Understanding the importance of Whole Life Carbon in the selection of heat-generation equipment

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ABSTRACT

Addressing climate change has traditionally focused on reducing carbon emissions from operational energy consumption. However, as electricity generation increasingly decarbonises, embodied carbon represents a higher proportion of Whole Life Carbon (WLC).
This study investigates WLC of four types of heat-generation equipment: gas boiler, gas fired combined heat and power (CHP), air source heat pump (ASHP), and variable refrigerant flow systems (VRF). For ASHP and VRF, carbon emissions from refrigerant leakage make up a large proportion of WLC because of the global warming potential of refrigerants currently most commonly used. In some situations, refrigerant leakage has a higher impact than operational carbon emissions, and the WLC impact of ASHP can become similar to gas boilers. However, when refrigerants with a global warming potential of 150 are used, ASHP emits approximately 80% less WLC than gas boilers and 85% less WLC than CHP. For boilers and CHP, operational efficiency has the highest impact on WLC, followed by extraction and processing of raw materials. The study shows that it is important to consider WLC when designing building services, and not just operational carbon emissions. Recommendations from the study include: widespread and consistent performance reporting to gain more reliable data; and further studies into refrigerant leakage in ASHP and VRF. The results show that, generally, the largest contributor to WLC is operational energy consumption, hence passive design and efficiency measures that reduce heat demand are encouraged.

KEYWORDS embodied carbon, whole life carbon, heat-generation equipment, refrigerant emissions

1. INTRODUCTION

Carbon emissions associated with buildings must urgently be radically reduced to meet our climate change targets.

Buildings account for a large proportion of carbon emissions (1) with 47% of all UK carbon emissions linked to the construction and operation of the built environment (2).To achieve global warming of no more than 1.5°C, building emissions must be reduced by 80–90% by 2050 (3). The World Green Building Council and others state that all new buildings need to be net zero carbon by 2030[a].

Building services must be optimised for buildings operating in 5-25 year's time

Building services equipment is often selected with the aim to reduce operational carbon emissions. As professionals in the building services industry we need to understand how future technological changes may affect our decision making. This is particularly important as buildings are completed and occupied roughly 5 years after they are designed, and building services will typically last for 20 years.

Future optimisation is not currently considered in policy or design thinking - this needs to change

In the last 10 years the UK electricity grid has rapidly decarbonised, from 0.49 $kgCO_2e$/kWh in 2008 to 0.28 $kgCO_2e$//kWh in 2018 (4). This has changed the relative carbon emissions of heat-generation equipment. However for Building Regulations calculations a carbon factor of 0.519 $kgCO_2e$/kWh is still used, meaning that systems are not necessarily selected based on lowest carbon emission in use. The carbon emission reductions in the UK grid were predicted 10 years ago, but this information was not embedded into policy or design thinking. To ensure our decision making is future-proofed we need to look at the wider context and consider how assumptions used in calculations may be changing in the future. Considering Whole Life Carbon (WLC) is one way of understanding this.

Embodied carbon is increasingly important

The uptake of passive design techniques and the decarbonisation of the UK electricity grid means that operational carbon emissions are getting smaller. This means that the proportion of embodied carbon within Whole Life Carbon is increasing.

Over the last few years embodied carbon (defined in Table 1) has started to be considered in the structure and architectural elements of buildings, but building services, accounting for an average of 11% of embodied carbon, are often left undiscussed. See Section 3.2.3 in the main body of the report and Appendix G for more details.

1.1 STUDY FOCUS

Providing a breakdown in WLC of key building services systems will help to understand where to focus efforts in reducing WLC. This study investigates WLC of

a. World Green Building council defines net zero as "*A highly energy-efficient building with all remaining operational energy use from renewable energy, preferably on-site but also off-site production, to achieve net zero carbon emissions annually in operation.*" (5)

four types of heat-generation equipment: boilers, Combined Heat and Power (CHP) Air Source Heat Pumps (ASHP), and Variable Refrigerant Flow (VRF.)

Embodied carbon or WLC are not currently being taken into account when selecting heat-generation equipment. Mechanical engineers typically take into account, plant space and capacity; capital and maintenance costs; running costs; and operational carbon emissions. This study aims to answer the following questions:

- Does considering WLC rather than operational carbon change decisions on which type of heat-generation equipment to select?
- What impacts WLC and what should be considered in the design of heat-generation equipment?
- Rather than a detailed WLC assessment, can a simpler proxy metric be used to consider WLC to make informed decisions in heating system design?

This study provides a starting point for investigation into WLC of building services.

1.2 DEFINITIONS

Table 1 outlines definitions relevant to this paper.

Table 1: Definitions relevant to this paper

Operational Carbon	***kgCO2e***	The carbon dioxide and equivalent global warming potential (GWP) of other gases associated with the in-use operation of the building, this usually includes, carbon emissions associated with heating, hot water, cooling, ventilation and lighting systems as well as energy used in cooking, by equipment and lifts. As this study is focusing on heat-generation equipment, operational carbon refers to the carbon emissions associated with generating heating and hot water.
Embodied Energy	***MJ***	The total primary energy consumed from direct and indirect processes associated with a product or service. This is considered within the boundaries of cradle-to-gate (6).
Embodied Carbon	***kgCO2e***	In this report the term Embodied Carbon is defined as including the product stage (the extraction and processing of materials, the energy and water consumption used by the factory or in constructing the product or building), the in-use stage (the maintenance, replacement and emissions associated with refrigerant leakage) and the 'end-of-life' stage (demolition, disassembly and disposal of any parts of product or building) and any transportation relating to the above.
Whole Life Carbon (WLC)	***kgCO2e***	This includes embodied carbon, as defined above, and carbon emissions associated with operational energy. The purpose of using WLC is to move towards a building or a product that generates lowest carbon emissions over its whole life (sometimes referred as 'cradle-to-grave').

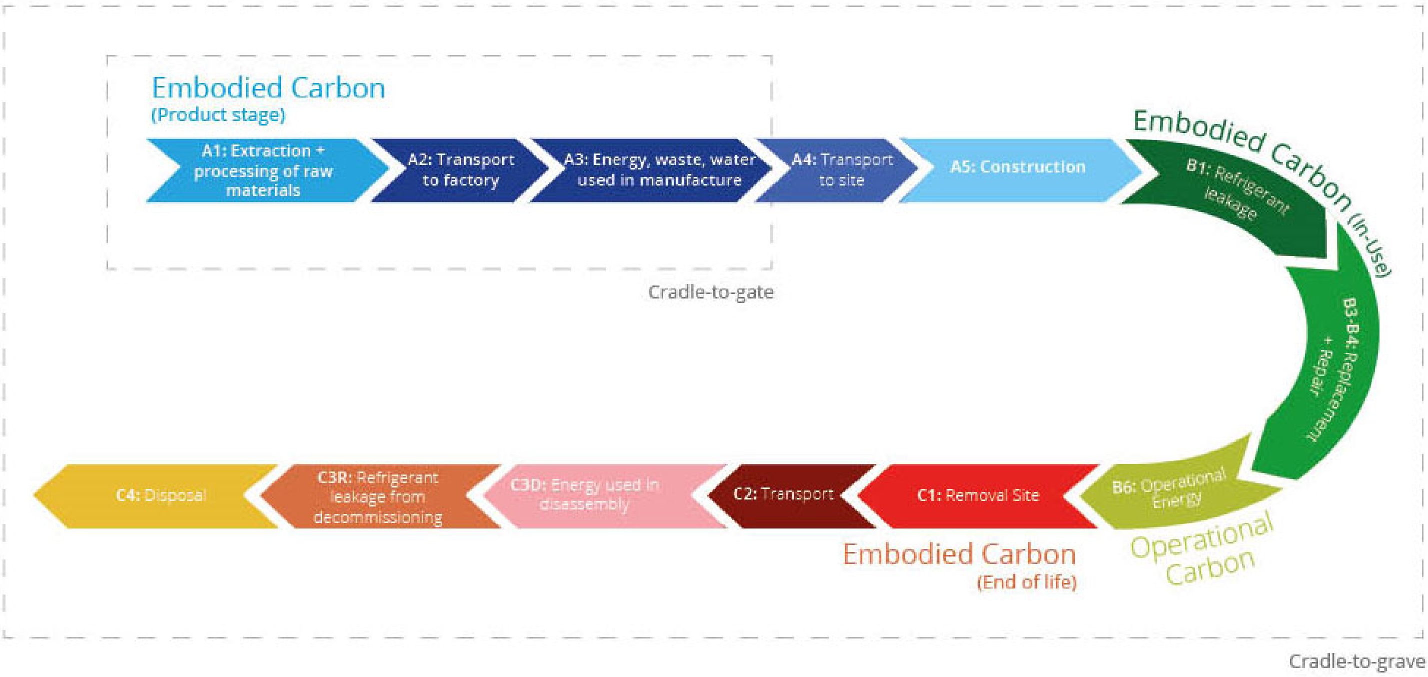
There are many different and often competing ways of studying embodied energy (7), whereas there are established methodologies to assess WLC, therefore this study assesses carbon rather that energy.

It is important to note that when the terms emissions or carbon emissions are used in this report, it encompasses all greenhouse gases, and thus the unit used is kg CO_2e (carbon dioxide equivalent).

1.3 WHAT IS INCLUDED IN A WHOLE LIFE CARBON CACLULATION

The calculation of WLC includes the following stages, as consistent with EN15978.

Figure 1: Whole Life Carbon calculation process diagram



1.4 WHOLE LIFE CARBON OF BUILDING SERVICES EQUIPMENT

Building services refers to the equipment and systems used to moderate the internal environment in buildings, providing heating, hot water, cooling, ventilation, lighting and power.

1.4.1 Embodied carbon

The embodied carbon of building services is a function of how effectively the building moderates its environment passively. The size of a heating system is based on providing the warmest required internal environment at the coldest external temperature; this depends on the thermal performance of the building envelope. The larger the capacity (kW) of the heating system the larger the required heat-generation equipment, distribution and heat emitters. Therefore, reducing the capacity of the heating system, will reduce the embodied carbon associated with the system.

1.4.2 Operational carbon

Operational carbon is related to the energy required by the building services systems to supply heating and cooling. For heating systems, this depends on the amount of time the building is heated to a certain temperature, as well as how effectively the building moderates this environment passively and the external temperature over the course of the year. Operational carbon can be reduced if the building has an efficient fabric, and has a system with a high operational efficiency. The focus in the industry to date has been operational carbon, as historically this has made up a significantly larger proportion of WLC. See Section 8.5 in Appendix B for further details on the relationship between embodied and operational carbon. Table 2 describes the heat generation equipment evaluated in this study.

