Life Cycle Assessment of Irish District Heating Systems: A Comparison of Waste Heat Pump, Biomass-Based and Conventional Gas Boiler

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Research Article

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Abstract

This paper presents a life cycle assessment (LCA) of heat supply scenarios for the replacement of fossil-based energy systems through a case study focusing on an existing gas-fired boiler supplying heat for buildings located in Tallaght, Ireland. The three replacement systems considered are a waste heat fed heat pump district heating system (WHP-DH), a biomass CHP plant district heating system (BCHP-DH), and an individual gas boiler system (GB). The study found that both DH systems have lower environmental impact than the GB, with the BCHP-DH being superior to WHP-DH. However, using 2030 electricity data showed almost similar overall impacts for both the DH systems. Human toxicity potential (HTP) was highest among all impact categories studied and was due to the large additional infrastructure requirement for all three systems. Whereas the other impacts; Global warming (GWP), Fossil fuel depletion (FFD) and Eutrophication (EP), were due to involving usage of natural gas and electricity in use phase. The BCHP-DH showed reduced greenhouse gas (GHG) emissions by 45% and FFD by 73% compared to the GB system. Using 2030 electricity data, the WHP-DH decreased GHG emissions by 42% and FFD by 47%. Further, replacing biomethane with the natural gas in the DH systems decreased GWP by at least 11.4%. The present study concludes that the environmental benefit of a DH system is largely dependent on the carbon intensity of the electricity it uses, thus recommending the DH systems for large scale retrofitting schemes in Ireland to reach Europe's 2030 GHG reduction targets.

Introduction

In the EU, building stock consumes 40% of energy and generates 36% of greenhouse gas (GHG) emissions (European Commission 2019a). In North West (NW) Europe, space heating is the largest domestic energy user as it provides comfort in winter months. The EU has adopted targets to reduce GHG emissions by 40% and increase the renewable energy production share by 32% by 2030 relative to 1990 levels (European Commission 2019b). Heat pumps are central to plans to decarbonise residential heating with many EU countries offering supports to incentivise uptake (David et al. 2017). NW Europe lags behind the EU average in uptake of district heating (DH) so there is little existing infrastructure (European Commission 2016). Most of the EU's housing stock was built before 1970 so predate the introduction of the first thermal regulations (European Commission 2015). These buildings have inherent technical barriers to retrofit as many were designed to use a high temperature (+60°C) wet radiator system leading to higher energy consumption, and associated emissions, tor meet the heating system demand. In cool climates, an air source heat pump's efficiency and heat capacity will decrease significantly when attempting to raise the outlet water temperature above 60°C (Wu et al. 2012). The low temperature waste heat (25–40 °C) in Ireland's free-air cooled data centres reduces temperature differences between the condenser and evaporator side of a heat pump increasing efficiency (Codema 2015). However, various factors may be considered to improve the residential buildings energy usage and environmental emissions, such as employing integrated energy systems, retrofitting energy systems to reduce energy consumption and usage of renewable energy (Bartolozzi et al. 2017).

DH is the most popular heat generation system currently employed in European countries to enhance the energy efficiency and GHG mitigation potential of heating systems (Gartland 2014). The advantages of DH are greater heating efficiency and lower production-phase emissions owing to its larger scale production compared to decentralised heating systems using fossil fuels (Gartland and Bruton 2016). DH can use different heating sources including combined heat and power (CHP) plants, distributing the co-product heat to a local heat demand. However, DH system can also depend to a greater extent on fossil fuels, resulting in higher fuel costs and more GHG emissions compared to renewable energy technologies (Puettmann and Lippke 2013). Integrating
DH with CHP has shown a wider application in domestic heating due to its contribution towards eco-efficient use of renewable energy resources such as geothermal heating system (GHS) and biomass (Nikkiewicz and Sekret 2014).

Currently, low temperature GHS has been gaining popularity due to its suitability for large scale systems, wider availability, and surging market for heat pumps. Moreover, it has a significant potential to reduce the fuel consumption, costs and GHG emissions and increase energy savings by combining DH with waste heat recovery systems (David et al. 2017). However, it should be emphasised that GHS utilises fossils fuels for operation along with electricity for driving the compressor and gas for driving the generator (Lund et al. 2014). Utilisation of biomass as an alternative fuel for CHP has been also considered as an effective GHG mitigation strategy (Eriksson et al. 2007). Biomass CHP has a lower CO₂ contribution compared to equivalent hard coal or natural gas CHP (Bartolozzi et al. 2017). In addition, biogas can also be employed as a heating source in boilers or CHP as biogas produces 33% less CO₂eq per unit of energy compared to natural gas (Whiting and Azapagic 2014).

