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A Comparison of the Operational Energy Demand of Both Low Pressure and Vacuum Collection Systems

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Abstract

Climate change is regarded as the greatest threat to society in the coming years, and directly affects the water industry; with changes in temperature, rainfall intensities and sea levels resulting in increased treatment and subsequent energy costs. As one of the largest global consumers of energy, the water industry has the opportunity to significantly prevent climate change by reducing energy usage and subsequent carbon footprints. Wastewater treatment alone requires an estimated 1% - 3% of a country overall energy output while producing 1.6% of its global greenhouse gas emissions; over 75% of which can be due to the collection system. Gravity flows should therefore be incorporated where possible, reducing pumping requirements and therefore minimizing costs and subsequent carbon footprints. This study has assessed the operational energy usage of the alternative collection systems low pressure and vacuum, for use in situations in which a conventional gravity system is not practicable. This was carried out through hypothetical scenario testing using design parameters derived from literature, generating 60 hypothetical collection mains with variations in population, static head and main length. From this study, it was found that the energy demand of a low pressure system is 3.2 - 4.2 times greater than that of its equivalent vacuum system in the same scenario. Energy demand for both systems increases with population, static head and main length. However, population and therefore flow changes were found to have the greatest effect on the energy usage of both systems. Therefore, flow reduction measures should be adopted if the decarbonization of the water industry is to be achieved.

Keywords

Wastewater Collection, Carbon, Energy, Sustainable Development

1. Introduction

The World Commission on Environment and Development (WCED) defines sustainability as "development which meets the needs of the present without compromising the ability of future generations to meet their needs" [1]. Climate change is regarded as the greatest threat to society in the coming years [2], making sustainable development an urgent global priority [3]. The water industry is critical in almost every aspect of society [4], and is directly affected by climate change, with changes in temperature, rainfall intensities and sea levels resulting in increased treatment and subsequence energy costs [5]. Sustainable development is therefore vital for the water industry, as it aims to meet social needs in a changing climate, while conserving resources and protecting the environment at a sustainable price [6].

The water industry is one of the largest global consumers of energy, with wastewater treatment alone requiring an estimated 1% - 3% of a countries overall energy output [7], and 1.6% of global greenhouse gas emissions [8]. The industry is therefore in an important position, with the opportunity to significantly prevent climate change by reducing energy usage and subsequent carbon footprints [9]. A sewerage system can contribute over 75% of the carbon footprint of a sanitation system [10], therefore gravity flows should be incorporated where possible, reducing pumping requirements and therefore minimizing costs and carbon footprints [11].

The conventional gravity system has been used for thousands of years, therefore all other collection options can be considered to be "alternative" systems [12]. Numerous studies have been carried out on these systems; however the existing literature does not consider the energy demands of the various design options, nor does it evaluate the effects population or elevation changes have on these. This study has sought to help fill this knowledge gap by assessing the operational energy usage of the alternative collection systems low pressure and vacuum. This will help designers evaluate the operational and environmental costs of each option, enabling them to create the smart designs required to minimize pumping costs and subsequent carbon footprints [11].

2. Background

The provision of sufficient sanitation is an important requirement for providing a population with a good standard of living [13]. Gravity sewers are the most common form of wastewater collection system [14] and have been found to be an efficient system for areas with a high population density. This system has been used for thousands of years; therefore, all other collection system options can be considered to be "alternative" systems [12] [15]. However, gravity sewers have several limitations, and may not be the most suitable option for certain situations, including where the site topography is flat or the groundwater level is high, leading to infiltration [16].

