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Beatrice M. Smyth[1,2], Paul Davison [1] & Paddy Brow[1]
[1]Northern Ireland Water, Westland House, 40 Old Westland Road, Belfast, BT14 6TE
[2]Corresponding author. Current address: Dr Beatrice Smyth, School of Mechanical & Aerospace Engineering, Queen's University Belfast, BT9 5AH

Abstract

The water and wastewater industry has been tasked with reducing its greenhouse gas (or carbon) emissions. A key component of any emissions reduction strategy is emissions measurement. While operational emissions are reported by the sector on an annual basis, there is a lack of robust data on embodied carbon. The aim of this paper was to develop a practical solution for assessing the embodied carbon in wastewater assets. The analysis revealed a linear relationship between carbon emissions and capital investment in the construction of wastewater treatment works (1.3 tCO_2/£1000) and wastewater pumping stations (0.3 tCO_2/£1000). Carbon emissions from sewer construction were found to increase linearly with increasing pipe diameter, with ductile iron pipelines responsible for higher emissions than polyethylene. Operational carbon is the major component in the whole life carbon of wastewater treatment works, but future decarbonisation of the electricity grid may increase the relative importance of embodied carbon.

Keywords

Embodied carbon, greenhouse gas emissions, pumping station, rising main, sewer, wastewater treatment works, whole-life carbon

Introduction

Background

Concerns over the effect that human activities are having on climate have led to the introduction of measures to reduce greenhouse gas (GHG) emissions, and the UK Environment Agency (2012) has stated that the water and sewerage sectors have a responsibility to contribute to the national emissions reduction target. The water and sewerage sectors' combined GHG emissions account for just over 1% of total GHG emissions in the UK, while water heating in the home accounts for a further 5% (Ofwat, 2010). To put it in perspective, the sectors' emissions are equivalent to those from all buses in the UK (Ofwat, 2010a). The term GHG emissions refers to the 'basket of six' GHGs (i.e. carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF_6)), measured in tonnes of carbon dioxide equivalent (CO_2e). CO_2 and CO_2e are both commonly referred to as carbon emissions. CO_2 is the dominant GHG, accounting for 76% of total global emissions (IPCC, 2014). The terms carbon emissions and GHG emissions are used interchangeably in this paper.

To reduce GHG emissions, the 'carbon footprint' must first be measured. 'Carbon footprint', however, is a term for which there is no standard definition despite its widespread use; that said, there general agreement on the overall concept (Peters, 2010; Wiedmann & Minx, 2008). A review of the literature by Wiedmann & Minx (2008) proposed a working definition for 'carbon footprint' of 'a measure of the exclusive total amount of carbon dioxide emissions that is directly and indirectly caused by an activity or is accumulated over the life stages of a product'. Arising from the definition of 'carbon footprint' are further related concepts (Peters, 2010), such as 'embodied carbon' and 'operational carbon', the definitions of which vary depending on the specific boundaries, scale and scope of the analysis. Embodied carbon, for example, can be defined differently for a carbon study at a national (Chen & Chen, 2010) or international scale (Chen & Chen, 2011) than for a company-specific study in the water and wastewater industry (UKWIR, 2012). In the context of this paper, which focuses on company-level emissions in the water and wastewater sector, the components of the 'carbon footprint' comprise operational and embodied emissions. Following guidelines from UKWIR (2012), the UK water and wastewater industry research body, operational emissions are assumed to be those resulting from operational activities, e.g. energy and chemical usage, while embodied emissions are taken as those associated with constructing the asset, e.g. emissions from raw materials, manufactured products, on-site construction activities and off-site removal of waste.