Life cycle assessment (LCA) is an environmental accounting tool that measures a process or product environmental burden over the life cycle (Neirotti et al. 2020). Many authors have performed comparative LCA studies on DH with different energy generation systems such as non-renewable fossil fuels and renewable (biomass, geothermal etc) based CHP, and conventional and renewable energy-based boiler to identify the technologies with relatively higher sustainable viability and greater GHG mitigation potential. Puettmann and Lippke (2013) performed comparative LCA to assess the environmental impacts of a DH system in Seattle, USA, employing 56% biomass (wood) and 44% natural gas. The heating system with biomass as energy sources indicated a considerable decrease in GWP (104%) in comparison with all the natural gas boiler. This result indicates that a biomass boiler emits less carbon than sequestered by the trees, leading to negative annual GWP. Koroneos and Nanaki (2017) conducted LCA to evaluate the environmental performance of ground source heat pump installed at Town Hall of Pylaia in Greece. The study found acidification potential as dominating impact (74%), attributing mainly to the release of emissions like sulphur dioxide (SO₂) and nitrogen oxides (NOx) during the production of raw materials and operation of system. Feoliovš et al (2019) assessed the environmental impacts of different scenarios towards modernising the existing or traditional DH system (TDH) to the low temperature DH (LTDH) system located in eastern part of Latvia. The differences in the scenarios were mainly in terms of supply and return temperatures for new LTDH (60/35°C), new DH (90/60°C) with solar panel and TDH (90/60°C). The results showed an improved environmental performance for LTDH over TDH but inclusion of solar panels in the DH system provided the most favourable system. Neirotti et al (2020) estimated the impacts associated thermal energy supplied using fossil-based CHP system to Turin DH system and compared with energy supplied from natural gas fired boiler. The LCA results revealed the combustion stage was the main contributor (74%) towards the GHGs emissions in both the heating systems. However, the authors observed the 25% share of emissions were due to gas infrastructure, which has a significant influence on GHGs that could increase the impacts by 31%. The majority of studies are related to production and distribution phases involved in DH systems, with co-generation system i.e., CHP, focussing on energy consumption and evaluation of environmental performance in terms of GHG emissions. However, up to the authors knowledge, only a few studies have considered the real-time data and studied a broader assessment perspective towards accounting for the raw material extraction for equipment and infrastructure impacts of the DH systems.

The present work was based on the EU Interreg Heat Net project, which aims to address the challenges of reducing CO₂ emissions in NW Europe by creating an integrated transnational NWE approach to the supply of
renewable and low carbon heat (incl. waste heat) to residential and commercial buildings (HeatNet NWE 2019). In Ireland, South Dublin County Council (SDCC) plans to develop Dublin's first large scale DH system, harnessing the waste heat of a data centre via a heat pump (Codema 2015).

Therefore, the goal of this paper was to evaluate and compare the environmental impacts of Dublin's first large scale DH employing three different heat supply systems i.e., heat pump-based CHP (WHP-DH), biomass-based CHP (BCHP-DH) and conventional gas fired boiler (GB) system. Through this study, the authors aimed to identify the best combination of heating systems along with the stages of life cycle of heating systems that contribute significantly towards environmental impacts. As the infrastructure impacts of district heating are exacerbated in NW Europe due to a lack existing infrastructure and heat planning, this work also determines if the impact of the infrastructure necessary to match waste heat supply to demand outweighs the use of fossil fuel combustion for heating and subsequently ascertain if Heat pump WHP-DH has a potential role in decarbonising NW Europe's heating. Since EU HeatNet is a demonstration project, the learnings will be applied to other similar projects throughout NW Europe (HeatNet NWE 2019).

Materials And Methods

Life cycle assessment

This study presents an LCA of heat supply scenarios for the replacement of an existing gas-fired boiler supplying heat for three buildings located in Dublin, Ireland. The three replacement systems considered are a waste-heat fed heat pump district heating system, a biomass CHP plant district heating system, and an individual gas boiler system. The LCA was carried out in accordance with ISO14040 standards in four steps i.e., goal and scope definition, inventory analysis, impact assessment and interpretation. The LCA was performed using the 8.2.0.55 version of Gabi which is an LCA accounting tool developed by Thinkstep (Thinkstep 2018).

Scope and Functional unit

The scope of the current study was to evaluate the life cycle environmental impacts of waste heat fed heat pump district heating system (WHP-DH) and biomass CHP plant district heating system (BCHP-DH) and compare with an individual gas boiler system (GB). The system boundary was considered as ‘cradle to gate’ that includes infrastructure facility (equipment, construction work and buildings related to each system), equipment raw material extraction, fuel extraction, electricity generation, and distribution and transportation of raw materials.

As the replacement heating system in the SDCC buildings was only in the planning stage this LCA is prospective using data provided by Dublin's Energy Agency (Codema 2015) and published LCA studies. Moreover, the study area has heat densities two to three times above 150TJ/km² which is considered highly feasible for district heating systems from a Danish perspective (Euroheat and Power 2013). As stated previously, the boundary "cradle to gate" would follow the study carried out by Nitkiewicz and Sekret (2014) which states a 20-year lifecycle and excludes disposal due to probable advances within the timespan considered in the LCA. 20 years was chosen as it is the lifespan of most of the equipment, but it should be noted that the pipeline's lifespan is much longer.

Materials to make the equipment specifically for the system, such as the heat pump, were included. Avoided use of other fuels due to the energy generated within the system were also not included. A system diagram showing the processes within the cradle-to-gate the system boundary is shown in Fig. 1.
In the heat pump DH system (WHP-DH), the boundary starts at the collection of the waste heat and includes all necessary steps, along with equipment, needed to process this heat. The product is the heat produced. The BCHP-DH system includes the generation of the fuel from the forest nursery phase comprising all the infrastructure necessary to deliver the heat to the required buildings. Waste disposal and the machinery needed for generating fuel or construction in all phases were excluded.

The main function of the studied system was to produce heat for the SDCC buildings, so the functional unit is 1 MWh of heat produced. In a CHP plant, both electricity and heat are useful outputs, so electricity was allocated a proportion to the environmental impact. In the absence of Irish case study data this allocation was based on an average Irish CHP efficiency of 86% (54% Heat and 32% electricity production) (SEAI 2015).

**System description**

Data centres are computer warehouses that store data, with high energy demands and large amounts of heat generated. In 2016, total data centre energy use made up 4.8% of Ireland’s total electricity demand (Bitpower 2017). Lu et al. (2011) used real production data from Finland to calculate that waste heat could be captured from 97% of the total power consumed in the data centre creating large sources of potential heat. The use of waste heat from data centres to power a district heating system via a heat pump has been demonstrated in Mäntsälä, Finland (EHPA 2019).