A vacuum sewer utilizes negative air pressure generated at a centralized vacuum pump to transport wastewater through the network, which is composed of three main components; vacuum valve chambers, vacuum mains and a vacuum station [17]. This collection system was invented by Charles Liernur in 1866 and was installed in towns in Europe including Amsterdam [16], with the first commercial system created by the Lijendahl Corporation (now Electrolux) in 1959 [17]. Vacuum sewer collection systems are considered to be an "eco-innovative" wastewater collection system, preventing the seepages and odors which can occur in a conventional gravity system [18]. These systems have been found to be suitable in different situations including; areas with existing septic tanks; high water tables or nearby watercourses, flat ground topography or difficult ground conditions [19]. Vacuum sewers are limited by their ability to transport wastewater uphill, with the expected capacity to overcome a maximum head of 9.144 m - 12.192 m [20]. However, BS EN 16932; *Drain and sewer systems outside buildings—Pumping systems* recommend a maximum static head of 5 m. Vacuum collection systems are therefore not viable in locations where the site topography requires wastewater to be transported up large elevations.

Conversely, low pressure sewers have been seen to be an efficient collection system in areas where a conventional low gravity system would not be practicable [21]. A low pressure collection system uses a grinder pump to break up the solids, reducing their size and therefore helping prevent blockage in the pressure sewer. Pipes therefore do not need to maintain a negative gradient and can be constructed at a fixed smaller cover depth, following the land topography and reducing construction costs [22].

Molatore [23] stated that "every sewering option has its place". Significant research has been and is currently being carried out into these systems, with [16] finding that the initial capital costs of conventional gravity sewage systems can be 20% - 50% greater than that of alternative systems in difficult areas, including locations with high water tables, flat terrain and unstable or rocky conditions.

Furthermore, the use of onsite wastewater treatment systems (OWTS) was assessed against alternative sewage collection systems by [24], who carried out a cost analysis to determine the best option based on the area's population density. This analysis compared the use of a conventional gravity, vacuum or low pressure grinder pump systems against four OWTS alternatives; namely the use of Conventional OWTS, Landscape Irrigation OWTS, Secondary Biological Units and Advanced Biological units. The results of this analysis concluded that the low pressure grinder sewer is the cheapest collection system for areas of low population density (>0.5 acre average property size), however onsite treatment was considerably cheaper for these options. Conversely, vacuum systems were found to be the most efficient option for medium (0.25 - 0.5 acre) and high (<0.25 acre average property size average) density areas. These results are in line with findings from a cost analysis of alternative systems in small communities by [25], which found that the provision of collection systems and WWTWs for small communities was not practicable or economically viable.

The existing literature however does not consider the energy demands of the various design options, nor does it evaluate the effects population or elevation changes have on these. This study has sought to help fill this knowledge gap by assessing the operational energy usage of the alternative collection systems; low pressure and vacuum. This will help designers evaluate the operational and environmental costs of each option, enabling them to create the smart designs required to minimize pumping costs and subsequent carbon footprints [11].

3. Methodology

The purpose of this project was to assess the operational energy requirements, and subsequent carbon footprint, of the alternative low pressure and vacuum collection systems. Molatore [23] stated that "every sewering option has its place", indicating that different systems are better suited to different scenarios. Hypothetical scenario tests were therefore carried out to obtain data for the alternative systems in different situations. This testing method allowed for the creation of accurate data, while assessing several parameters simultaneously [26] [27]. The design parameters were derived from literature, generating 60 hypothetical collection mains with variations in population, static head and main length as seen in **Table 1**.

Maximum static head was taken as 5 m in accordance with BS EN 16932; *Drain and sewer systems outside buildings—Pumping systems*. Airvac Design Manual [28] states that a maximum line length cannot be defined, however recommends that 10,000 ft ≈ 3048 m be taken as an initial maximum by the designer. The maximum line length for the hypothetical scenario tests was therefore taken as 3000 m. No maximum population was found in literature for either collection system. The maximum population for the hypothetical scenario tests was taken as the largest system found in literature of 10,000 people [15].

The following parameters remained constant for each vacuum system:

- 150 liters per person per day taken in accordance with British Water Flows and Loads Code of Practice and Irish Water Code of Practice for Wastewater Infrastructure [29] [30].
- HDPE pipes were selected in accordance with [31], with industry standard SDR 17 from [32].
- Air/water ratio—taken as a 2:1 volume ratio in accordance with [28].
- Frictional head loss in each system was calculated using the modified Hazen-Williams Formula in accordance with system design manuals [28] [33].