Table 2: Description of heat generation equipment

Boiler	For the purpose of this paper, the term boiler refers to a device that burns natural gas to heat water. Immersion boilers are also available that use electricity. Renewable fuels are available such as woodchip and biogas.
CHP	The term CHP refers to a combined heat and power unit that utilises a gas fired reciprocating engine. CHP generates hot water and electricity. The electricity generated is included in the calculations. It is important to note that CHP rarely operates on its own, as it is often only used for base load, and includes boilers for peak load. However, for clarity, the WLC of the equipment is shown independently.
ASHP	Heat pumps use the properties of the refrigeration cycle to move heat. For the purpose of this paper, the term heat pumps refers to ‘Air to Water’ Air Source Heat Pumps (ASHP). ASHP use the heat from the external environment to generate hot water.
VRF	A variable refrigerant flow system (VRF) splits the refrigeration cycle into two parts. The evaporator is located in an ‘outdoor unit’, whereas the condenser is located in an ‘indoor unit’ located in the room that requires heat. Refrigerant is piped around the building connecting the two units. For the purposes of this study the VRF unit only includes the ‘outdoor unit’ and the refrigerant in the whole system (distribution and emitters are not included in the study).

1.5 LIFE CYCLE ASSESMENT METHODOLOGIES

Life cycle assessment (LCA) refers to a multi-step procedure for calculating the lifetime environmental impact of a product or a service. ISO 14040/44 (8) is the overarching global standard for LCA. EN 15978 (9) provides calculation rules for the assessment of the environmental performance on a building scale; EN 15804 (10) provides information and standards at a product level. The RICS WLC assessment for the built environment provides practical guidance for the interpretation and implementation of the methodology in EN 15978(9) in carbon calculations (11). For more information on LCA methodology see Appendix D.

Out of the six companies providing LCA tools contacted, only *OneClickLCA* and *GabiDatabase* included building services in the scope of tools. This is largely due to the fact that there is so little data available and only one rating system, BREEAM UK 2018-MAT 1 (12), currently requires building services to be included in the LCA scope. For more information see Appendix D.

Figure 2: Rating systems that include embodied carbon of building services

1.6 REFRIGERANT EMISSIONS

Heat pumps utilise the refrigeration cycle (vapour compression cycle) to extract heat. Integral to this process is a refrigerant, a suitable fluid which evaporates and condenses at suitable temperature. Refrigerant leakage occurs during manufacture of equipment, and there is annual in-use leakage and leakage through decommissioning. The Global Warming Potential (GWP)[b] of refrigerants currently used in heat pumps varies widely. The commonly used R410a has a GWP of 2088. Under EU legislation, the GWP of refrigerants over 150 will be banned in new heat pump equipment from 2022. Refer to Appendix E for more information regarding refrigerant emissions.

1.7 CARBON EMISSIONS IN THE EXTRACTION AND PROCESSING OF RAW MATERIALS (A1)

WLC associated with raw material extraction and processing depends on the quantity and type of material used. Insulation and metals like aluminium and stainless steel typically have a high embodied carbon content. Materials typically found in heat-generation equipment are shown in Table 3. It is important to acknowledge that these figures are approximate - the embodied carbon depends on the type of energy used in production, the efficiency of the facility and the proportion of recycled content.

[b].GWP is a measure of how much energy the emissions of 1 ton of a gas will absorb over a given period of time, relative to the emissions of 1 ton of carbon dioxide (CO_2).

Table 3: Carbon emissions assumptions for the extraction and processing of raw materials(A1)

Material	kg $CO_{2\,e}$/kg	
Aluminium (cast)	9.22	Worldwide average – recycled content 33%
Stainless steel	6.15	Worldwide average data from institute of stainless steel forum (ISSF) life cycle inventory data.
Electronics	2.71	Assumed to be the same as copper
Cast iron	2.03	Value assumed the same as *General Iron* as data was not available for cast iron
Copper	2.71	EU production data. 37% recycled content (3 year world average)
Brass	2.64	Used general values, ICE noted that poor data availability for Brass
Zinc	3.09	30% recycle content
PU foam insulation	4.26	
Rockwool insulation	1.2	
Galvanised steel	1.54	EU 3 year average of 59% recycled content
Glass	0.91	Primary glass manufacture only
Paper	1.29	Paper for construction grade use
Wood	0.31(fos)+0.42 (bio)	Includes bioenergy, excludes carbon storage
Other	1.54	Remaining material that was not assigned, has been assumed to have the same embodied carbon as steel.

Source: Inventory of Carbon and Energy (ICE) database (6)

1.8 CIRCULAR ECONOMY

To avoid resource depletion and carbon emissions associated with extraction and processing of raw materials, a circular approach to building services is needed (Figure 3). Many of the materials in heat-generation equipment, e.g. copper, have intrinsic value, and are thus recycled. Recycling rates are 95% for heat pumps and 84% for VRF (13). Recycling can be part of the circular journey, as long as products are not downcycled. Because it takes significant resources to recycle materials, retaining or re-using components should be prioritised.

Figure 3: Circular economy principles relevant to the construction inductry and building services

2 METHODOLOGY

Environmental performance assessments or LCA aim to assess the full environmental impact of a product or service. This study only includes the carbon emissions impact category which is quantified as carbon dioxide equivalent. As the system boundary of the assessment includes all stages (A1-C4) this represents WLC in this study, see Figure 1. Other categories such as Eutrophication, Acidification, Ozone depletion etc are not included. Although these other categories are important, this study focuses on carbon, as reducing carbon has been highlighted as the biggest growing issue concerning climate change. The scope and goal of the study is outlined below as per PAS2080 (14) and BS EN 15978:2011 (9).

2.1 THE GOAL OF THE CARBON EMISSIONS QUANTIFICATION

The goal of this study is to calculate and understand the carbon emission equivalent, (referred to as Global Warming Potential in LCA) of heat generation equipment in order to help in the decision process of choosing building service equipment with lowest WLC. This refers to a micro-level decision support context, as specified in ILCD Handbook (27).

2.2 THE SYSTEM THAT IS THE SUBJECT OF A QUANTIFICATION

This study considers the WLC of four types of heat-generation equipment: boiler, CHP, ASHP and VRF. This study is relevant for **multi-residential, schools, hotels and office developments**, as these types of development have a similar kWh heating and hot water demand per kW of installed capacity.

2.3 THE FUNCTIONAL UNIT

The functional unit is $kgCO_2e$ per 100kW of heating capacity of each heat generation equipment type.

2.4 BOUNDARIES OF THE STUDY

The study includes all elements of the building life cycle A1-C4, (See Figure 1) as defined by BS EN 15978:2011 (9), excluding the following;

- B7- Operational water use, as water is not used to generate heat or maintain the equipment.
- B2- Maintenance, as it is assumed that the maintenance is carried out by in-house facilities management.

The carbon emissions associated with recycling, cleaning and re-modification of the materials at end of life is not included in the assessment, as it is assumed that these emissions are associated with the subsequent product. This is defined as stage D in BS EN 15978:2011(9). See Appendix A for details of inclusions, exclusions and justifications.

2.5 THE QUANTIFICATION METHODOLOGY

The WLC calculation methodology is based on the RICS guidance (11) as this is seen as industry standard. The methodology deviates from the RICS methodology for the end of life stages (C1-C4) as heat-generation equipment is not disassembled on site but goes to a separate location for disassembly, as suggested by Simon Sturgis, lead author of the RICS methodology.

2.6 DATA COLLECTION (ALLOCATION PROCEDURES)

To understand WLC for the equipment different WLC scenarios (low, medium and high) were established for each type of heat generating equipment. See Appendix A for assumptions used and Appendix B for data sources used.

Very little data is available on embodied carbon or WLC of heat generation equipment in published data sources. Therefore, WLC calculation models are based on primary data collected for 27 heat-generation units for this study (Table 4). When carrying out these calculations, assumptions on carbon emissions in the extraction and processing of raw materials (A1) were taken from the ICE database (2011).[c] Assumptions for transport, disposal and disassembly were used from the RICS guidance.

Low, medium and high scenarios were established using the WLC calculations based on the primary data. Manufacturer refrigerant leakage rates were amended using published information, (see Appendix E). The scenarios were sense checked against published data for similar products, using the Oekobaudat database (15) and Environmental Product Declarations (EPD's) of similar products. This study used data from sources like CIBSE TM56- Resource Efficiency (16) and EUP product report (17). Refer to Appendix A for calculations.

2.7 RAW DATA COLLECTED

Sixty manufacturers were contacted, 15 were able to produce the minimum data required for this study and this provided data for 27 heat-generation units, (see Table 4).

Table 4: Number of primary data points used in study

	Manufacturers providing data	Number of heat generation equipment
Boiler	6	9
CHP	4	6
ASHP	5	8
VRF	3	4

It is important to note that the use of ICE assumptions is not strictly compliant with EN15804, as the figures are supplied in terms of kg CO_2e. (GWP characterisation are already applied).

2.8 SERVICE LIFE

A typical reference period used in WLC assessments for buildings is 60 years (11). As this study concerns equipment, the service life of the product has been used. The service life of heat generation equipment varies, see Appendix B, Section 8.2. In reality equipment is often in-use for longer than its service life. For ease of comparison a standard service life of 20 years has been applied to all heat-generation equipment. Sensitivity analysis has been carried out on this assumption in Appendix F.

2.9 COMPENSATION METHODOLOGY

Data quality submitted by manufacturers varied. For most data points up to 99% material by weight was disclosed. Where this was not the case it was assumed that the remaining material had the same embodied carbon as steel.

2.10 ASSUMPTIONS

Key assumptions used in this study are outlined in Table 5. Appendix A includes detailed assumptions.

Table 5: Key assumptions in study

Carbon factor	A 20 year projected average carbon factor of 0.12 $kgCO_{2e}$/kWh was used (18)
Energy used in manufacture	188 kWh of energy is used in manufacture, independent of equipment type (average data from 4 manufacturers). To convert the energy consumption into carbon, a UK grid carbon factor has been used of 0.3072 kgCO2/kWh
Water used in manufacture	0.35 m^3 of water is used in manufacture, independent of equipment type (average data from 4 manufacturers)
% Components	60% of material by weight is assumed to be manufactured into a component before being transported to the fabrication factory. This increases A2-A4 emissions by 60%
Material waste	1% of materials by product weight is wasted in manufacture
Annual demand	Various annual heating and hot water demand were used, see Section 8.5 in Appendix B

2.11 CONSTRAINTS AND LIMITATIONS

Little data is available on the environmental performance of heat generation equipment; not many EPD's are available and many product databases do not contain information on building services equipment. The study relied largely on primary data collected from 15 manufactures.

