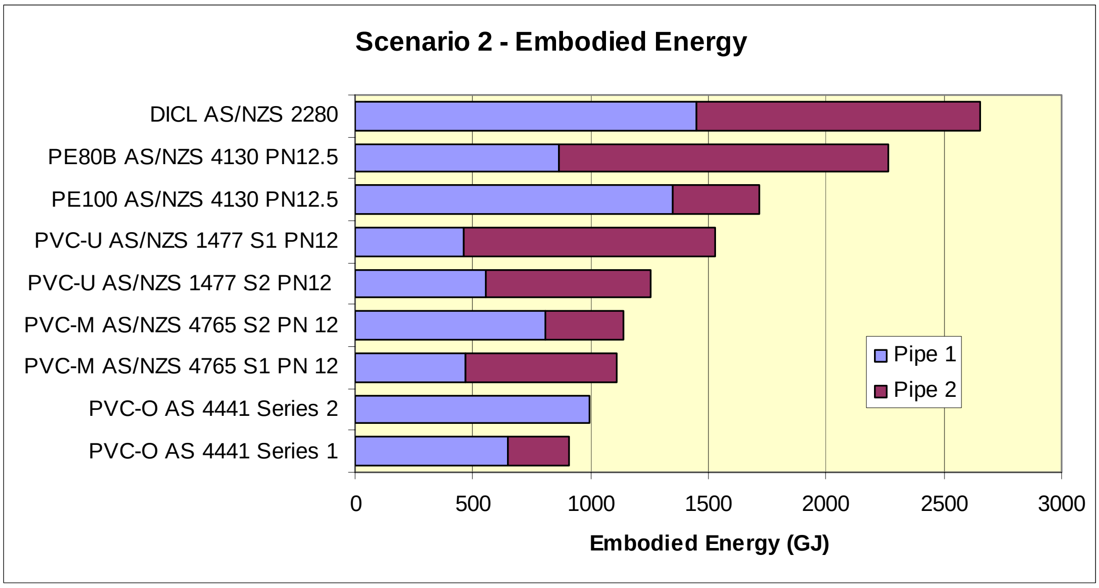

Figure 3 Scenario 2 embodied energy

Scenario 3

Table 4 lists the results for scenario 3 and unlike the previous two scenarios; this scenario resulted in a smaller set of alternative solutions. This was due mainly to the general unavailability of larger pipe diameters within PVC pipes with the largest nominal size generally being 375mm. Nevertheless, alternatives were possible with DICL and PE100 piping systems. Results show that the baseline PVC-O piping system was the best solution for embodied energy with a total of 2183GJ. The DICL piping system was again the highest with a total of 5150GJ or 236% higher than the baseline case. The results are shown in Figure 4.

Table 4 Scenario 3 results

	DN375					
Pipe	**Length (m)**	**Head Loss (m)**	**Length (m)**	**Head Loss (m)**	**Total H (m)**	**Total EE (GJ)**
PVC-O AS 4441 Series 2	**1000**	**1.76**			**1.76**	**2183**
	DN300		**DN450**			
DICL AS/NZS 2280	180	1.09	820	0.68	**1.77**	5150
	DN355		**DN500**			
PE100 AS/NZS 4130 PN12.5	62	0.45	938	1.31	**1.76**	3993