Table 1. Hypothetical scenario design parameters.

Description	Design Parameter
Population (served by collection system)	100, 1000, 2500, 5000 and 10,000
Static head (m)	0, 2.5, 5
Main length (m)	500, 1000, 2000 and 3000

- Pipe design coefficient *C* taken as 150 in accordance with system design manuals [28] [33].
- Vacuum pumps selected from [34], with horizontal centrifugal discharge pumps being selected in accordance with [28].
- Environment One model DH071/DR071 simplex grinder pump stations were used for each low pressure scenario, stated to be the "ideal choice for single-family homes" [35], assuming one pump, and 2.7 people per household in accordance with the Irish Water Code of Practice for Wastewater Infrastructure [30].
- Vacuum collection main pipe diameter was selected based on recommended flowrates from the Airvac design manual [28]. To allow direct comparison between collection systems the low pressure pipe diameter was initially taken as the same as the corresponding vacuum system scenario. Calculations were then repeated with increased pipe diameters to allow an assessment of how the power usage was affected by the pipe size used.
- Daily energy costs were calculated from the SSE Airtricity standard unit rate figure of 19.01 pence per kWh taken from SSE Airtricity statement.
- Daily effective carbon emissions for the UK were calculated from power consumption using the UK Department for Business, Energy & Industrial Strategy (BEIS) 2019 figures of 0.2556 kgCO_2e per kWh [36]. These were compared to Ireland's daily effective carbon emissions using an all island average figure of 0.291 kgCO_2e per kWh taken from SSE Airtricity statement.

Using these parameters, derived from literature, 60 hypothetical collection mains were developed as seen in **Table 2**. A calculation spreadsheet was therefore developed to enable efficient comparisons between systems and scenarios.

Table 2. Hypothetical design scenarios.

	Pop.	Static head	Distance		Pop.	Static head	Distance
		m	m			m	m
Scenario 1	100	0	500	Scenario 31	2500	2.5	2000
Scenario 2	100	0	1000	Scenario 32	2500	2.5	3000
Scenario 3	100	0	2000	Scenario 33	2500	5	500
Scenario 4	100	0	3000	Scenario 34	2500	5	1000
Scenario 5	100	2.5	500	Scenario 35	2500	5	2000
Scenario 6	100	2.5	1000	Scenario 36	2500	5	3000
Scenario 7	100	2.5	2000	Scenario 37	5000	0	500
Scenario 8	100	2.5	3000	Scenario 38	5000	0	1000
Scenario 9	100	5	500	Scenario 39	5000	0	2000
Scenario 10	100	5	1000	Scenario 40	5000	0	3000
Scenario 11	100	5	2000	Scenario 41	5000	2.5	500
Scenario 12	100	5	3000	Scenario 42	5000	2.5	1000
Scenario 13	1000	0	500	Scenario 43	5000	2.5	2000

Continued

Scenario 14	1000	0	1000	Scenario 44	5000	2.5	3000
Scenario 15	1000	0	2000	Scenario 45	5000	5	500
Scenario 16	1000	0	3000	Scenario 46	5000	5	1000
Scenario 17	1000	2.5	500	Scenario 47	5000	5	2000
Scenario 18	1000	2.5	1000	Scenario 48	5000	5	3000
Scenario 19	1000	2.5	2000	Scenario 49	10,000	0	500
Scenario 20	1000	2.5	3000	Scenario 50	10,000	0	1000
Scenario 21	1000	5	500	Scenario 51	10,000	0	2000
Scenario 22	1000	5	1000	Scenario 52	10,000	0	3000
Scenario 23	1000	5	2000	Scenario 53	10,000	2.5	500
Scenario 24	1000	5	3000	Scenario 54	10,000	2.5	1000
Scenario 25	2500	0	500	Scenario 55	10,000	2.5	2000
Scenario 26	2500	0	1000	Scenario 56	10,000	2.5	3000
Scenario 27	2500	0	2000	Scenario 57	10,000	5	500
Scenario 28	2500	0	3000	Scenario 58	10,000	5	1000
Scenario 29	2500	2.5	500	Scenario 59	10,000	5	2000
Scenario 30	2500	2.5	1000	Scenario 60	10,000	5	3000