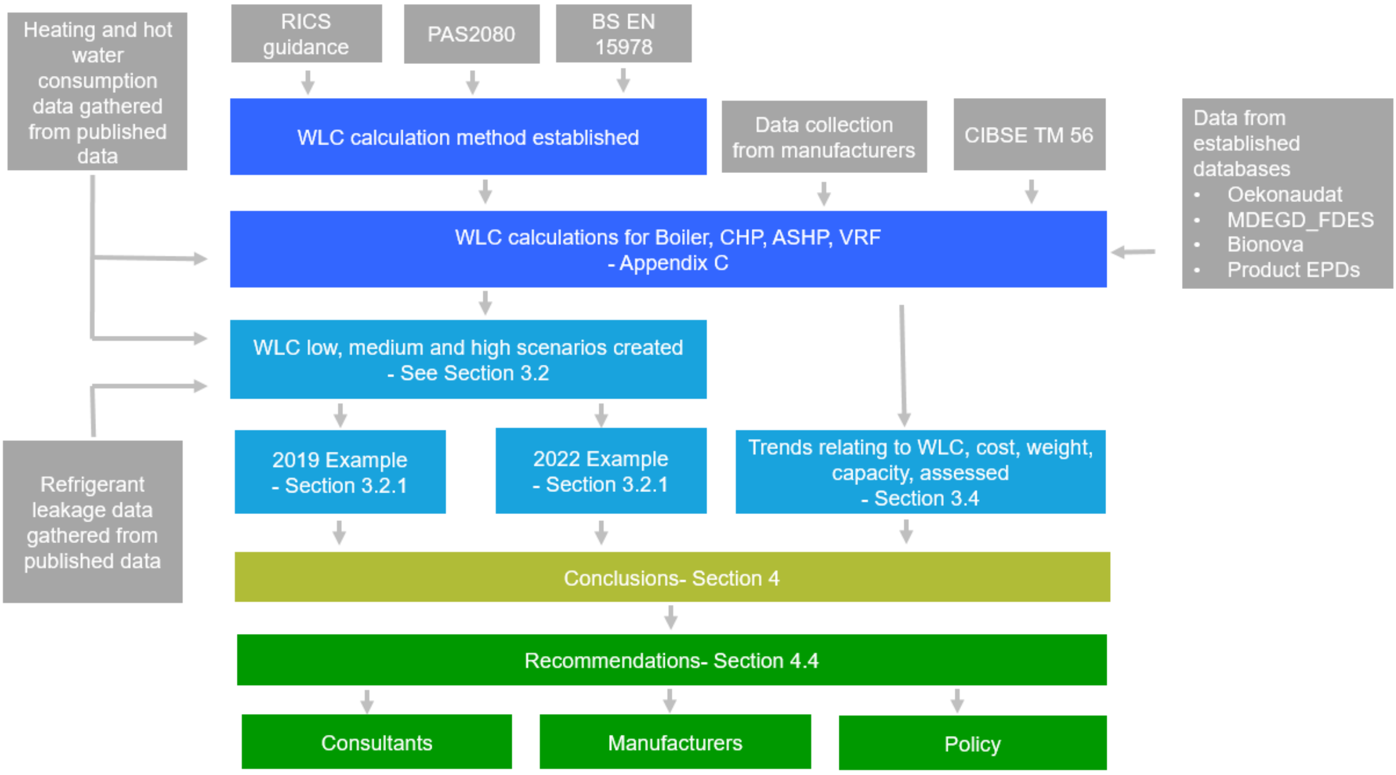
2.12 THE STUDY REVIEW PROCESS

The study has been reviewed by a broad range of consultants, see Section 0 Acknowledgements, and CIBSE symposium reviewers, as well as internally by Elementa Consulting. This is deemed appropriate and proportionate to the intended use of the assessment.

2.13 METHODOLOGY DIAGRAM

The methodology is summarised in the diagram below.

Figure 4: Methodology diagram



3 ANALYSIS AND RESULTS

For each of the four heat-generation equipment types, a low, medium and high WLC scenario was established. The information on how the scenarios were established is in Section 2.6, and the assumptions used in Appendix A. The scenarios varied in the following factors:

- Operational efficiency
- % reused materials
- Weight and embodied carbon of materials
- Transport type and distance
- Refrigerant leakage and global warming potential

Refrigerant leakage assumptions are shown in Table 6.

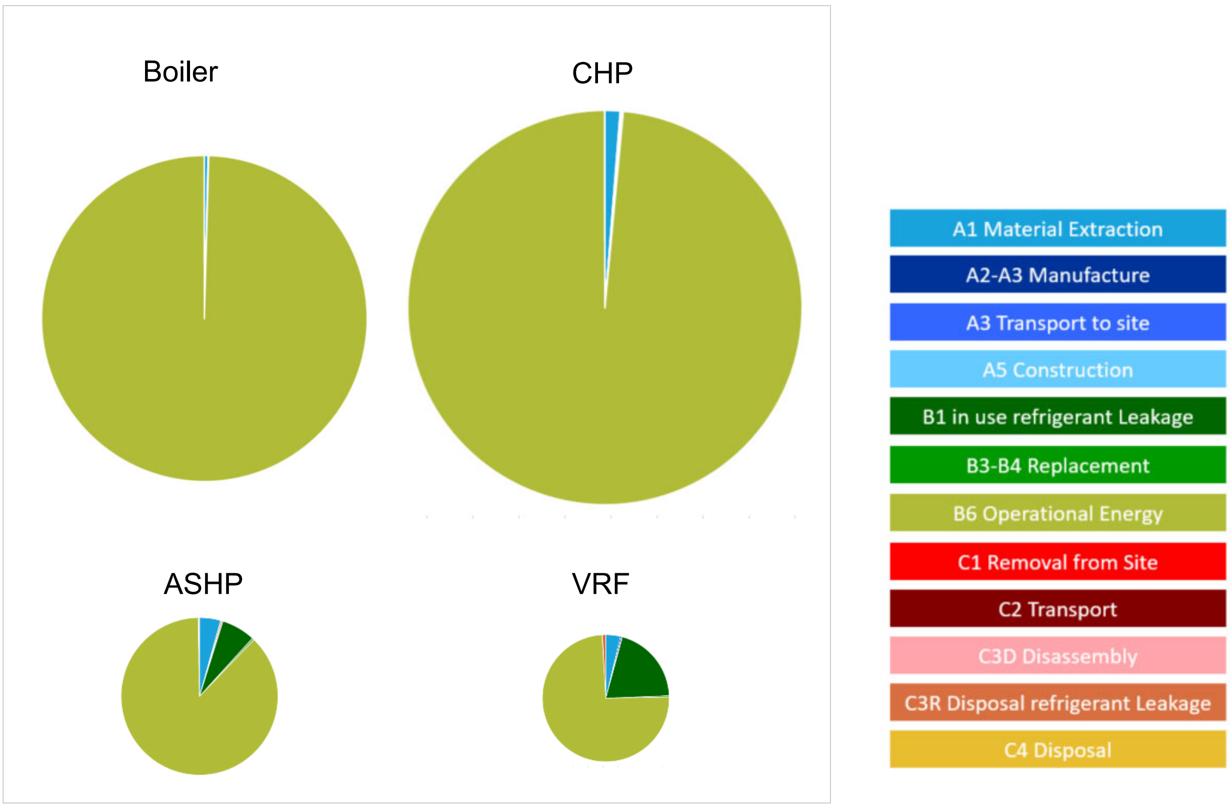
Table 6: Assumptions on refrigerants; installation in 2019

	Heat pumps			VRF		
	Low	Med	High	Low	Med	High
GWP	1	150	2088	1	150	2088
Annual leakage/ End of life recovery	1%/ 99%	3.8%/ 98%	6%/ 90%	1%/ 99%	6%/ 90%	10%/ 85%

3.1 PROPORTION OF WLC

The series of graphs below show the proportions of the WLC stages for the different heat-generation equipment studied for the medium scenario, for new buildings. The size of the pie chart represents the absolute value of WLC.

Figure 5: Proportion of WLC



3.2 COMPARING WLC OF HEAT GENERATION EQUIPMENT

The graphs below show the absolute WLC values for low, medium and high WLC scenarios for each heat-generation type. For details of assumptions see Appendix A. In addition to the 3 scenarios, the results were tested using a variety of heating and hot water demands, this is because the energy demand of a building has a large effect on the WLC breakdown, (Table 6).

Table 7: Heating and hot water demand used in analysis

	Heating and hot water demand kWh
Existing building	114,152
New building	57,076
Passivhaus type building	20,755

3.2.1 Installing in 2019

See Table 6 for refrigerant leakage assumptions used in this section of the analysis.