In the first system (WHP-DH), waste heat from the data centre was harnessed through a collector coil with exhaust air heating water of 20–35°C. This warm water gets heated in the energy centre by an ammonia heat pump with a seasonal performance factor of 3.6, to 70°C on the primary side. Average Irish grid electricity was assumed with a carbon intensity of 428 kg CO₂/MWh (SEAI 2018). The hot water was transported 701 metres through a heat exchanger and distributed to the customer. The end user buildings had the existing gas boiler replaced by a pump, control valves and a meter situated in the heat exchanger substation. The water was pumped to the council building with the existing radiator system being maintained. The total installed pipeline was 2,142 metres long, consisting of a 5MW gas boiler to top up the temperature of the DH system in winter and act as a back-up. The gas boiler provides 20% of the heat with the heat pump providing the remainder.

The second system consisting of a 5MW Biomass CHP district heating system (BCHP-DH) was built on the Council brownfield site to meet the base load while the existing gas boilers were replaced to meet the peak demand. A feasibility study on the potential DH system in Tallaght was found to have a payback period of 15 years (Gartland 2014). The CHP produces temperatures of 75°C and has an efficiency of 86% (54% heat and 32% electricity production) (SEAI 2015). A pipeline of 137 metres connects the CHP to the Council building. The CHP plant transports hot water to a heat exchanger substation after which it is distributed to the end user. The impacts of biomass production and processing was based on the biomass supply chains in Murphy et al. (2014) and Murphy et al. (2016). Biomass consisted of wood chips sourced from the Laois, Ireland, area.

The third system consists of maintaining the existing individual gas boilers in each of the Council buildings. These boilers were installed 18 years ago so require replacement. The LCA examines the replacement of these boilers with a new efficient gas boiler while maintaining the rest of the heating system.

**Impact categories**
The impact categories examined in the current study were Global warming potential (GWP), Eutrophication potential (EP), Fossil fuel depletion (FFD) and Human toxicity potential (HTP). Environmental impact assessment was performed according to CML 2001 methodology (Valente et al. 2011). The above considered impact categories (except EP) were chosen over more policy relevant indicators like particulate matter due to the representativeness of the impact of mining in infrastructure, so better meeting the goal of the study. However, EP was included as it is important to measure the impact on flora and fauna as NW Europe has large land water bodies (Bartolozzi et al. 2017).

**Assumptions**

The efficiency of the large boiler in the district heating system was assumed to an average of 90% over the lifetime, based on the GaBi database with the smaller boilers in the SDCC buildings assumed to be 85% over their lifetime including degradation (Thinkstep 2018). It was assumed that all raw materials were produced in the EU-28 apart from cast iron. An assumption was made that the material is transported from Rotterdam port to Dublin Port to the system site. The only exception to this is the wood chips which would be sourced from Laois sawmills.

As there was limited information on waste heat being taken from a data centre, an assumption is made that the collector coil for the waste heat within the data centre exhaust is of a similar size to the heat exchanger. This assumption is based on both pieces of equipment performing the same function. The thermal store for the district heating systems was assumed to be 1.5 cm thick with insulation made up of high-density polyurethane (HDPU). Both systems were assumed to use gas boilers to provide 20% of the required heat. The transmission heat losses for the district heating systems were 3% for the Heat pump and 2% for the Biomass CHP, which was adopted from analysis carried out by Codema (2015). The decreased losses in the analysis were attributed to the superior system characteristics such as better insulation and capability to generate higher heat density.

For most of the equipment, dimensions and material type were sourced from the equipment manufacturers. Therefore, the assumed density of the materials was needed to calculate the weight of equipment. The density of steel, high density polyurethane (HDPU) and high-density polyethylene (HDPE) was assumed to be 7850 kg/m$^3$, 950 kg/m$^3$ and 100 kg/m$^3$, respectively. Ammonia refrigerant in the heat pump was assumed to have no GWP impact (ASHRAE 2017).

**Life cycle inventory**

The life cycle inventory stage requires collection of input and output data for the studied system. To analyses the different DH systems, two types of data were used. Foreground data describes the data related to the inputs (electricity, fuel usage etc.,) for the heat pumps and gas boiler, along with the material used for manufacturing these equipment's and building infrastructure. Background data refers to data that represents the generic materials, energy and transport involved in production processes and delivered to the foreground system as aggregated datasets. These datasets are generally taken from databases and literature. In this study, a 2016 average Irish grid electricity data was adopted from SEAI report (2018). All other fuel types were taken from GaBi’s professional database of Irish fuel emissions, as extraction and transport were included in these datasets. Data for the heat pump DH (WHP-DH) and gas boiler systems were both provided by the Codema (2015) report with the Biomass CHP district heating system (BCHP-DH) taken from Gartland (2014), Murphy et al (2014) and Murphy et al (2016). These data sources were used to define the three system's equipment needs (Table 1) with fuel needed to produce one MWh of heat calculated from efficiency data. The piping systems employed in the study were adopted from Logstar catalogue (2018) and Codema (2015). Further, inventory related to pipes in terms of
construction materials and dimensions considered in the model are shown in Table 2. When the system processes were defined, the background data for these heating systems were taken from Ecoinvent 3.7, GaBi professional database (Thinkstep 2018) and other published LCA studies (Table 1).

The data and sources for the WHP-DH are outlined in Table 1. The seasonal performance factor for the heat pump is assumed to be 3.6 with average 2016 Irish electricity used to power it. Heat losses in transmission are assumed to be 3% of total heat. The refrigerant used in the heat pump was ammonia.