4. Results and Discussion

4.1. Effect of Collection Main Diameter Change

Power usage results for a low pressure collection system using two different collection main diameters, operating in the 60 hypothetical scenarios described above can be seen in Figure 1. It can be seen that the design with the smaller diameter mains required more energy in all 60 scenarios, requiring 1.01 - 4.55 times the amount of energy compared to their larger diameter alternative. This equates to an energy saving of 0.03 - 129.9 kWh per day, resulting in the prevention of up to 12,188.89 $kgCO_2e$ emissions per year. It can also be seen from Figure 1 that the energy demand difference from collection main diameter changes in each scenario increases with collection main length. This is due to the difference in frictional head loss per meter between pipe sizes.

Due to the difference in energy demand seen in Figure 1 it can be seen that a low pressure system may require a greater diameter collection main than a vacuum system operating in the same scenario. All further analysis below will therefore use results from the increased diameter low pressure systems, with reference to the original diameter results for comparison. Further work is required to find the optimum pipe sizes for low pressure systems serving different population sizes.

4.2. Effect of the Energy Industry

The water industry is one of the largest global consumers of energy, with wastewater treatment alone requiring an estimated 1% - 3% of a countries overall

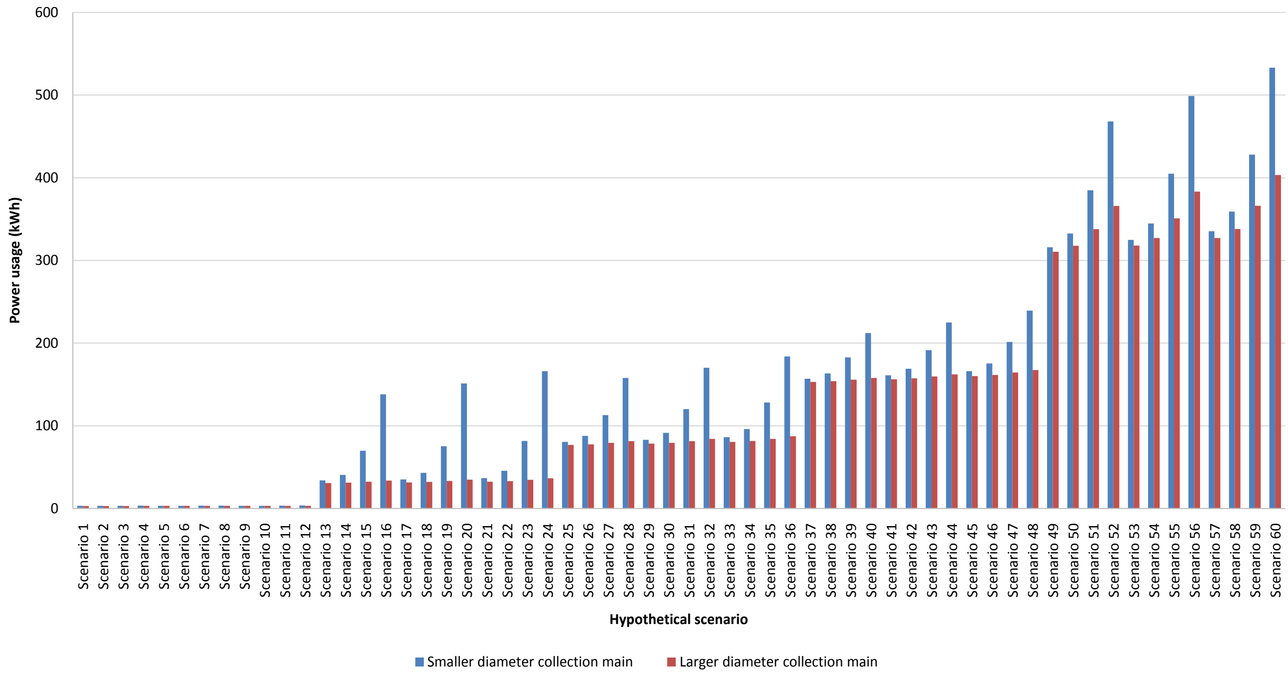

Figure 1. Effects of collection main diameter change on the daily energy demand of a low pressure collection system.