Figure 6: Installing in 2019- Existing buildings

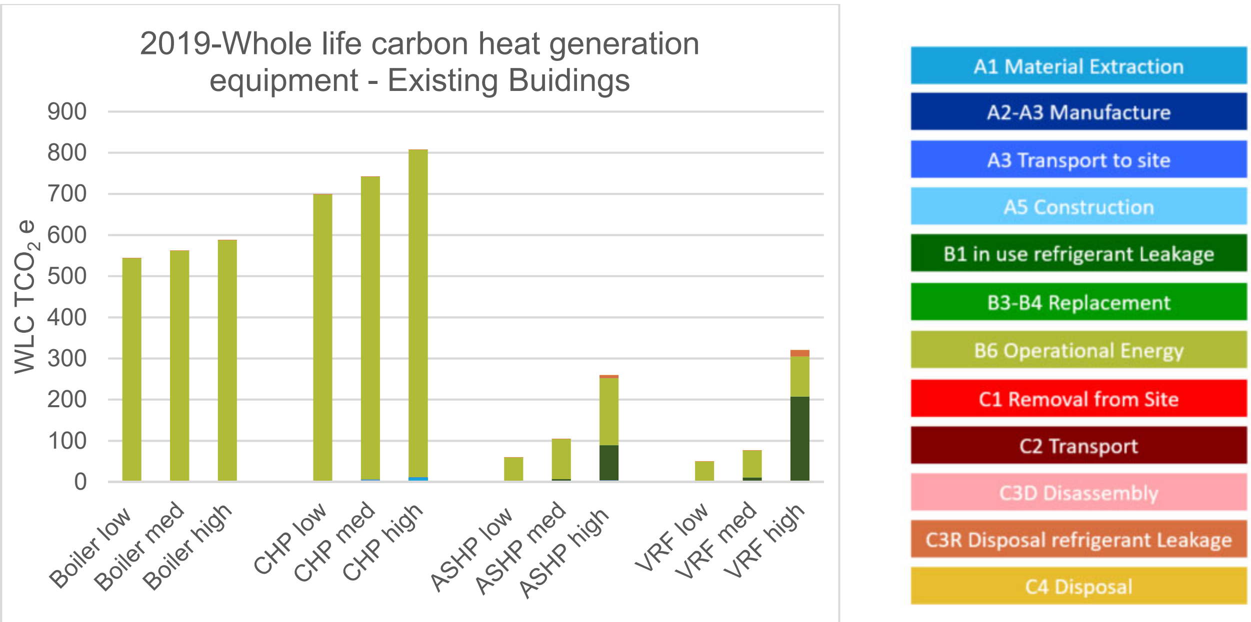


Figure 7: Installing in 2019-New builds

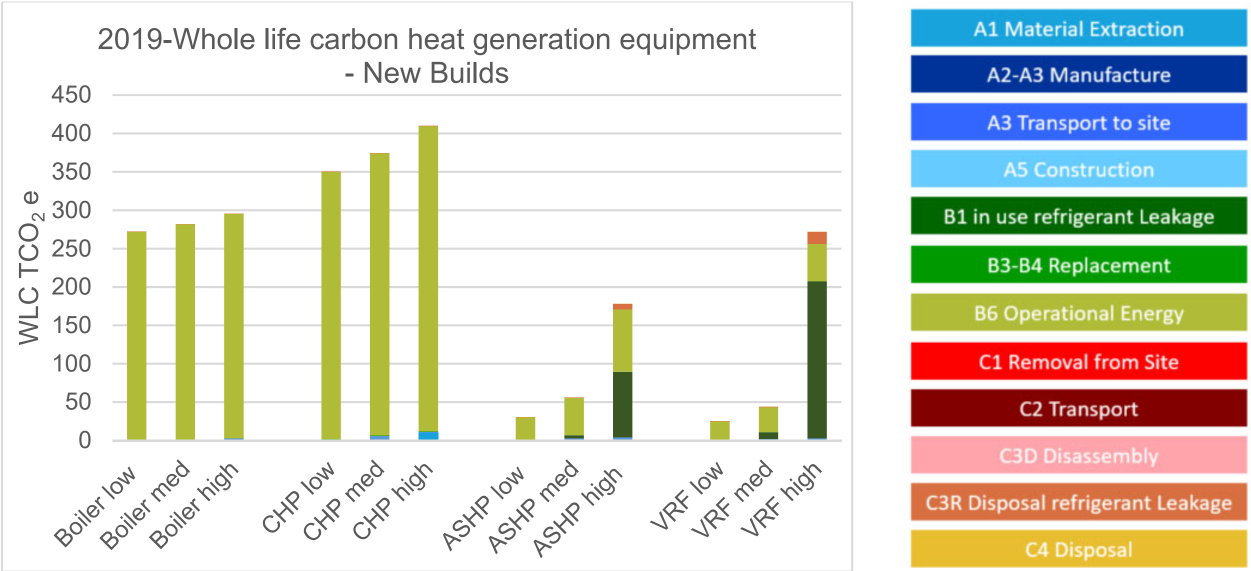
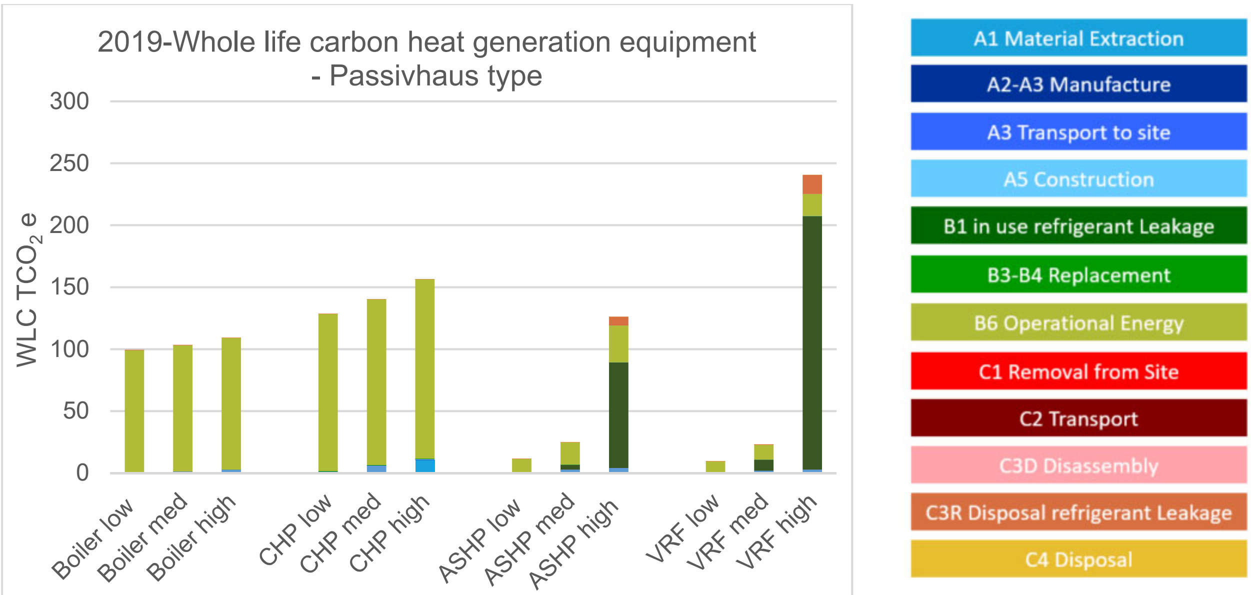


Figure 8 : Installing in 2019- Passivhaus type building



With gas CHP and gas boilers, operational energy is by far the largest contributor to WLC, with gas CHP emitting the most carbon due to operational energy in all scenarios.

ASHP and VRF

ASHP and VRF have the potential to produce very low WLC, but only if refrigerant leakage and refrigerant GWP is low. The ASHP high scenario (i.e. current GWP for commonly used refrigerants) has a higher WLC than the gas boiler for 2019 installations in Passivhaus type buildings. For ASHP and VRF installed in Passivhaus type buildings, the largest contributor of WLC is annual refrigerant leakage, in the medium and high scenarios.

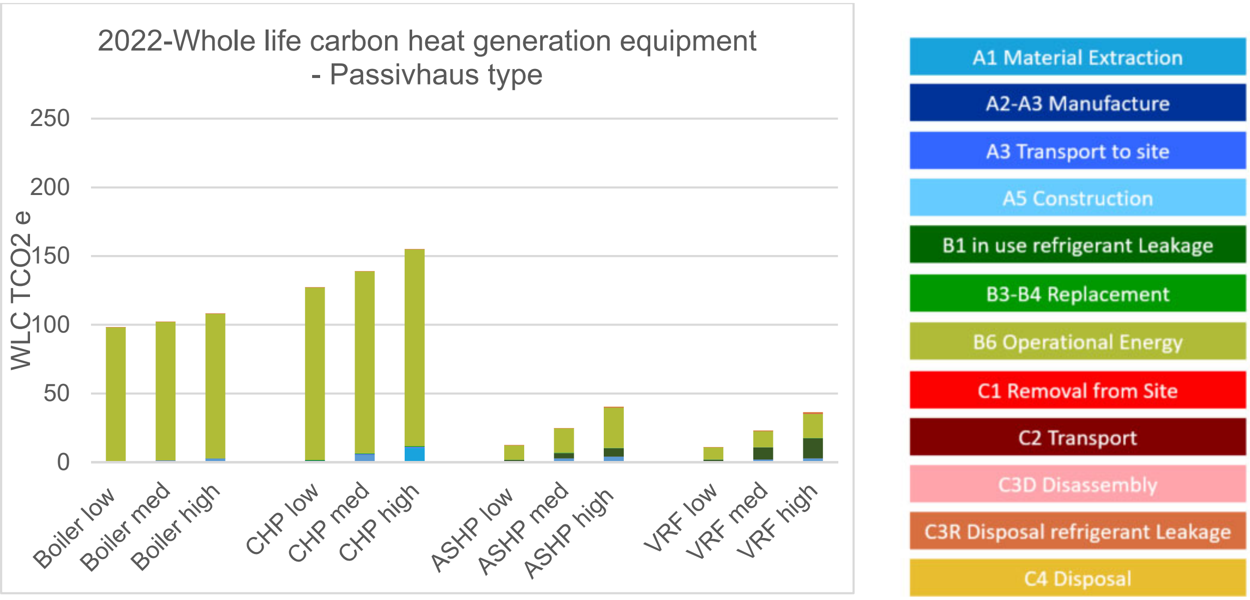
3.2.2 Installing after 2022

In 2022 EU legislation will come into force that stipulates GWP of refrigerants to be no more than 150. This changes the relationship between WLC of the heat-generation equipment types.

Table 8: Assumptions on refrigerants for installations after 2022

Assumptions on refrigerants for installations after 2022						
	Heat pumps			VRF		
	Low	Med	High	Low	Med	High
GWP	150	150	150	150	150	150
Annual leakage/ End of life recovery	1%/99%	3.8%/98%	6%/90%	1%/99%	6%/90%	10%/85%

Figure 9 : Installing in 2022- Passivhaus type building



The WLC for ASHP and VRF for all scenarios is lower than boiler and CHP. However, refrigerant leakage still is a significant contributor to WLC for ASHP and VRF.

3.2.3 Comparing embodied carbon of heat generation equipment

Embodied carbon becomes more important as operational carbon reduces. Net zero carbon definitions will soon encompass WLC. Figure 10 shows a hypothetical solution on how WLC of a building could be drastically reduced. At present it is hard to envisage how the embodied carbon of building services will reduce. It is therefore important to understand what elements contribute to embodied carbon most. For more information on percentage of embodied carbon related to building services in published papers see Appendix G.