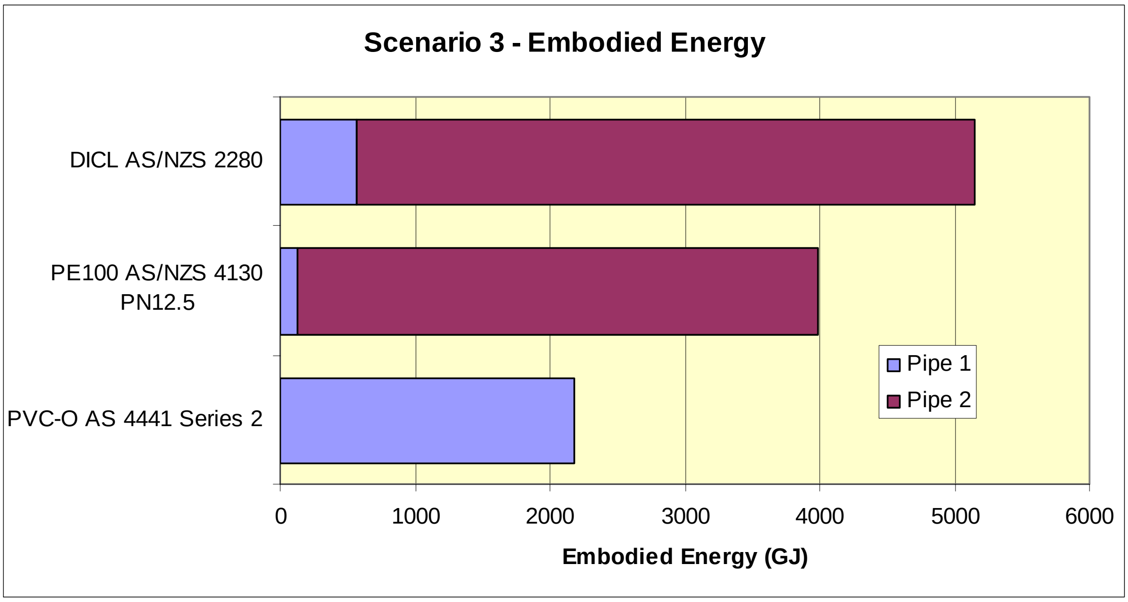

Figure 4 Scenario 3 embodied energy

General principles for lowering embodied energy

There are some general principles that can be followed when trying to make pipe material choices with regard to the impact of embodied energy. In general, the basic factors that influence embodied energy are:

- Pipe size - the bigger the pipe the more embodied energy.
- Amount of materials used - more materials, higher embodied energy.
- Pipes produced with significant recycled material - these materials usually have a lower overall embodied energy due to the "inherited" energy they gain from the recycled material.
- Piping systems, which are more durable and have a longer life expectancy - less repair and replacement leads to lower embodied energy over the life cycle of the system.
- Piping systems, which can last longer with appropriate maintenance - extending life, rather than replacing reduces embodied energy for that system over its life cycle.

Conclusion

The embodied energy of piping systems is an important factor to consider in the design of such systems. This paper has shown that various pipe materials have a broad range of embodied energy coefficients and that selecting a particular piping material for a piping solution can have a significant effect on the embodied energy total for a system. The three scenarios that were modelled resulted in a range of solutions for each hydraulic situation and revealed that certain piping materials perform consistently better, in regard to embodied energy, than other materials. In particular PVC-O pipes, appear to provide a better embodied energy solution in many situations. Within all scenarios virtually all the various forms of PVC pipes produced lower embodied energy results than any other piping material.

In all three scenarios the ductile iron concrete lined piping solutions delivered the highest embodied energy total for each situation. However, as pipe sizes increased the percentage difference decreased.

It is important to note that this paper only dealt with the energy embodied in products up to the time of installation and that the life expectancy of materials and their maintenance requirements over time are equally important issues to consider in assessing the life cycle of pipe networks. In particular, PE pipes are known to have an exceptionally long life expectancy with very low maintenance requirements and this could significantly change the scenario results when modelled over time. If, for example, PE has a life expectancy twice that of PVC, then over time a PE network would have a lower embodied energy total than the majority of PVC networks modelled.

Of course, there are many considerations when designing a piping system with embodied energy being only one of these, but this study has shown that significant differences do exist in the choices that can be made to satisfy a particular design requirement. Being aware of the embodied energy implications for a particular system will help engineers design piping solutions that not only deliver required hydraulic performance but also deliver lower embodied energy impacts and thus lower environmental impacts.

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