In the literature relating to carbon emissions in the water and wastewater sector, operational carbon emissions are already widely analysed (Smyth et al, 2013; Gu et al, 2016; Kalbar et al, 2015) and are also reported by UK water and sewerage companies on an annual basis. There are, however, issues relating to the consistency of data and methodologies (Frijns, 2012), and there is a lack of consistent data on embodied carbon and on methods of estimating its contribution to whole life carbon. Ofwat (the economic regulator for the water and sewerage industry in England and Wales) collected data on embodied emissions from water and sewerage companies for the first time in 2009 (Ofwat, 2010a). The study found that embodied and operational emissions constituted ~35% and ~65% respectively of total projected emissions over the next five years, but there was large uncertainty in the projections, particularly for embodied carbon, where the error margins were as high as +/- 100% in some cases (Ofwat, 2010b). The relationship between capital expenditure and embodied carbon was also explored (Ofwat, 2010b). Values ranged from highs of over 1200 tCO_2/£M and ~660 tCO_2/£M in the water and sewerage sectors respectively, to lows of ~170 tCO_2/£M in both sectors. Differences between company estimates were likely to be due to different investment programmes and the 'inherent inaccuracies' in projecting embodied emissions. The report noted many inconsistencies and errors in the datasets.

In a related paper, Keil et al (2013) analysed emission data submitted to Ofwat for five expenditure categories (capital maintenance, enhanced service, supply/demand, quality, and large projects). Embodied emissions were found to add 50% to companies' operational emissions over five years, and capital maintenance programmes were the largest single source. Emissions intensity in the sewerage service was 415 tCO_2e/£M across all categories, ranging from 242 tCO_2e/£M for large projects to 748 tCO_2e/£M for supply/demand. Another industry report (UKWIR, 2012) contains a metadatabase of embodied carbon emission factors. The data include an equation from a UK water company that shows a linear relationship between GHG emissions and construction costs. For civil installations, embodied carbon emissions are estimated as ~900 tCO_2/£M, which similar to estimates in the Ofwat study.

Ofwat (2010a) has stated that knowledge of carbon emissions is an area requiring development. Keil et al (2013) argued that embodied emissions need to be accounted for if the water and sewerage sectors want to reduce their environmental impact, and also highlighted that the understanding and measuring of embodied emissions requires improvement. The current uncertainties surrounding embodied carbon estimates and the problems associated with a lack of data are issues not just for the water and wastewater sectors. It is problem also in the wider construction literature (Moncaster and Symons, 2013). Across the UK, the water and sewerage sector is responding to the need to improve estimates of embodied carbon. In Northern Ireland, the Department for Regional Development (DRD, 2010) (which became part of the new Department for Infrastructure (DfI) on 9 May 2016) required that Northern Ireland Water (NIW), the region's water and sewerage provider, take whole life emissions into account in the assessment of significant capital projects.

Aim, objectives and scope

The aim of this paper is to respond to regulations, fill the knowledge gap and develop a practical solution for assessing the embodied carbon in wastewater assets in NIW. The objectives are:

- To conduct detailed bottom-up estimates of embodied carbon for wastewater treatment works (WWTWs), waste water pumping stations (WWPSs) and sewers (rising mains);
- To examine the relationship between embodied carbon and project size;
- To investigate the importance of embodied carbon with respect to whole-life carbon for WWTWs.

The data used in the analysis are specific to recent construction projects in NIW. NIW provides water and wastewater services to the whole of Northern Ireland (population ~1.8 million), supplying 560 million litres of clean water and treating 320 million litres of wastewater each day. NIW owns 656 wastewater treatment works (WWTWs), 23 water treatment works, 1277 wastewater pumping stations (WWPSs), 360 water pumping stations, 15,200 km of sewers and 26,700 km of water mains. There are 795,000 domestic, agricultural, commercial and business properties connected to the public water supply and 660,000 connected to the public sewerage system.

Methodology

Overview

Using an adapted form of life cycle analysis (LCA), bottom-up estimates of embodied carbon were conducted by applying carbon factors to each item in the construction specifications for WWTWs, WWPSs and sewers. A bottom-up approach, which relies on process-based LCA and is often used for products, households and businesses, is at a finer scale than a top-down approach, which is based on input-output (I-O) models and is typically used at a national level (Peters, 2010). An explanation of the differences between bottom-up and top-down approaches in the water and wastewater sector is provided by Keil et al (2013), who notes that, although there are uncertainties with both approaches, a bottom-up approach could be expected to be more reliable as fewer assumptions are made. A hybrid approach, which combines the strengths of both LCA and I-O approaches, has also been proposed and is an area under active research (Peters, 2010; Williams et al, 2009).