The woodchips for the BCHP-DH system are harvested according to Scenario 3 proposed by Murphy et al. (2014). The energy of the woodchips at moisture content 35% is 11GJ/t which is adapted from Murphy et al. (2016). The wood at the sawmill has a moisture content of 20% and has an energy content of 12.65 GJ/t. Losses in wood during chipping is assumed to be 5%

The wood is assumed to come from a large, forested area in Laois which is 80 km away from the CHP plant site. The data for the biomass boiler was taken from the gas boiler information for the district heating system as both were assumed to have heating capacity of 5 MW (Table 1). The building area which houses the biomass boiler was 100 m² and the pipeline to the end users was 137 m with a heat exchanger substation. Allocation of burden to heat in the CHP was done according to the average Irish CHP efficiency, with heating allocated 62.8% of the burden and electricity burden excluded from this study.

For the gas boiler system (GB), the only infrastructure change was the gas boiler, with the quantity and size provided from Dublin’s Energy Agency (Codema). Efficiency of the boiler was assumed to be 85% with a connection to gas already established.

**Results**

The results section shows the studied systems contribution to each impact category, categorised into three groups: use phase, infrastructure and other. The use phase relates to emissions and energy used in the heat generation stage. Infrastructure includes all equipment, construction work and buildings related to each system. The other category includes the transport impact across all materials in the system and the production of woodchips in the biomass CHP DH system.

**Global warming potential (GWP)**

The LCA results showed that the individual gas boiler (GB) system has a significant GWP (268kg CO₂eq/MWh), which is 34% and 44% higher than WHP-DH and BCHP respectively (Fig. 2a). The higher emissions from the GB system were mainly due to the higher usage of gas as fuel (i.e. around 95%) in comparison to electricity which accounts for around 4.5% (Table 3).

Figure 2a shows that across all the heating systems, the use phase contributed considerably to the GWP, owing to the fuel usage which accounts for at least 84.7% of the GWP in each system. The overall impact of the use phase along with percentage contribution of certain energy sources within the full system results are shown in Table 3. The heat pump DH system needed electricity derived from gas to maintain the efficiency of the heat pump. However, it was electricity that contributed 56% of the GWP as electricity provides 80% of the heating output. In
the BCHP-DH system biomass makes up 80% of the heat generation, but it was the natural gas which made the largest contribution.

In total, natural gas was responsible for largest proportion of the GWP in GB and BCHP-DH systems, whereas electricity was dominating in the HP-DH system. However, data on electricity production can change significantly depending on location and time which can lead to uncertainty in comparison. And importantly the difference in the results in GWP for non-fossil fuel system is due to the related infrastructure, as the biomass considers CO₂ sequestration from atmosphere resulting in lower GWP values in comparison to fossil-based heating systems.
| Equipment          | Material       | WHP-DH     | BCHP-DH   | GB                          | Source                                         | Geo-coverage | Time coverage |
|--------------------|----------------|------------|-----------|-----------------------------|------------------------------------------------|-------------|--------------|
| Pipes              | Steel (kg)     | 30152.8    | 1654.9    | Original pipework maintained | Logstar catalogue, 2018 & Codema, 2015          | Europe       | Current      |
|                    | HDPU (kg)      | 11251.1    | 450.7     |                             |                                                 |             |              |
|                    | HDPE (kg)      | 17213.3    | 586.3     |                             |                                                 |             |              |
| Thermal store      | Steel (kg)     | 12952.5    | 12952.5   | n/a                         | Codema, 2015                                   | Ireland      | 2018         |
|                    | HDPU (kg)      | 973.75     | 973.7     | n/a                         |                                                 |             |              |
| Heat pump          | Steel (kg)     | 3762.5     | n/a       | n/a                         | Nitkiewicz & Sekret, 2014                       | Poland       | 2014         |
|                    | Ammonia (kg)   | 134.7      | n/a       | n/a                         |                                                 |             |              |
|                    | Water (kg)     | 175        | n/a       | n/a                         |                                                 |             |              |
|                    | Stainless Steel (kg) | 105  | n/a       | n/a                         |                                                 |             |              |
|                    | Cast Iron (kg) | 17.5       | n/a       | n/a                         |                                                 |             |              |
|                    | SPF            | 3.6        |           |                              |                                                 |             |              |
| Trenching          | Cement (kg)    | 94464      | 5260.8    | n/a                         | Oliver-Solà et al., 2009                        | Spain        | 2009         |
|                    | Concrete (kg)  | 141696     | 7891.2    | n/a                         |                                                 |             |              |
|                    | Aggregates (kg)| 888060     | 49457     | n/a                         |                                                 |             |              |
|                    | Diesel (MJ)    | 84870      | 4726.5    | n/a                         |                                                 |             |              |
| Large scale gas boiler | Steel (kg)   | 19285.7    | Assumption made that boiler would be the same | n/a | European Commission, 2014 | Europe | 2014 |
|                    | Paint work (kg)| 7.1        | n/a       |                              |                                                 |             |              |
|                    | Brick lining (kg) | 935.7 | n/a       |                              |                                                 |             |              |
| Domestic gas boiler | Quantity      | n/a        | 4x250kw; 2x120kw; 2x635kw | GaBi professional database | Europe | 2016 |
| Heat exchanger     | Steel (kg)     | 12376.9    | 12376.9   | n/a                         | Adolfsson & Rashid, 2016                        | Sweden       | 2016         |
| Equipment                                    | Material               | WHP-DH | BCHP-DH | GB  | Source                                | Geo-coverage | Time coverage |
|----------------------------------------------|------------------------|--------|---------|-----|---------------------------------------|--------------|---------------|
| Heat Collection Coil                        | Steel (kg)             | 12376.9| n/a     | n/a | Assumed same as Heat exchanger        | Sweden       | 2016          |
| Building                                    | Aluminium (kg)         | 750    | 300     | n/a | Ecoinvent v3.7 & Codema, 2015         | Europe       | 2007          |
| Building                                    | Brick (kg)             | 26750  | 10700   | n/a |                                       |              |               |
| Building                                    | Concrete (kg)          | 168000 | 67200   | n/a |                                       |              |               |
| Building                                    | Diesel (MJ)            | 59500  | 23800   | n/a |                                       |              |               |
| Building                                    | Electricity (kwh)      | 2625   | 1050    | n/a |                                       |              |               |
| Building                                    | Cement mortar (kg)     | 5250   | 2100    | n/a |                                       |              |               |
| Building                                    | Fibre Cement (kg)      | 8250   | 3300    | n/a |                                       |              |               |
| Building                                    | Glass (kg)             | 1125   | 450     | n/a |                                       |              |               |
| Building                                    | Polystyrene (kg)       | 8350   | 3340    | n/a |                                       |              |               |
| Building                                    | Steel (kg)             | 9150   | 3660    | n/a |                                       |              |               |
| Building                                    | Rock wool (kg)         | 3300   | 1320    | n/a |                                       |              |               |
| Building                                    | Other accessories       | n/a    | n/a     | n/a |                                       |              |               |
| Building                                    | Concrete pad (kg)      | 34560  | n/a     | n/a | Ecoinvent v3.7 & Codema, 2015         | Europe       | 2007          |
| Building                                    | Cast Iron (kg)         | 807    | n/a     | n/a |                                       |              |               |