energy output [7], and 1.6% of global greenhouse gas emissions [8]. The industry is therefore in an important position, with the opportunity to significantly prevent climate change by reducing energy usage and subsequent carbon footprints [9].

A comparison of the effective carbon emissions for the hypothetical scenario testing of a low pressure system with an increased diameter collection main can be seen in **Figure 2**. Daily effective carbon emissions for the UK were calculated from power consumption using the UK Department for Business, Energy & Industrial Strategy (BEIS) 2019 figures of 0.2556 $kgCO_2e$ per kWh [36]. These were compared to Ireland's daily effective carbon emissions using an all island average figure of 0.291 $kgCO_2e$ per kWh taken from an SSE Airtricity statement. The importance of the energy industry on the emissions of a collection system is highlighted by the variation in results between energy supplies, with a difference of 0.0354 $kgCO_2e$ per kWh equating to a difference of up to 18.88 $kgCO_2e$ per day between suppliers. This confirms the statement from the Committee on Climate change [37] that it will be difficult for the water industry to achieve net-zero emissions without the decarbonization of the energy industry.

4.3. Comparison of Alternative Collection Systems

The results of the hypothetical scenario tests of the low pressure and vacuum collecting systems can be seen in **Figure 3**. There is no vacuum collection system solution for scenario 60 as it is out of the operational range of the largest available Busch Mink MM vacuum pump. This confirms that the parameters selected for the hypothetical scenario testing have covered the entire operational range