Carbon factors were taken from 'CESMM3 Carbon & Price Book 2011' (ICE, 2010), which is used in the UKWIR (2012) embodied carbon guidelines. CESMM3 reports CO_2 emissions (not CO_2e) and draws on Hammond & Jones (2011), a widely used UK dataset. Where the CESMM3 emission factors did not exactly match the specification, the item with the closest description was chosen. Since the embodied carbon associated with MEICA (mechanical, electrical, instrumentation, control and automation) systems is typically low compared to that from civil construction works (UKWIR, 2012), it was excluded from the analysis. Design team activities were also excluded, as was decommissioning and disposal of the asset at end of life.

Embodied carbon of wastewater treatment works and pumping stations

As the aim of the paper was to develop a practical solution for assessing the embodied carbon in wastewater assets in NI Water, the analysis was based on recent construction projects carried out by the company. These projects comprised five recently constructed WWTWs and two WWPSs (there were six individual sites; one site comprised both a WWTW and WWPS). Bill of quantities (BOQ) information was obtained for each site, and was used as the basis for the life cycle inventory. Due to a lack of carbon factor information, some BOQ items were excluded; however, as these were typically minor ancillary items, their exclusion is unlikely to make a significant difference to the overall result. To allow comparison between projects, total carbon was expressed in terms of project size. Because many projects in NIW are upgrades to existing works, measuring project size as the quantity of sewage treated or population served would not give comparable results; project size was therefore defined as the capital construction cost. To allow comparison between projects, costs relating to design, project management, risk, overhead and profit, and site supervision were excluded.

Four of the WWTW projects had costs in the region £2.4M-£3.1M, two WWTWs were in the £0.3M-£0.4M range, and both WWPSs had costs of approximately £0.1M. This clustering of data was unavoidable. NI Water’s construction programme is dictated by the water and wastewater needs of the region; the analysis was based on the availability of real-world construction data and, unlike a laboratory experiment, additional points could not be simply ‘tested’, i.e. new plants could not be constructed just to fill in data points. Consideration was given to the use of data from earlier construction projects in the company, but this proposal was rejected as the values are out of date. The authors also considered the inclusion of data from other water companies, but, as NI Water is the sole supplier of water and sewerage services in N Ireland, such data would not have been directly relevant due to regional differences in costs and construction programmes.

Embodied carbon of sewers (rising mains)

Embodied carbon was calculated per meter length of ductile iron (DI) and polyethylene (PE) pipes of various diameters laid in both fields and roads (Eqn. 1 and Eqn. 2) according to typical NIW installation details (Table 1). The pipe diameters analysed were chosen based on relevance to NIW’s operations and availability of emission factor data in CESMM3. If the exact size of item was not listed in CESMM3, known values were interpolated/extrapolated to estimate the required emission factor.

$$EC_{pr} = EC_p + EC_b + EC_{bg} + EC_d + EC_{rr} + EC_m + EC_v \quad \text{Eqn. 1}$$

$$EC_{pf} = EC_p + EC_b + EC_{be} + EC_{rt} + EC_m + EC_v \quad \text{Eqn. 2}$$

where EC is embodied carbon ($kgCO_2/m$) and the subscripts relate to the various components involved in the pipe laying works (Tables 1 and 2).