Waste heat fed heat pump district heating system (WHP-DH); Biomass CHP plant district heating system (BCHP-DH); Gas boiler system (GB); High-density polyurethane (HDPU); High-density polyethylene (HDPE); Seasonal performance factor (SPF)
Table 2
Inventory for piping system used in the LCA model

| Pipe dimension & material | WHP-DH | BCHP-DH |
|--------------------------|--------|---------|
| Diameter (m)             | 40     | 65      |
|                          | 125    | 200     |
|                          | 250    | 125     |
| Length (m)               | 186    | 78      |
|                          | 374    | 1066    |
|                          | 483    | 137     |
| Steel (kg)               | 544.9  | 408.7   |
|                          | 4517.9 | 8718.1  |
|                          | 15963.1| 1654.9  |
| HDPU (kg)                | 226.9  | 123.2   |
|                          | 1230.4 | 6033.5  |
|                          | 3636.9 | 450.7   |
| HDPE (kg)                | 228.7  | 149.9   |
|                          | 1600.7 | 8959.6  |
|                          | 6274.1 | 586.3   |

Waste heat fed heat pump district heating system (WHP–DH); Biomass CHP plant district heating system (BCHP–DH); Gas boiler system (GB); High-density polyurethane (HDPU); High-density polyethylene (HDPE).

**Fossil fuel depletion (FFD)**

The individual gas boiler (GB) system uses twice as much fossil fuel than either of the DH systems (Fig. 2b). The heat pump DH system (WHP-DH) uses close to twice the fossil fuel than the biomass CHP DH system (BCHP-DH). The lower fossil fuel consumption of BCHP-DH can be attributed to the usage of gas and replacing electricity with biomass for heat generation. Whereas the other two systems (HP-DH and GB) rely on both electricity and gas for heat generation.

Figure 2b shows the main contributor to FFD is again the use phase which makes up at least 69.7% of the total contribution in each system. Table 3 shows that gas makes up higher proportion of FFD than its contribution to heat output as expected. However, it also highlights the contribution of electricity to FFD with it being the largest contributor in the heat pump DH system. In the biomass CHP system, there is also a large contribution from the production of the wood chips which is included in the other category (20.8% of total system FFD).

**Human toxicity potential (HTP)**

The individual gas boiler (GB) system (3.68kg DCBeq/MWh) has the lowest associated HTP which is five times less than the BCHP-DH (17.2kg DCBeq/MWh) system and eight times less than the WHP- DH system (26.4kg DCBeq/MWh). The results for HTP show the largest contribution came from infrastructure (Fig. 2c). This is
highlighted by the low HTP of the gas boiler (GB) as much of the infrastructure for this system is already in place in comparison to the other systems.

The results were further categorised into pipeline infrastructure and other infrastructure. Pipeline relates to all materials needed and the trenching works to build the pipeline to connect to the end user. While the other infrastructure relates to any other equipment needed such as the heat pump or the energy building. The WHP-DH and BCHP-DH systems have similar HTP values in terms of infrastructure other than the pipeline. For the pipeline however, the values of the two systems diverges significantly with the heat pump pipeline having close to four times the attached HTP for its pipeline. This is due to the total length of the heat pump pipeline being 2,187 metres compared to the BCHP-DH pipeline of 137 metres.

**Eutrophication potential (EP)**

The WHP-DH (0.0317kg PO$_4^{3-}$eq/MWh) has the largest eutrophication potential with the BCHP-DH (0.022kg PO$_4^{3-}$eq/MWh) having the least with the individual GB system having an EP of (0.023kg PO$_4^{3-}$eq/MWh). However, these results show the smallest difference between systems of any of the impact categories (Fig. 2d). EP also has a more even contribution from the different phases in each system apart from the GB system where the use phase accounts for over 99% of total EP.

**Sensitivity analysis**

To identify the most relevant source of uncertainty in the study, sensitivity analysis was performed. It estimates the consequences of changes in uncertainty factors on the global warming potential (GWP) of the heating system (Eriksson et al. 2017). The uncertainty factors considered in the current study are transport distance, time range of electricity, replacement of renewable energy source with fossil-based fuels and changes in geographic location of system.