Figure 10: Importance of Embodied Carbon in Building services

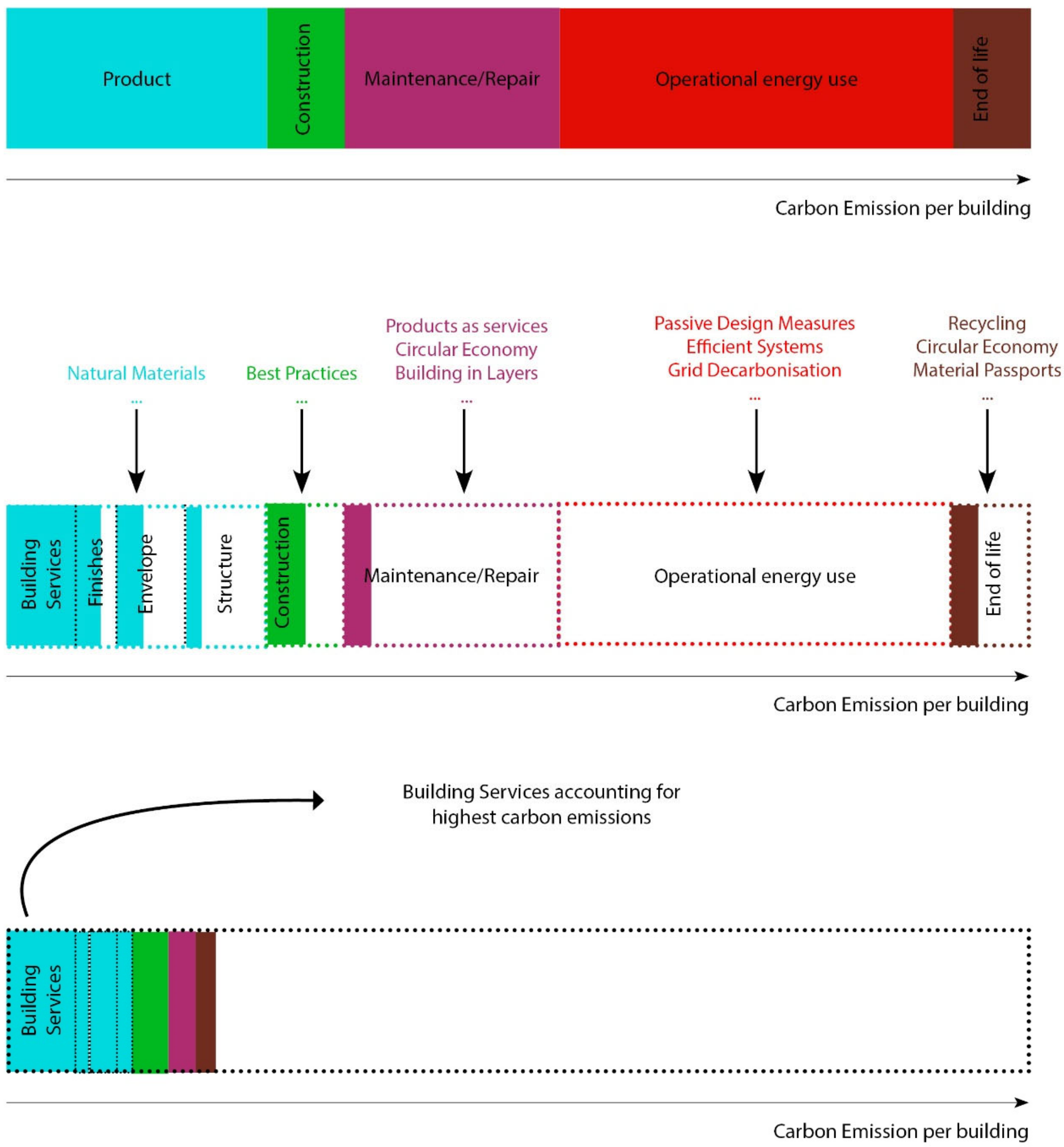
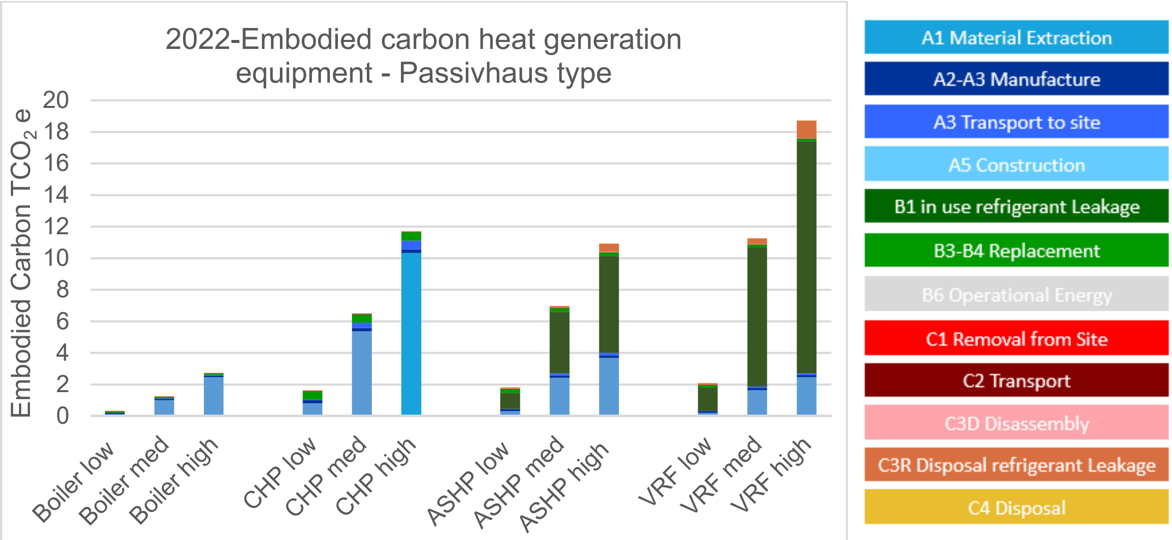


Figure 11 shows the embodied carbon of heat generation equipment using the 2022 case.

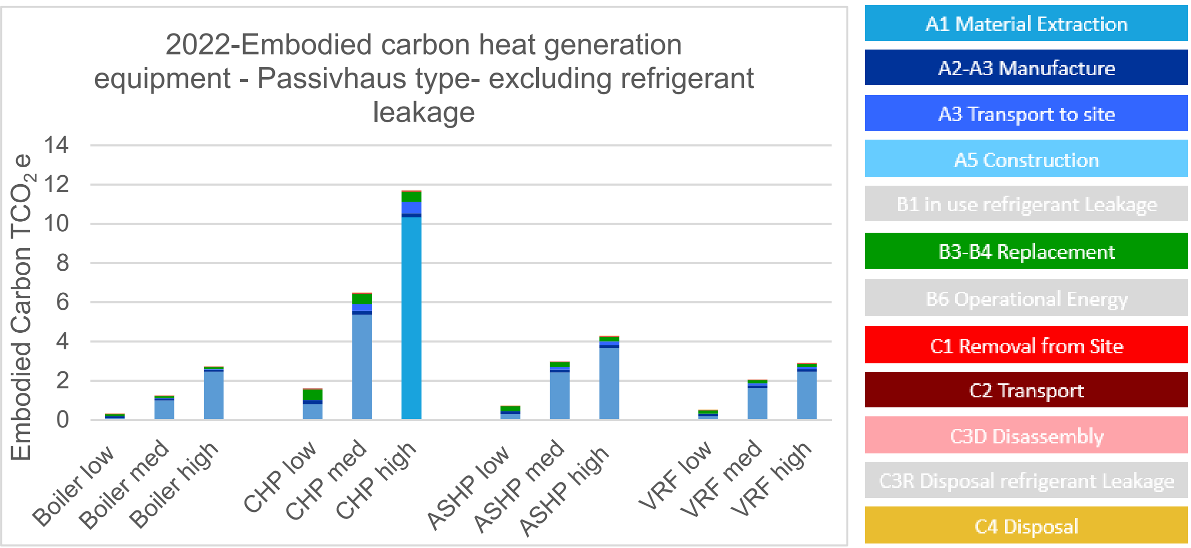
Figure 11: Embodied carbon of heat generation equipment



For ASHP and VRF, the refrigerant leakage for the medium and high scenario is by far the largest proportion of WLC.

If refrigerant leakage is excluded, other elements of WLC can be more easily understood, see Figure 12. This graph is relevant for both installation years, 2019 and 2022.

Figure 12: Embodied carbon of heat generation equipment excluding refrigerent leakage

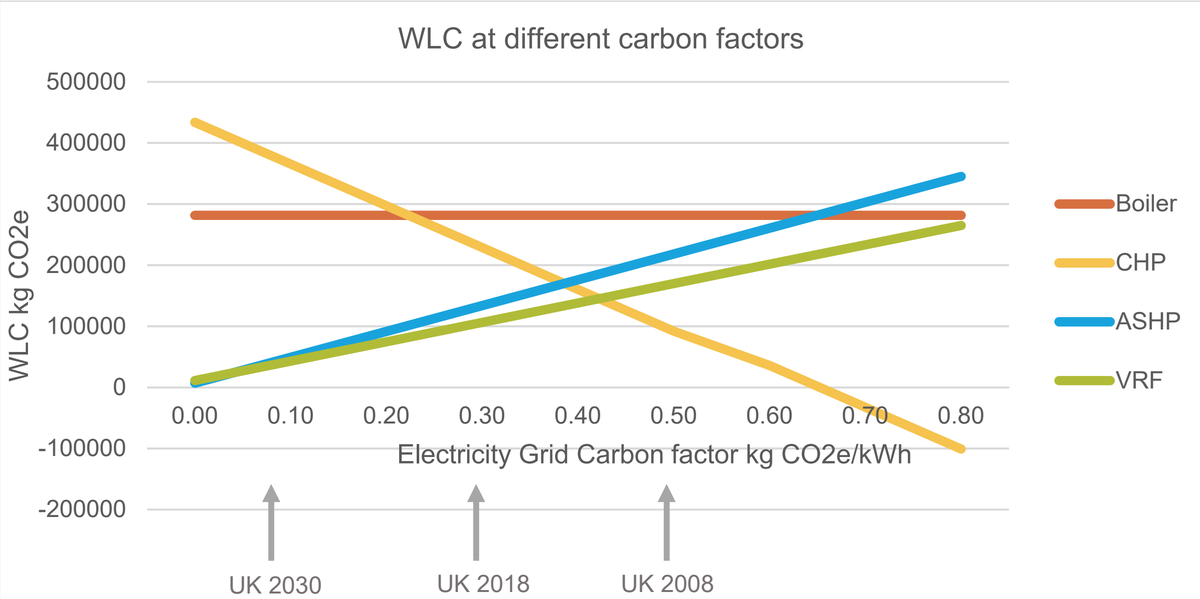


When refrigerant leakage is excluded, the largest contributor to embodied carbon is material processing and extraction (A1). The second largest contributor is replacement, indirectly linked to A1 material extraction.

3.3 WLC OF HEAT GENERATION EQUIPMENT AT DIFFERENT CARBON FACTORS

A large influence on WLC is the carbon factor of the electricity grid. In the sections above a carbon factor of 0.12 kgCO_2/kwh was used as this represents the expected average carbon factor over the lifetime of the equipment, if installed in 2019. Figure 13 shows, for the medium scenario for new buildings how the WLC of heat generation equipment change as the carbon factor of the grid changes.

Figure 13: WLC at different carbon factors



Aside from a gas boiler, the WLC of heat generation equipment depends on the carbon factor of the electricity grid. When the carbon factor is higher than 0.4 CO^2e/kWh, CHP has the lowest WLC. CHP generates electricity with a certain carbon content, when this is 'cleaner' than the electricity grid, this is a net carbon benefit and when this is 'dirtier' than the grid it adds to the carbon emissions of the equipment.