Whole life carbon assessment

The three WWTWs constructed on greenfield sites (Figure 1) were analysed for whole-life carbon, i.e. embodied plus operational emissions. The population equivalent (p.e.) values were 320, 5287 and 14,511 for the £0.26M, £2.42M and £3.12M WWTWs respectively. Project lifetime was taken as 40 years. Total lifetime emissions from electricity were calculated by multiplying projected grid average public sector electricity emission factors (DECC, 2015) by typical current electricity usage, which was taken as the average from available site invoices. Other operational emissions were assumed to remain constant for the project lifetime (as recommended by UKWIR (2012)), and were estimated using the company-level relationship between electricity and total operational emissions from NIW's 2011 Annual Information Return (AIR11). AIR11 reported on operational emissions from grid electricity (including an allowance for renewable electricity), other fuels, and sewage treatment and sludge processes.

Results and discussion

Embodied carbon of wastewater treatment works and pumping stations

The analysis was based on recent company construction data, and the values are clustered in two regions: £0.1M-£0.4M and £2.4M-£3.1M. A better correlation between points is achieved when the information is analysed as one dataset, rather than as two, and a linear relationship was observed between embodied carbon and capital investment (Figure 1). Although there is a range of values, the results correlate reasonably well with previous work (Ofwat, 2010b; Keil et al, 2013; UKWIR, 2012) and variation between projects is not unexpected due to site-specific construction requirements. The average value for WWTWs is 1348 tCO_2/£M investment ($n=5$, $\sigma=0.3$), the average for pumping stations is 338 tCO_2/£M ($n=2$, $\sigma=0.04$) and the average for all plants analysed is 1059 tCO_2/£M ($n=7$, $\sigma=0.55$). There are higher carbon emissions per unit investment for larger projects (i.e. WWTWs), which is likely to be due to economies of scale; in larger projects, more construction materials can be purchased per unit investment. Concrete was responsible for a significant proportion of embodied emissions in WWTWs, with in-situ concrete accounting for approximately 50 to 70% of the total in each case.

Figure 1

Embodied emissions vs investment for civil construction projects (WWTWs and WWPSs)

Embodied carbon of sewers (rising mains)

For both PE and DI rising mains laid in fields and roads, emissions increase linearly with pipe diameter (Figure 2). The installation of DI rising mains has higher embodied carbon than the installation of PE rising mains, which is mainly due to the embodied carbon in the pipe material, i.e. ductile iron (Figure 3). Also of note is that pipes laid in roads have higher embodied emissions than those laid in fields; this is due to higher emissions from the reinstatement of roads compared to the reinstatement of grass (Figure 3). Although the analysis considered the installation of sewers using standard construction, the results can also be used as an approximation for low-dig sewers (since the pipe itself constitutes the majority of emissions). The decision whether to use the 'road' or 'field' factors will depend on the particulars of the project and the frequency and location of pits.

The results may also be used for certain types of pipeline rehabilitation. Sewer rehabilitation can be either by pipe replacement or by relining, while water mains rehabilitation can use open-cut, horizontal directional drilling, pipe bursting and slip lining techniques. The embodied carbon of pipe replacement (sewers) and open-cut techniques (water mains) is assumed to be the same as for laying new pipes (Figure 2). The embodied carbon of pipe relining (sewers) is estimated as 146 $kgCO_2/m$ (based on data from CESMM3). However, it is recommended that pipe rehabilitation is considered on a case-by-case basis and site specific emission factors calculated if required.

Figure 2

Embodied carbon emissions for PE and DI rising mains laid in fields and roads

Values were calculated according to Equations 1 and 2 and the specification and assumptions outlined in Table 1.

Figure 3

Component embodied carbon emissions for PE and DI rising mains laid in fields and roads

Values were calculated according to Equations 1 and 2 and the specification and assumptions outlined in Table 1.

Importance of embodied carbon in whole life carbon assessment of WWTWs

DECC (2011) projections are for a significant reduction in the emissions from electricity due to the decarbonisation of the UK grid; average public sector grid emissions are predicted to drop from 0.4955 kgCO_2e/kWh to 0.027 kgCO_2e/kWh from 2010 to 2049. Based on these emission factors, embodied carbon as a percentage of whole life carbon was determined as 30%, 43% and 55% for the three greenfield WWTWs with capital investment costs of £3.12M, £2.42M and £0.26M respectively. These values are ball-park estimates; embodied carbon factors are reported in terms of CO_2, while operational emissions are given in kgCO_2e, and the operational emissions values used do not account for all emissions in this category (e.g. chemicals).