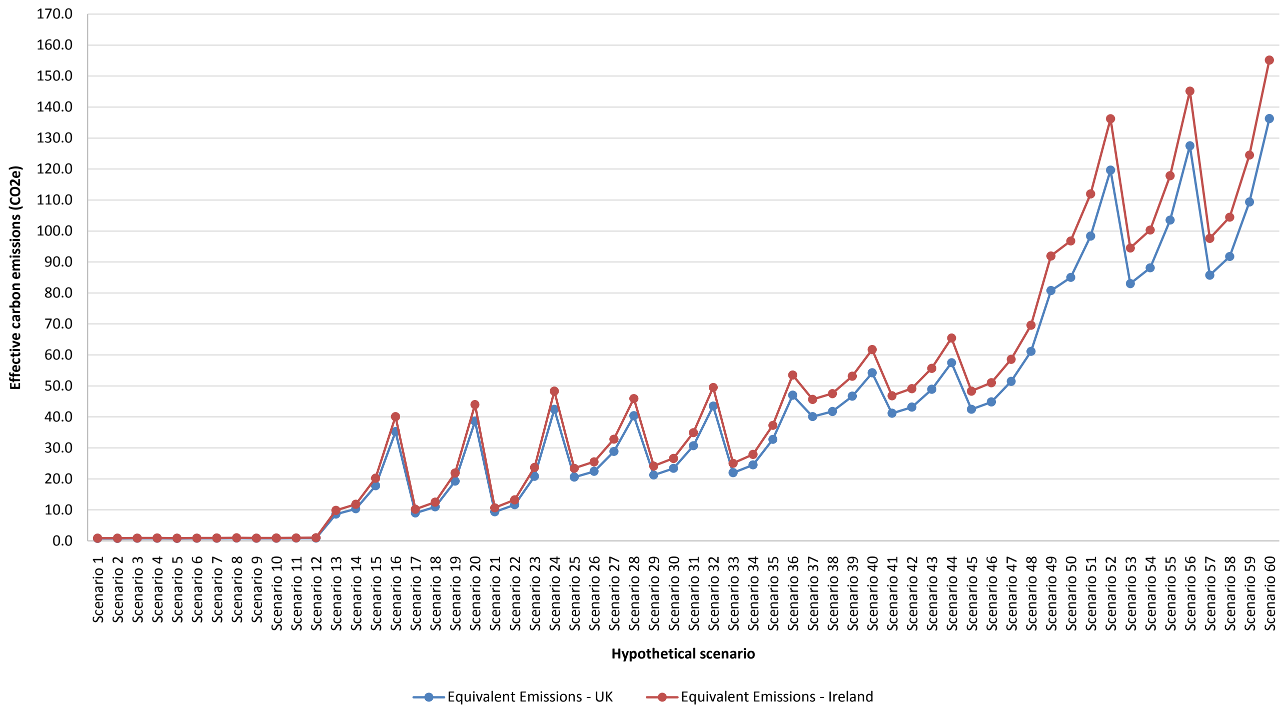

Figure 2. UK and Ireland carbon emissions comparison from the low pressure collection system.

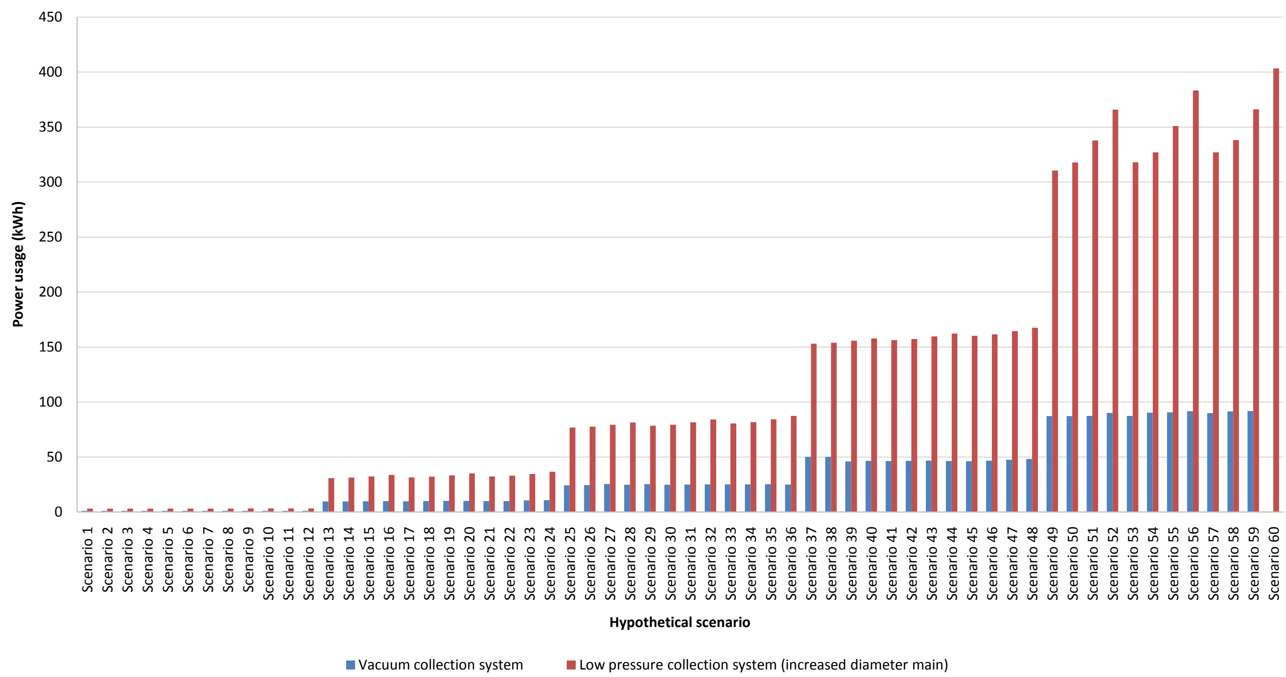

Figure 3. Hypothetical scenario test results for vacuum and low pressure collection systems using different diameter collection mains.

of the vacuum collection system, with all other scenarios seen in Figure 3 requiring a significantly lower energy demand for vacuum than low pressure collection systems.