3.4 CAN A PROXY METRIC BE USED TO CONSIDER WLC

Currently the cost of building services is used as a proxy for embodied carbon and WLC, but it is widely known that this method has limitations. This section investigates whether cost or a different proxy metric could be used to understand WLC of heat-generation equipment rather than carrying out equipment specific WLC calculations.

Figure 14 -16 explore possible relationships between WLC and factors such as cost and weight of equipment. These figures are based on the WLC calculations that were carried out using the primary data collected in this study. The 'New build' kWh consumption was used. See Appendix B for data sources used in the calculations.

Figure 14: Comparing cost of equipment and WLC

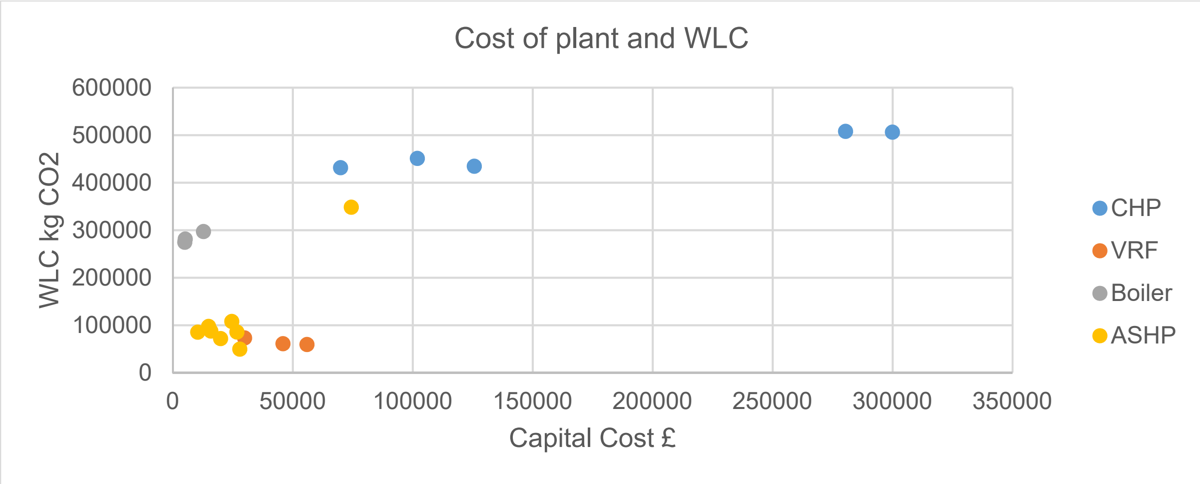


Figure 15: Comparing weight of equipment and WLC

Figure 16: Comparing capacity of equipment and WLC

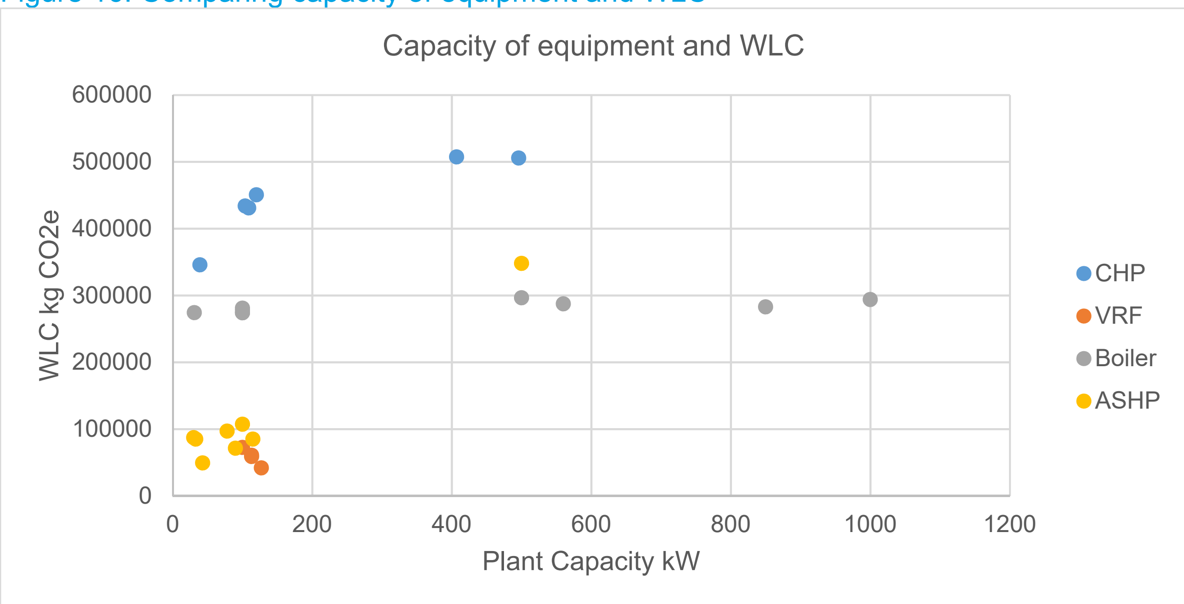


Figure 14-16 show that capital cost, weight, capacity have no correlation with WLC.

3.4.1 Separating building life cycles stages to create a proxy metric

The life cycles stages were broken down to understand if a proxy metric could be developed.

Figure 17: Comparing weight of equipment and product stage (A1-A3) CO2e emissions

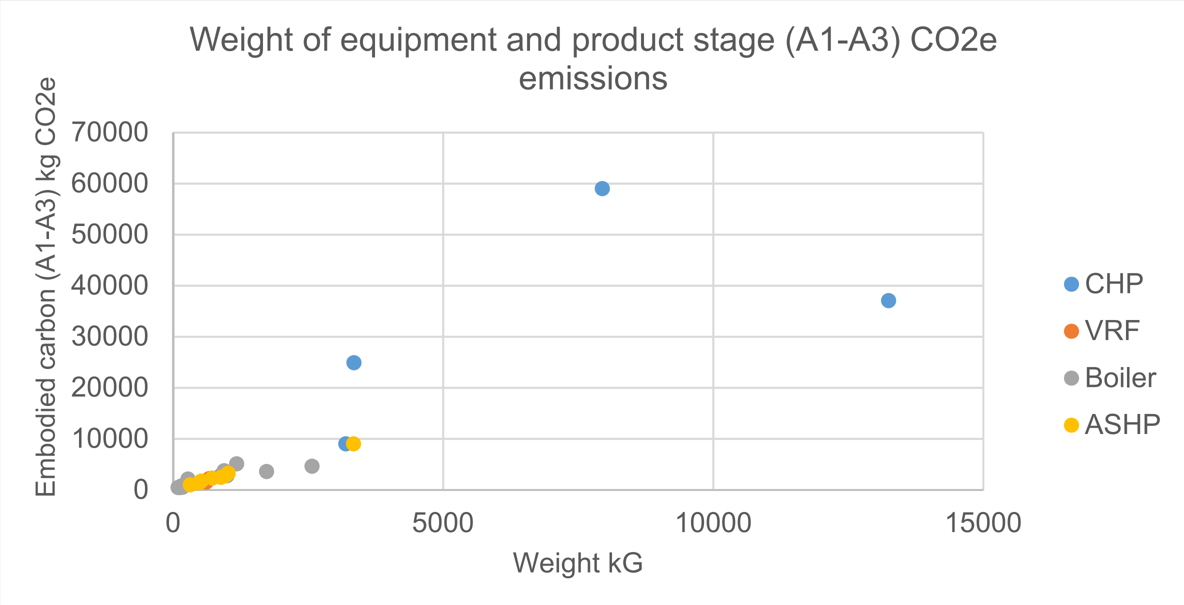
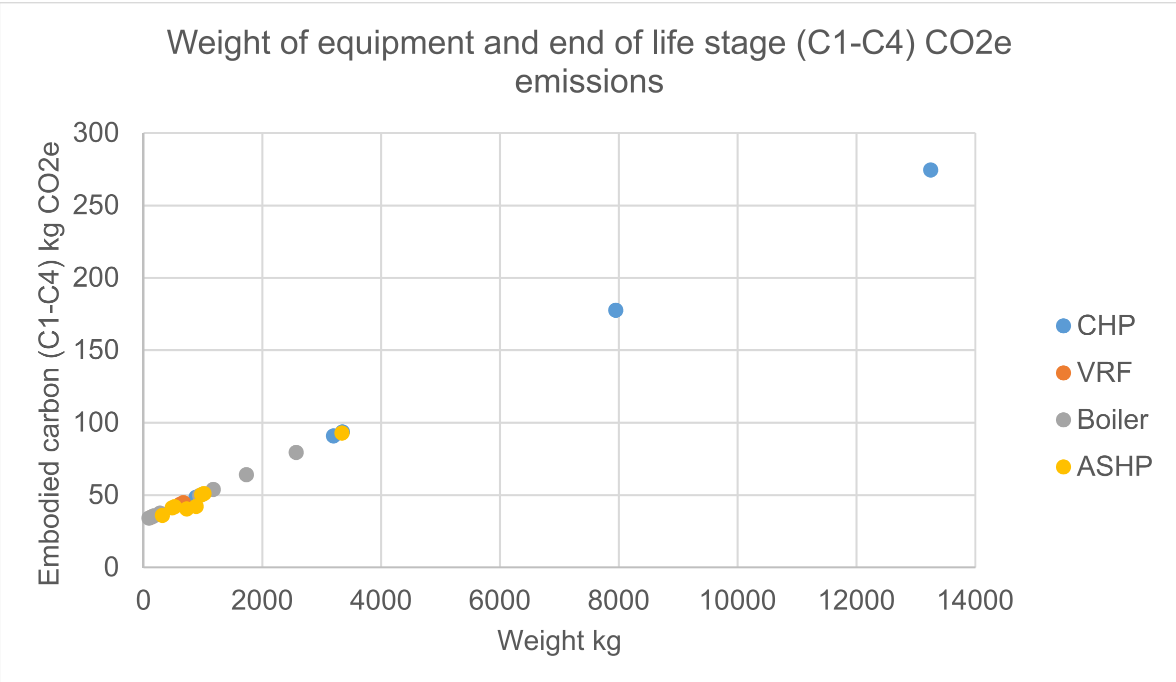


Figure 17 shows that there is some correlation between weight of equipment and product stage emissions, (this has been judged visually from the graphs).

Figure 18: Comparing weight of equipment and end if life stage (C1-C4) CO2e emissions

The below results exclude refrigerant leakage from stage C3R.



From a visual inspection, Figure 18 implies that a linear correlation exists between weight of equipment and end of life stages.

4 CONCLUSIONS AND DISCUSSIONS

4.1 DOES CONSIDERING WHOLE LIFE CARBON RATHER THAN OPERATIONAL CARBON CHANGE DECISIONS ON WHICH TYPE OF HEAT-GENERATION EQUIPMENT TO SELECT?