**Transport**

As this LCA study is prospective, an assumption of where the material was transported from was needed for the infrastructure with Rotterdam port being used. The sensitivity analysis explored the effect of transport distance on the GWP. Materials such as concrete, sand and cement can be made in Ireland, so the transport distances may even decrease. The data for woodchips was specific to Ireland so no changes were made. For the increased distance scenario all materials excluding woodchips were modelled to come from Stuttgart, Germany which is one of the most industrialised areas of the EU. In the decreased distance scenario, cement, sand and concrete was modelled from Westmeath, Ireland. Details of the transport distances are in Table 4.
Table 4
Scenarios for materials transport by truck and ship with varied distances

| Scenario/Material → | Concrete and Cement (km) | Other materials (km) | Woodchips (km) |
|---------------------|--------------------------|----------------------|----------------|
| Transport           | Ship                     | Truck                | Ship           | Truck | Truck |
| Increased distance  | 1307                     | 629.5                | 1307           | 629.5 | 80    |
| System model        | 1307                     | 16.5                 | 1307           | 16.5  | 80    |
| Decreased distance  | 63.2                     | —                    | 1307           | 16.5  | 80    |

Figure 3a indicates that changing the transport distance by well over 10% has a low relative impact on the overall GWP results. With the heat pump system decreasing by 1kg of CO$_2$eq/MWh and increasing by 3kg of CO$_2$eq/MWh when the respective changes are made. This confirms transport distances are not the main driver of overall impact if sourced from within Europe.

**Electricity**

As stated earlier (Sect. 3.1.1) electricity used in the use phase has a large impact on both the individual GB system and WHP-DH environmental impact. However, as there can be large differences in the electricity data depending on the geographical coverage it is important to study the impact using different data may have. As the lifetime of the study is twenty years, then taking projective electricity data at the halfway point of the project, 2030, may create a more accurate result. Irish EPA (2019) predicts that there will be a 27% drop in CO$_2$eq if additional measures are implemented.

Adopting the 2030 electricity data reduced the GWP in each system with the difference being most pronounced in the WHP-DH system, as shown in Fig. 3b. If the 2030 electricity data was adopted into the model, then the difference in the GWP between the heat pump system and the BCHP-DH plant is much smaller. However, it is important to note that using predictive data introduces more uncertainty into the results but could increase accuracy.

**Biogas**

The use of gas is a large hotspot in the use phase, but natural gas could be displaced by biomethane. The data for the biogas production was taken from GaBi professional database. The data was adjusted to consider the 43kg CO$_2$eq/MWh due to the upgrade from biogas to biomethane, injection and delivery in the gas grid (DBFZ 2016). Data has a geographical coverage of Germany due to data availability. Figure 3c clearly shows that the adoption of biomethane over natural gas would lower GWP by 11.4% in the WHP-DH system, 14.2% in the BCHP-DH system and 38.2% in the individual gas boiler (GB) system.

**Pipe length change**

Human toxicity impacts in previous studies have been due to infrastructure, so to reduce the quantity of material in the pipeline, analysis was carried out on relocating the energy centre from the data centre to the proposed BCHP-DH. This would lead to the heated water of 20 to 35°C degrees leaving the data centre and being transported 700 metres to the new energy centre. The lower temperature water would not require the steel pipes
used to carry the 70°C water. These steel pipes could instead be replaced by high density polyethene pipes which would be lighter and easier to install. However, using polyethylene pipes instead of steel pipes at 20 to 35°C could result in a significant increase in biofilm growth and Legionella sps. (Van Der Kooij 2005). The relocation would see 700 metres of the 200mm steel pipe replaced by 720 metres of polyethene pipe. As shown in Fig. 4, there would be a small decrease in FFD and HTP if the energy centre was relocated however it is not significant enough to carry out due possible impact on future expansion of the system. Figure 2c and Fig. 4 indicates that it is the total length of the pipeline and sequential trenching work that had the biggest impact on the human toxicity. This suggests minimising infrastructure health impacts by better matching of heating demand and waste heat supply is needed.

Discussion

2016 or 2030 electricity data?

Table 3 and Fig. 3b show the impact that electricity consumption has in each system. The set of electricity data used makes a large difference in the impact of the heat pump system. Most LCAs are static in terms of time with a steady state assumed over the lifecycle. However, Ma and Kim (2015) argue that a more accurate study of future systems would involve predictive modelling.

In this study, electricity production during 2016 and 2030 has been evaluated to predict the future consequences using the developed models. If the 2016 electricity data is used, then the BCHP-DH is most beneficial. Electricity generation is due to change dramatically across Europe over the next decade so the use of 2030 prediction would be more accurate in predicting lifecycle impacts. This data assumes that peat and coal have been replaced which have high HTP and EP impacts (Atilgan and Azapagic 2016). Therefore, adopting 2030 electricity data into the model not only had a significant impact in decreasing the GWP of the WHP-DH system (Fig. 3a), but also a resulted in a significant decrease across all indicators. While BCHP-DH may still have lowest environmental impact, its GWP would be only 5% less than the heat pump DH system when using the predicted 2030 electricity grid mix.

The BCHP-DH system model has greater uncertainty than the WHP-DH system due to positioning of the plant being assumed and the exclusion of the pelleting stage by allocation, the most energy intensive step of wood processing. This uncertainty makes it difficult to give a definite assessment on which system would have the least environmental impact and would depend on the specifications of the systems.