Decarbonisation has to date not been as substantial as planned and there is debate over whether or not the UK electricity grid emissions will decrease as projected. To explore the effect of a business-as-usual (BAU) scenario, operational carbon was recalculated assuming a constant factor of 0.5452 kgCO_2e/kWh (which is from AIR11 and specific to NIW), giving embodied carbon as 16%, 26% and 35% of lifetime carbon for the £3.12M, £2.42M and £0.26M greenfield WWTWs respectively. Although the relative importance of embodied carbon increases as the grid becomes less carbon-intensive, operational carbon still constitutes the majority of whole life emissions in both low-carbon and BAU scenarios. The split between embodied and operational carbon correlates reasonably well with the higher estimates from previous studies (Table 3), although differences in boundary conditions mean that comparisons can be considered indicative only.

Carbon assessment for project appraisals and wider application of findings

The embodied carbon calculations were time-consuming and labour-intensive (and would be impractical for every project appraisal in NIW), but the resulting carbon curves provide a straightforward evidence-based approach for estimating embodied carbon. As the projects analysed were typical of the wastewater sector, the results are applicable to other such projects in the UK and elsewhere. Although the focus was on wastewater facilities, it is anticipated that analysis of water treatment assets would yield similar results. A limitation of the curves is that they are only for standard construction. Novel techniques and materials should be assessed on a case-by-case basis, but the carbon curves provide a benchmark for comparing innovative solutions. Carbon assessment is a science that is still under development. It is recommended that NIW's approach is updated if required in light of changes in guidelines or advances in knowledge. Ongoing research, such as the development of automated carbon estimates for construction (Yeo et al, 2016) and analysis of whole life and embodied carbon of buildings (Moncaster and Symons, 2013), may inform future work.

Conclusions

1. The water and wastewater sector already had a good understanding of operational emissions. The carbon curves developed from an evidence-based approach in this paper can be used in project appraisals to estimate embodied carbon and whole life emissions and to help inform management decisions.
2. It is recommended that the embodied carbon curves developed in this paper are used for investment appraisals of standard construction in the wastewater industry.
3. Care needs to be taken when estimating whole-life carbon emissions due to uncertainty regarding future operational emissions, especially those from grid electricity which constitute the largest share of the carbon footprint in the wastewater industry.

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Figure captions

Figure 1 Embodied emissions vs investment for civil construction projects (WWTWs and WWPSs)

Figure 2 Embodied carbon emissions for PE and DI rising mains laid in fields and roads

Figure 3 Component embodied carbon emissions for PE and DI rising mains laid in fields and roads

Tables

Table 1 NIW specification for rising mains and assumptions for associated calculations