The energy demand of a low pressure system, as seen in Figure 3, is 3.2 - 4.2

times that of its equivalent vacuum system in the same scenario, with an average ratio of energy usage for a low pressure to a vacuum collection system of 3.39:1. The major increases in energy usage can be seen to be due to increases in population, causing an increase in flow which therefore increases frictional head loss and pumping duration. Conversely, when using the same diameter main, the energy demand of a low pressure system uses 3.3 - 15.5 times that of its equivalent vacuum system using the same collection system, with an average ratio of energy usage for a low pressure to a vacuum collection system of 4.78:1.

5. Conclusions

This study has aimed to compare low pressure and vacuum sewerage systems based on both price and carbon. Hypothetical scenario tests were therefore carried out to obtain operational energy demand and subsequent costs and emissions data for the alternative systems in different situations. This testing method allowed for the creation of accurate data, while assessing several parameters simultaneously. These design parameters were derived from existing literature, with variations in static head, sewer main length and population. The results from these scenario tests have brought about the following conclusions:

1) Increases in the population served by a system, the static head of a system, or the length of the collection main in a system will all result in an increase in the energy demand and subsequent cost and equivalent carbon emissions. Increases in the population served however was found to have the greatest effect, due to the increased population causing an increase in flow, resulting in increased frictional head and pumping times. This highlights the importance of flow reduction for the decarbonization of the water industry.

2) Increasing the diameter of a collection main reduces the energy demand and subsequent cost and equivalent carbon emissions of a system.

3) Depending on the population served a low pressure system may require a greater diameter collection main than a vacuum system in the same scenario. Systems with smaller diameter mains required 1.01 - 4.55 times the amount of energy compared to their larger diameter alternative. This equates to an energy saving of 0.03 - 129.9 kWh per day, resulting in the prevention of 2.8 - 12,188.89 $kgCO_2e$ emissions per year.

4) The equivalent carbon emissions of a collection system is directly affected by the sustainability of the energy source, with a difference of 0.0354 $kgCO_2e$ per kWh between UK and Ireland energy sources equating to a difference of up to 18.88 $kgCO_2e$ per day for the scenarios tested. Therefore, the adoption of sustainable energy sources should be prioritized for the decarbonization of the water industry to be achieved.

5) The energy demand of a low pressure system is 3.3 - 15.5 times greater than that of its equivalent vacuum system in the same scenario using the same diameter collection main. Conversely, when using a larger diameter main for the low pressure system the energy demand is 3.2 - 4.2 times that of its equivalent

vacuum system in the same scenario. The use of the increased diameter pipes may therefore be necessary for low pressure systems to minimize the whole life cost of the system.

6) The average energy demand of a low pressure system is 3.4 times greater than that of a vacuum system.

6. Recommendations for Further Research

This research has highlighted knowledge gaps that require further research. These include:

1) To allow for a comparison between the two collection systems this study carried out hypothetical scenario testing based on scenarios in which both systems could operate. As discussed above, these scenarios covered the operational range of the vacuum system, with no possible solution being found for the final scenario. This study therefore has not assessed the energy demands of a low pressure system in further scenarios beyond the capabilities of the vacuum system. Further research is required to provide designers with the operational energy demands of this system for the remainder of its operational range.

2) The energy requirements of the alternative collection systems septic tank effluent gravity and septic tank effluent pressure systems have not been assessed in this study. Further research is required to provide designers with the operational energy demands of these systems.

3) Analysis of the optimum diameter collection main should be carried out to minimize pumping and subsequent whole-life costs of a low pressure system.

4) This study has provided data regarding the operational carbon emissions due to energy usage. Further research is required to assess the carbon emissions from construction, maintenance and demolition of alternative collection systems to assess the whole life footprint of the systems.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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