For all four heat generation equipment types, operational energy is the largest component of WLC; this highlights the importance of passive design and efficiency measures that reduce heat demand.

The carbon emissions associated with refrigerant leakage form a significant proportion of WLC for ASHP and VRF and can account for more carbon emissions than operational energy.

The WLC calculation is very sensitive to energy demand, and the lower the energy demand, the higher the impacts of refrigerant leakage. With current refrigerants such as R410a and R407C with an annual leakage rate of around 6%, for Passivhaus type buildings ASHP can have higher WLC emissions than the low scenario for gas boilers. This is significant because if only operational carbon is used exclusively to make decisions on which heat-generation to select, ASHP and VRF would be selected without considering the impacts of refrigerants.

The Kigali amendment to the Montreal protocol came into force on the 1st of January 2019; this along with the European F-gas regulation that prohibits the use of refrigerants with GWP of over 150 in new equipment, will drastically change the impact of refrigerant leakage for the better. In installations after 2022, ASHP and VRF have significantly lower WLC than the gas boilers or CHP. The medium scenario ASHP emits approximately 80% less WLC than gas boilers and 85% less WLC than CHP and the ranking of heat-generation equipment in order of WLC would be the same as the ranking in order of operational carbon.

However even if GWP is lower than 150 and the annual leakage is 3.8%, emissions associated with refrigerant leakage are still significant; thus the industry will need to look towards refrigerants that have GWP lower than 150.

4.2 WHAT IMPACTS WLC AND WHAT SHOULD BE CONSIDERED IN THE DESIGN OF HEATING GENERATION EQUIPMENT?

WLC reduction measures that have the biggest impact are outlined below.

1. Refrigerant GWP
2. Refrigerant leakage rate
3. High thermal efficiency
4. Reducing the emissions associated with extraction and processing of raw materials

WLC reduction measures that have negligible impact are outlined below.

- Location of where the equipment is fabricated
- Emissions associates with transport
- Emissions associates with energy and water use in manufacture

Reducing carbon emissions associated with extraction and processing of raw materials has a significant impact for boilers and CHP and is likely to have a significant impact on ASHP and VRF in the future. Emissions associated with extraction and processing of raw materials can be reduced by using circular economy principles (See Section 1.8) by:

- Reducing material usage
- Re-using components from dismantled equipment, this means that the equipment must be easily disassembled.
- Using materials that have lower embodied energy.

4.3 CAN A PROXY METRIC BE USED TO CONSIDER WLC AND THUS BE USED TO MAKE INFORMED DECISIONS IN HEATING SYSTEM DESIGN?

No clear correlation was found in this study between the cost of equipment, weight of equipment, capacity and WLC. However, there is a positive correlation between the weight of equipment and the emissions associated with the product life cycle stage (A1-A3) and end of life emissions (C1-C4) excluding emissions from refrigerant leakage in decommissioning. Therefore, with a broader dataset, a 'rule of thumb' calculation could be developed to estimate the WLC of the heat-generation equipment, with weight, refrigerant emissions and operational energy as inputs.

Rule of thumb calculation= α.kg + ((B1 + B6) ε)+((α.kg). δ)+C3R+β.kg= $kgCO_2e$

α- Product stage (A1-A5) constant

β- End of life stage (C1-C4) constant

kg- Weight of equipment

δ- % of product that is replaced over the lifetime of the equipment

ε- Life time of the equipment in years

B1- Annual emissions associated with refrigerant leakage

B6- Annual emissions associated with use

C3R- Refrigerent emissions associates with decomissioning

4.4 RECOMMENDATIONS

4.4.1 Building services consultants

Consultants should consider WLC when making decision regarding which type of heat-generation equipment to specify. Additionally when selecting heat-generation equipment, the WLC reduction measures outlined in Section 4.2 should be considered.

4.4.2 Manufacturers

Refrigerant leakage

Data on refrigerant leakage associated with annual leakage and decommissioning submitted by manufacturers as part of this study are significantly lower than published data. Manufacturers should provide data on real life studies of refrigerants for the life time of the equipment. This study shows that refrigerant leakage is a significant proportion of WLC even with refrigerants with a GWP of 150, this means that manufacturers must look to using refrigerants that tend towards 1, in order to reach our climate change goals.

Disclosure of information

Although some manufacturers contacted for this study were very willing to provide as much information as they could, it was still difficult to obtain data with sufficient completeness, because data is not routinely collected. Manufacturers should be encouraged to publicly disclose through the use of EPD's.

Reducing product stage (A1-A3) emissions

To reduce the WLC related to product stage (A1-A3), manufacturers must look to using a high proportion of components that are re-used from disassembled equipment. This is made easier thorough the use of leasing arrangements. Leasing and other circular economy principles should be investigated by all manufactures.

4.4.3 Policy and regulation

Due to the increasing importance of WLC, it should be included in Building regulations and local policy (The Draft London Plan states that future developments to fully capture their carbon impact (statement 9.2.9A and 9.2.10 k) (19). We must ensure that the Kigali amendment to the Montreal protocol and the EU directive that GWP of refrigerants must be less than 150 for all new equipment is adhered to in the UK from 2022. Refrigerant leakage is still significant if GWP is lower than 150, thus legislation must be in place that limits refrigerant leakage as well as GWP. Cities, states and countries that do not have regulation limiting the GWP of refrigerants must rapidly implement such policy. Future policy should mandate that information is disclosed that is needed to calculate calculations thorough the use of EPD's.

4.4.4 LCA calculation tools

More information needs to become available on building services systems so that they are included in more LCA tools that calculate WLC. All of the tools based embodied carbon on weight, if there was not detailed information available, this should be amended to include refrigerant leakage where relevant.

4.5 FURTHER WORK

This study represents the first steps needed to understand WLC in building services. Further work is needed so that consultants and design teams can understand the impact of design decisions on WLC through development of 'rule-of-thumb' tools to estimate WLC. Such further studies should include the following;

- Incorporate elements of Circular Economy thinking into WLC, and investigate wider questions of how we can make building services more adaptable so that they are not demolished and replaced when the building changes use.
- Investigate distribution network size. Recent trends in the industry suggest a move towards larger distribution network sizes, i.e. increased ducts sizes to decrease specific fan power and thus decrease fan energy

consumption, but this increases material content and thus embodied energy
- Investigate how distribution options affect WLC, for example the difference between fancoil units and displacement ventilation or plastic vs metal pipework

In the long term this could lead to the development of a design information tool that lets designers understand the impact of design decisions on WLC, depending on the typology of the project.

5 ACKNOWLEDGEMENTS

Thanks to the following for reviewing, providing comment and proof reading;

Aaron Gillich - LSBU
Simon Sturgis
Julie Godefroy
David Hawkins - UCL/Skelly & Couch
Roger Hitchin
Tim Pryce
Robbie Epsom - WSP
Robb James - WSP
Rick Wheal - Elementa Consulting
Nathan Millar- Elementa Consulting
Dave Barker- Elementa Consulting
Monica Madrigal- Elementa Consulting
Peter DeMercurio - Elementa Consulting
Hugh Dugdale - Elementa Consulting
Elisabeth George
Rebecca Goodson
Stephan Madle

Thanks to the following colleagues at Integral Group that assisted with data collection;

Richard Drouin
Arootin Ghazarian
James Kral
Christopher Piche
Mudit Srivastava
James Tosh
Aaron Wouters

Thanks to the manufactures that assisted by submitting details on their products used in the study;

Aldrich
Centrica Business Solutions
Dakin
Fulton
Hamworthy
Hoval
Ideal boilers
Lochinvar
Mitsubishi
Rhoss
SAV Systems

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7 APPENDIX A- ASSUMPTIONS IN WLC SCENARIOS

The assumptions used in creating the low, medium and high WLC scenarios are outlined below.

Table 9: Variables in the WLC scenarios across heat generation equipment and scenarios

	Scenario - Low	Scenario - Med	Scenario - High
A1:Extraction and processing of raw material	40% lower that the medium scenario This value is then further multiplied by 0.25, to account for 75% reused components. Adjusted as per published databases	Average A1 for products with capacity close to 100kW. Adjusted as per published databases	25% more than the medium scenario Adjusted as per published databases
A4:Transport from factory to site	Locally manufactured (50km by HGV)	European manufactured (300km by HGV)	Global manufactured (1500km by sea and 200km by HGV)
B6:Operational Energy	Boiler: 98% CHP: 56%Th 34% El ASHP: COP 5 VRF: COP 6	Boiler: 95% CHP: 52%Th 37% El ASHP: COP 3 VRF: COP 4.5	Boiler: 91% CHP:47%Th 38% El ASHP: COP 1.8 VRF: COP 3
B1/C3R: Refrigerant Leakage	Boiler: 0 CHP: 0 ASHP: 1% annual, 99% end of life GWP 1 VRF: 1% annual, 99% end of life GWP 1	Boiler: 0 CHP: 0 ASHP:3.8% annual, 98% end of life GWP 150 VRF: 6% annual, 90% end of life GWP 150	Boiler: 0 CHP: 0 ASHP:6% annual, 90% end of life GWP 2088 VRF: 10% annual, 85% end of life GWP 2088

Th=Thermal efficiency , El= Electrical efficiency, COP =Coefficient of performance

Table 10: Constants in the WLC scenarios across heat generation equipment and scenarios

	Scenario - Low	Scenario - Med	Scenario - High
A2: Transport to factory	300km by HGV		
A3: Energy, water, waste in manufacture	188 kWh per unit, 0.35 m2 per unit,1% waste		
A5: Construction	Not included		
B4: Replacement	10% of components (by weight) are replaced over the 20 year lifetime of the equipment		
C1: Removal from site	As per RICS guidance		
C2:Transport to dismantling/ disposal	50km with HGV to disassembly and 50km with HGV to disposal		
C3: Process of dismantling	50% of energy used to fabricate the equipment		
C4: Disposal	30% by weight is disposed; 70% recycled (carbon emissions associated with recycling not included as this is within the boundary of the next product.)		