Component	Specification and assumptions
Pipes	The pipes analysed range from 900 to 400 mm diameter for PE and from 100 to 1600 mm diameter for DI. Pipes ≤ 600 mm diameter are laid at a depth not exceeding 1.5 m. The total depth of excavation is 0.9 m + pipe diameter + bedding thickness. For pipes of larger diameter, the centre of the pipe is placed at the centre of the 1.5-2 m zone. The depth of excavation is (2+1.5)/2 + (0.5 x pipe diameter) + bedding thickness.
Bedding/surround	The specification for pipe bedding and surrounds is the same for pipes laid in roads, grass verges and fields, and is summarised as: width = pipe diameter + 300mm; thickness = 150 mm above and 150 mm below pipe; material = pea gravel.
Backfill	The trench is backfilled with excavated material for pipes laid in fields and with well compacted Type 3 granular material for pipes laid in roads. The width of backfill is pipe diameter + 300 mm. The backfill thickness is depth of excavation - (thickness of bedding and surround + pipe diameter + thickness of reinstatement).
Reinstatement	NIW follows the NIRAUC (Northern Ireland Road Authority and Utilities Committee) (undated) specification for the reinstatement of openings in roads, which encourages first-time permanent reinstatement. Where pipelines are installed in grass verges or fields, the surface of the trench is reinstated using stockpiled topsoil and grass seeding.
Manholes	For rising mains laid at a constant gradient, manholes are installed every 500 m, but, if the pipeline rises and falls (rising mains generally follow the topography), additional manholes are required at high and low points. Each rising main will therefore have a different requirement for the number of manholes. For this analysis, it was assumed that manholes are installed every 500 m. The size of the manhole depends on the pipe diameter and is outlined in the NIW specification (WRC, 2010). It is assumed that all manholes are installed at a depth not exceeding 1.5 m.
Valves	For pipelines laid at a constant gradient, a hatch box and two DI gate valves are installed at each manhole location, one on either side of the manhole. If the pipeline rises and falls, air valves are installed at high points and scour valves at low points. Each rising main will therefore have a different requirement for the number and type of valves. The valve diameter is typically the same as the pipe diameter. For this analysis, it was assumed that two gate valves are installed every 500 m. The diameter of the gate valve is assumed to be the same as that of the pipe.

Table 2 Explanation of subscripts in Eqns 1 and 2

Subscript	Description
pr	Pipe laid in road
pf	Pipe laid in fields/grass verge
b	Bedding/surround
bg	Backfill with gravel
be	Backfill with excavated material
d	Disposal of excavated material
rr	Road reinstatement
rt	Topsoil reinstatment
m	Manholes
v	Valves

Table 3 Review of studies on impact of embodied carbon on lifetime emissions of water and wastewater treatment works

Embodied carbon	Location	Details	Reference
16-55% of whole life carbon	N Ireland	Carbon emissions from construction and operation (over 40 years) of three greenfield WWTWs (320, 5387 and 14511 p.e.) investigated under two scenarios: (i) electricity grid emissions assumed to remain constant (ii) decarbonisation of electricity grid.	This paper
GHGs from construction are 11% of operational GHGs	France	140,000 p.e. urban WWTW. Operational emissions include WWTW, chemicals manufacturing, production of electricity, transport of chemicals, waste and sludge, land-filling and sludge-spreading. Electricity generation is 70% nuclear, 16% hydro. Assumes 20-year life.	Renou et al, 2008
2.5-20% life cycle emissions to air	UK	Three small-scale sewage treatment processes investigated. Life cycle emissions to air include CO_2 and other airborne pollutants from commissioning, operation and demolition. Operational emissions include electricity, vehicle fuel and process (chemicals are excluded). Assumes 15-year life.	Emmerson et al, 1995
- 2.5%		- Activated sludge plant serving about 1000 population.	
- Approx. 20%		- Biological filter (radial flow) and biological filter (vertical flow), each serving about 1000 population.	
16-21% of life cycle CO_2 emissions	UK	Three aerated biological filter treatment plants investigated (12 p.e., 60 p.e. and 200 p.e.). Operational emissions include electricity, process, sludge removal and transport, maintenance. Assumes 10-year life.	Dixon et al, 2003
4% (or less) of total environmental indicator scores	Australia	Potential environmental impacts of Sydney Water's total operations (integrated water and wastewater system) in 2021. Impacts of production of construction materials included, but energy used during construction process excluded. Operational emissions include the production of electricity and chemicals and avoided fertiliser through reuse of biosolids.	Lundie et al, 2004
10% of lifecycle carbon	USA	Carbon emissions associated with embodied energy of construction of WWTW with design capacity of ~363,400 m3/day. Analysis also considered resource consumption and recovery in wastewater systems using onsite energy generation through combined heat and power systems, nutrient recycling through biosolids land application, and water reuse for residential irrigation.	Mo & Zhang, 2012

CO_2 = carbon dioxide; GHG = greenhouse gas; p.e. = population equivalent; WWTW = wastewater treatment works.