In Ireland, marginal electricity generation is usually generated by carbon intensive coal or gas power plants. 82% of renewable electricity in Ireland (SEAI 2018) is from wind power which despite output peaking in the evening, produces a large output throughout the night when demand for electricity drops. When demand drops the total contribution of renewable electricity to the total electricity consumption greatly increases as it displaces carbon intense marginal electricity generation. Heat pumps with thermal storage can take advantage of this lower carbon intensity attribute as it could be run mostly at night to offset the load with this heat, which can then be stored and used throughout the day (Carbon Counter 2019). Further research is needed on the environmental benefits of additional thermal storage in load levelling.
Is gas the right peak energy source?

Both district heating systems require the use of a peak energy source due to feasibility or to work as a back-up source during plant downtime. In both the systems the natural gas boiler functions as this peak energy source. However, Fig. 3c shows this is the least environmentally friendly option.

In Sect. 3.1.1 the individual GB system, system has the largest GWP per MWh. Table 3 shows that gas contributes 53.30% of the GWP related to the use phase in the BCHP-DH system and 28.7% in the WHP-DH system. An alternative that would require little adaptation would be the integration of biogas to supply some or all the of gas demand. However, a biogas boiler cannot compete on price with a natural gas boiler in Ireland, so a full replacement in the individual GB system is not feasible (REE 2016). With the odour concerns of anaerobic digesters, it is unlikely that a large-scale plant would get planning permission in such a built-up area.

An alternative is to buy credits for biomethane injected into the national grid, which would require no change to current systems. This supports the creation of biogas, but the price is usually higher due to processing costs. In the case of both the district heating systems the use of biomethane in place of natural gas would decrease CO$_2$eq/MWh of heat by 11.4% in the heat pump system and 14.2% in the biomass CHP DH system. These savings are significant enough that they should be considered if biomethane prices are at feasible levels by the time of project commencement.

BCHP-DH will decrease the carbon intensity of the electricity used in the heat pump, so deployment of both district heating systems together would create a mutually beneficial relationship. Whiting and Azapagic (2014) concluded that biogas produces at least twice the CO$_2$eq per unit than a woodchip CHP.

Comparison to other studies

Prospective LCA studies are used in a choice making LCA at the start of a planning stage between different systems, they are less detailed (Tillman 2000) but they are a useful tool for comparison. Nitkiewicz and Sekret (2014) performed a prospective LCA with a 20-year lifecycle and found that the heat pump had a lower overall environmental impact, however, its impact on human health was higher than a gas boiler. Further, Pehnt (2005) concluded that renewable and waste heat systems have much lower GWP and FFD rates than conventional gas boilers, but they are not significantly different in other environmental indicators. Similar results were found in this study where the heat pump did have a lower environmental impact, especially if 2030 electricity data was adopted, but showed higher impact in terms of HTP in comparison to the gas boiler. This is mainly due to the electricity grid mix and infrastructure having a large impact on renewable systems emissions especially on HTP (Pehnt 2005).

Electricity grid mix and infrastructure play a major role in influencing the environmental impacts of the heating systems. For instance, in contrast to the current study results, Greening and Azapagic (2012) found that a domestic heat pump was less environmentally beneficial than a gas boiler, noting that most of the environmental impact was due to the operation of pump. The higher impacts were attributed to the electricity grid mix, which derives a major part of energy from coal and natural gas. Further, Shah et al. (2008) carried out LCA of residential heating systems in four different regions in the US. In Minnesota, Pennsylvania, and Texas the heat pump had the highest impacts whereas in Oregon the heat pump had the lowest impacts. The lower impacts were attributed to the Oregon electricity mix containing much less coal and more renewables than the other three regions.
Koroneos and Nanaki (2017) studied absorption heat pumps in Greece finding that the largest environmental impacts were GWP and acidification. The authors ascertained that the impacts were linked to the extraction of the raw materials for the pump and the use of electricity which uses a large amount of coal power. However, an assessment into industrial waste heat use in Sweden found that a district heating system had a marginal environmental benefit at average heat source mix but with the use of waste heat the system had a clear environment benefit compared to the system in place (Ekvall and Ljungkvist 2014).

Valente et al. (2011) presented an LCA comparing using natural gas or biomass to power an Italian alpine district heating system. The biomass system integrates the use of wood residues such as sawdust and is shown to have a large environmental benefit with a smaller but still significant economic benefit over natural gas. Puettmann and Lippke (2013) performed comparative LCA to investigate the environmental impacts of a DH system in Seattle, USA, employing 56% biomass (wood) and 44% natural gas. The system with renewable fuel (biomass) showed a significant reduction in GWP (104%) in comparison with all the natural gas boiler. This result indicates that a biomass boiler emits less carbon than sequestered by the trees, leading to negative annual GWP. The authors also argued that the major contribution to GWP comes from feedstock combustion, but transportation contributes to less than 10%. On the other hand, Murphy et al. (2016) concludes that in the Irish biomass supply chain that transport is the most energy intensive stage and has the largest contribution to global warming potential.

Rinne and Syri (2013), using a consequential LCA, found if the electricity mix in the area mostly comes from condensing coal power, then CHP is a more environmentally friendly system than a large-scale heat pump as it displaces coal powered electricity generation. A consequential LCA by Eriksson et al. (2007) determined both biomass and natural gas systems CHP plants have an environmental advantage over district heating alone especially if the electricity it is replacing has a high carbon contribution. The results of the current study were in line with the above discussed works as the results show that employing waste heat utilisation (CHP) and renewable energy-based heating systems in a combined strategy could facilitate in an environmentally friendly DH system provided fossil-based energy sources are replaced with renewables in the background processes (electricity grid mix) (Bartolozzi et al. 2017). Therefore, to achieve sustainable energy systems, local DH systems development must comprise improved integration with renewable energy systems, application of blended-fuel technology and more flexible energy systems (Eriksson et al. 2007). Pehnt’s (2005) conclusions were reiterated in this study as the gas boiler is much higher in GWP and FFD than the biomass CHP or heat pump systems while EP and HTP are either similar or higher than the individual gas boiler system.

Policy

The EU has agreed a 40% reduction of GHG emissions on 2005 levels by 2030 (European Commission 2014). Figure 2a shows the clear impact that either WHP-DH or BCHP-DH could have in reducing GHG emissions in urban areas. The BCHP-DH system produces 45% less CO₂eq/MWh than the individual GB system which would equate to an avoided GHG release of 3,696 tonnes of CO₂eq over the lifetime of the heating system. The WHP-DH system produces 35% less CO₂ emissions however using 2030 electricity mix results in 42% less CO₂ emissions. One third of houses in Ireland are powered by gas with the majority in urban areas which can support large scale district heating systems. The replacement gas boilers with district heating could contribute to the 2030 GHG targets in large scale building retrofit schemes.
The EU Renewable Energy Directive committed Ireland to produce 16% of all energy consumed from renewable sources by 2020 (SEAI 2019). The 2010 National renewable energy action plan targeted 12% of heating to come from renewable sources by 2020. However, by 2020 only 6.3% of heating and cooling came from renewable sources with very little growth from the 2010 figure of 4.3% (SEAI 2020). As this target will likely be missed, planning for the 2030 target of a 27% renewable energy penetration is vital. The systems studied are possibly only the first phase of a district heating which could likely lead to much of localities heat demand being met.

Energy security is a large concern throughout the EU with the European Commission (2014b) highlighting supply vulnerability to geopolitical events and how the expansion of renewable energy may decrease this vulnerability. By 2025, if no new gas discoveries are made, Ireland will be importing 90% of its gas needs, with the decline in domestic production beginning by the early 2020's (SEAI 2015). Ireland has had clear problem with import dependency since 1990 relative to the rest of the EU (SEAI 2017). This import dependency is due to a lack of natural resources and a reliant on using fossil fuels to deal with energy needs. Renewable energy makes up 1.6% of imported fuel by energy, but it produces 11% of Ireland total primary energy requirements (SEAI 2020). A move from a fossil fuel system to renewable power systems, could be a potential solution to decreasing energy dependency and could provide potential economic benefit.

Figure 2b shows that both the BCHP-DH and the WHP-DH system will decrease the amount of fossil fuels used in heating compared to the individual gas boiler system. The WHP-DH system would decrease fossil fuel depletion by 18,024 MWh of gas over the lifetime of the project. If we were to consider 2030 electricity data, the saved fossil fuel would be much higher. The BCHP-DH system would reduce fossil fuel use by 28,114 MWh of gas compared to a gas boiler. The installation of district heating to replace the existing gas boilers in South Dublin County Council (SDCC) buildings would reduce dependency on fuel imports. To encourage the development of DH a national policy framework and a review on how to incentive uptake is required (Gartland and Bruton 2016).

Conclusions

The LCA results indicate that the district heating systems have a lower environmental impact in terms of fossil fuel depletion and global warming potential than individual gas boilers. Whereas BCHP-DH system showed lower environmental impact than the WHP-DH system across all the impact categories considered. However, if estimates for the electricity carbon intensity are adopted for the mid-way point of the project (2030), GWP of the WHP-DH is within 5% of the BCHP-DH. Further, BCHP-DH and CHP-DH has the potential to reduce GHG compared to the individual gas boiler system by 3,696 and 3,449 tonnes of CO₂eq, respectively. However, both district heating systems are highest in terms of human toxicity potential because of the effect of large amounts of infrastructure being built. Infrastructure impact was linked to the length of pipeline so could be minimised with improved co-ordinating of heat demand with waste heat supply. The main hotspots for the heating systems in terms of EU, FFD and GWP are due to the use phase of the lifecycle involving prominent usage of natural gas and electricity for heat generation. Moreover, the use of biomethane as a peak energy source instead of natural gas was likely to reduce GHG emissions by at least 11.4% in both district heating systems.

So, a conclusive decision on which system has the lowest environmental impact if 2030 electricity data is used will depend on the specification of the system. This study concludes that district heating, either through biomass CHP or heat pump, provides the lowest overall environmental impact for heating South Dublin County Council buildings and gives flexibility for future expansion. District heating should be considered when planning heating
systems for large scale retrofit schemes. Both district heating systems can help contribute the renewable heat and
could be replicated across NW Europe. BCHP-DH system could reduce fossil fuel use by 73% with the WHP-DH
reducing it by at least 47% compared to the existing gas boiler system however the impact of increased biomass
imports must be studied. To expand district heating in NW Europe countries should develop a district heating
policy framework and review how to incentive uptake. Future study of policy-oriented indicator like particulate
matter and the interaction of biomass combustion in an urban environment may be useful.

Declarations

Declaration of Competing Interest

The authors declare that they have no competing financial interests for this work.

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Figures
Figure 1

LCA model system boundary
Figure 2

Environmental impact contributions of the life cycle phases of the three heating systems towards (a) Global warming potential (GWP), (b) Fossil fuel depletion (FFD), (c) Human toxicity potential (HTP) and (d) Eutrophication potential (EP)
Figure 3

Sensitivity results showing the effect of (a) distance, (b) electricity data and (c) biogas replacement on GWP across all the three heating systems studied
Figure 4

Sensitivity analysis demonstrating the effect of change in geographical location of WHP-DH on different environmental impacts.

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