8 APPENDIX B- DATA SOURCES IN ANALYSIS

Table 11: Data sources in analysis

	Assumptions	Source
A1:Extraction and processing of raw material	% of breakdown of materials in the equipment	Data from manufacturers
	Embodied carbon assumptions for materials	Embodied carbon assumptions from ICE database
A2: Transport to factory	Transport from the raw material processing to the component factory is 300km with a HGV	Estimation/ aligned to transport distance for nationally manufactured product in RICS
	HGV transportation 0.10559 kg CO_2/T of material/ km of travel (BEIS conversion factors 2018)	BEIS conversion factors 2018
A3: Energy, in manufacture	188 kWh energy consumption	Averaged data from 4 factories
	Assumed that manufacturing is located in UK. Electricity factor- 0.3072 $kgCO_2$/kWh- generation, transmission and distribution	BEIS conversion factors 2018
A3:Water in manufacture	0.35 m^3 Water consumption	Averaged data from 3 factories
	CO_2 factor for water supply and treatment 1.052kg CO_2e/m^3	BEIS conversion factors 2018
A3:Waste in manufacture	1% of material by weight	Estimation
	0.013 kg CO_2 / kg of waste- disposal	RICS guidance
A4:Transport from factory to site	HGV transportation 0.10559 kg CO_2/T of material/ km of travel	BEIS conversion factors 2018
A5:Construction	Not included	
B1 Refrigerant leakage	Outlined in Table 20 in Appendix E	From a broad range of studies outlined in Table 19 in Appendix E
B2: Maintenance	Not included	
B3: Repair	Included as part of B4	
B4: Replacement	10% of components (by weight) are replaced over the 20 year lifetime of the equipment	
B7 Operational water use	Not included	
B6:Operational Energy	See Section 8.5	
C1:Removal from site	RICS guidance states 3.4 $kgCO_2e$/m2 GIA. As this study is only considering heat-generation equipment, this value is multiplied by 0.05 due to the fact the study is only including heat generation equipment not the whole building.	RICS guidance/ estimation
C2:Transport to dismantling	Assumed that the transport from site to disassembly location is 50km with a HGV. In line with RICs guidance the HGV vehicle has 50% load coming to site and leaving with 100% load	RICS guidance/ estimation
	HGV transportation 0.10559 kg CO_2/T of material/ km of travel	BEIS conversion factors 2018
C2:Transport to disposal	Assumed that the transport from site to disassembly location is 50km with a HGV. In line with RICs guidance the HGV vehicle has 50% load coming to site and leaving with 100% load	RICS guidance/ estimation
	HGV transportation 0.10559 kg CO2/T of material/ km of travel	BEIS conversion factors 2018
C3D: Process of dismantling	25% of energy used to fabricate the equipment	Estimation
C3R: Refrigerant Leakage	Outlined in Table 20 in Appendix E	From a broad range of studies outlined in Table 19 in Appendix E
C4: Disposal	Assumed that 30% by weight is disposed.	Estimation
	0.013 kg CO_2 / kg of waste- disposal	RICS guidance

8.1 EXCLUSIONS

- The study includes heat generation equipment, and the energy used by the equipment to generate heat. Distribution pipework and heat emitters can be responsible for a larger proportion of embodied carbon than heat generation equipment, assuming it is newly made, (7). This has not been included, as it is assumed that this is equal for all heat generation equipment.
- Heat pumps and CHP systems require buffer tanks, whereas boilers do not. This additional embodied carbon is not included in the calculations, because buffer tanks have a longer service life than heat-generation equipment.
- Many heat pumps and VRF can provide both heating and cooling. If they are used for heating and cooling some of the embodied energy could be apportioned to heating and some to cooling. This is not done in this study, as it is assumed that the building does not need cooling.
- Energy used in cleaning for re-use.
- Energy used in recycling the dismantled product, this is part of the boundary of the subsequent product that uses this material.
- Energy used in creating and manufacturing the refrigerant or the gas, this is due to unavailable data.

8.2 LIFETIME OF HEAT-GENERATION EQUIPMENT

Data on the lifetime of equipment from various sources was collected, see Table 12. It was concluded that the most relevant lifetime for the equipment was 20 years.

Table 12: Lifetime of equipment from various data sources

		Lifetime
Air-cooled chiller	TM56 (16)	20
Water-cooled chiller		25
Split system		15
VRF system		15
Boilers	Primary data from manufacturers	15,20,25,40
Heat pump		25,25
CHP		15,15
VRF		15,15
Heating and cooling systems	Redefining Zero (20)	min 15 years, typical 25 years, max 30 years

8.3 ENERGY USE IN MANUFACTURE

Data was collected on the energy used in the manufacture of heat generation equipment, see Table 13. The average value was used in the study for all types of heat generation equipment. There is a large variation in the data, sensitivity analysis carried out in Appendix F was based on the lowest and highest value of the data collected.

Table 13: Data collected on the energy used to manufacture heat generation equipment

	kWh	CO_2e	kg CO_2 e
Factory 1	39	0.3072	12.0
Factory 2	30	0.3072	9.1
Factory 3	406	0.3072	124.7
Factory 4	277	0.3072	85.2
Average	188	0.3072	57.7

8.4 WATER USE IN MANUFACTURE

Data collected on the water used in the manufacture of heat generation equipment, the average value was used in the study for all types of heat generation equipment.

Table 14: Data collected on the water used to manufacture heat generation equipment

	m^3	CO_2e	kg CO_2 e
Factory 1	0.3	1.052	0.26
Factory 2	0.2	1.052	0.22
Factory 3	0.6	1.052	0.63
Average	0.35	1.052	0.37

8.5 HEATING AND HOT WATER DEMAND

The proportion of embodied and operational carbon relating to heating and hot water depends on building typology. A stadium that is not used often, will have a large heating system needed for when the stadium is full, but this may only happen a few times a month, so the embodied carbon will make up a higher proportion of WLC of the heating system than for an office that has a regular occupancy.

In order to ensure that this study is applicable to a range of building typologies and sizes, rather than a single case study, a peak capacity of 100kW was chosen. The floor area of the project was then back calculated, based on W/m^2 assumptions. Annual kWh figures were then calculated based on published kWh/m^2 data. The study is based on the figures for multi-residential developments; however, as multi-residential, school, office and hotel all seem to have a similar relationship between capacity and annual heating and hot water demand the results of this study are relevant to these typologies.

Table 15: Heating and hot water calculations

	Floor area	Heating		Hot water		Peak Capacity	Annual heating and hot water demand- Existing buildings
	m^2	Peak W/m^2	kWh/m^2/ yr	Peak W/m2	kWh/m^2/ yr	kW	kWh/ yr
Multi-Residential	1038	60	60	36	50	100	114,152
School	1010	87	103	12	15	100	115,681
Office	1220	70	63	12	6	100	100,813
Hotel	714	60	97	80	48	100	114,766

<u>Notes</u>

- The kWh/m^2 demand for existing buildings was derived from data taken from the Building Energy Efficiency Survey (BEES) (21) for the School, Office and Hotel (assuming a 90% efficient gas boiler). The annual heating and hot water demand for existing buildings for residential buildings was assumed at 8000 kWh per dwelling.
- For the residential development $1038m^2$ corresponds to thirteen $80m^2$ flats.
- The domestic hot water has been sized on diversity relevant for a development of 150 flats.

Due to improvements in thermal performance of buildings, heating and hot water systems are often sized on hot water demand rather than heating demand. This means that the capacity of the heating system for existing, new and low energy (Passivhaus type buildings) are similar, however they have a different total heating and hot water demand, this is shown in Table 16

New builds were assumed to have 50% of the demand of the existing buildings. It was assumed that heating and hot water for Passivhaus residential developments was 20 kWh/m^2; this is in line with post occupancy data averaged from Lark Rise – Passive House Plus- Preliminary Energy Performance Evaluation Report (22) and Wimbish Passivhaus Development: Performance Evaluation (23). See Table 16 for the annual heating and hot water demand used in the study

Table 16: Annual heating and hot water demand used in study

Typology	Floor area (m2)	Peak Capacity (kW)	Annual heating and hot water demand (kWh/ yr)		
			Existing buildings	New builds	Passivhaus type
Multi-Residential	1038	100	114,152	57,076	20,755
School	1010	100	115,681	57,840	-
Office	1220	100	100,813	50,407	-
Hotel	714	100	114,766	57,383	-

9 APPENDIX C - WHOLE LIFE CARBON – PRIMARY CALCULATIONS

The primary WLC calculations were undertaken using the method outlined in Section 2, using assumptions and data sources outlined in Appendix B. Low, medium and high scenarios were established, using assumptions in Appendix A.

9.1 BOILER

Figure 19: WLC of boilers - Primary data collected in this study and the established WLC scenarios

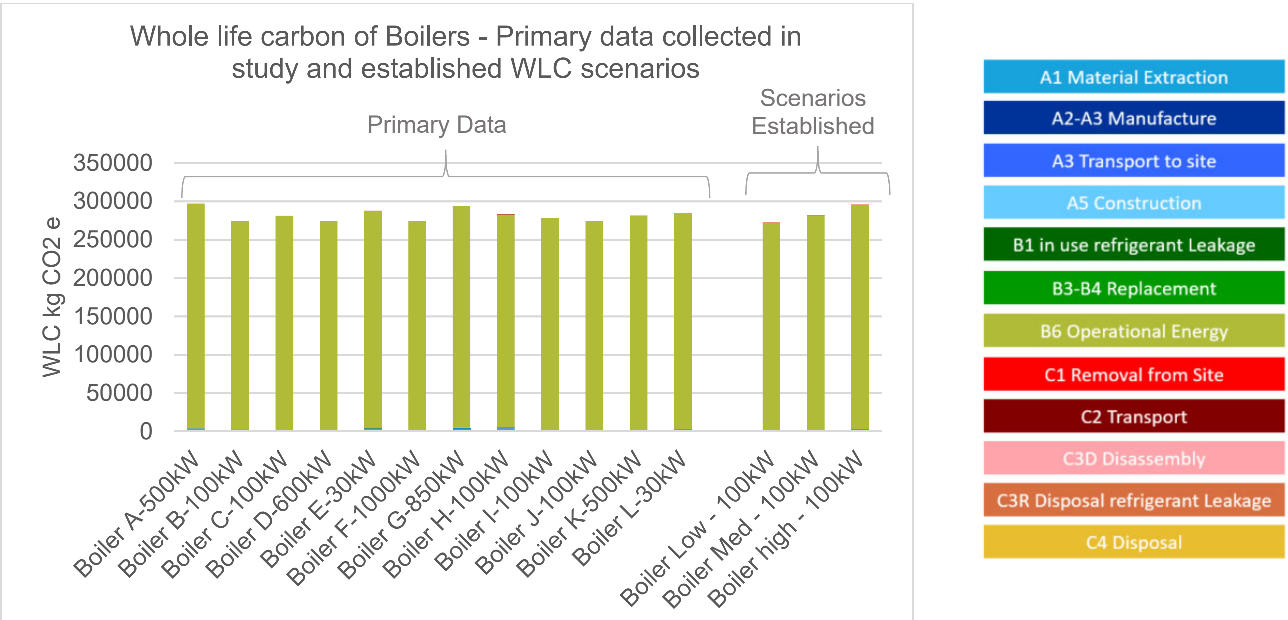
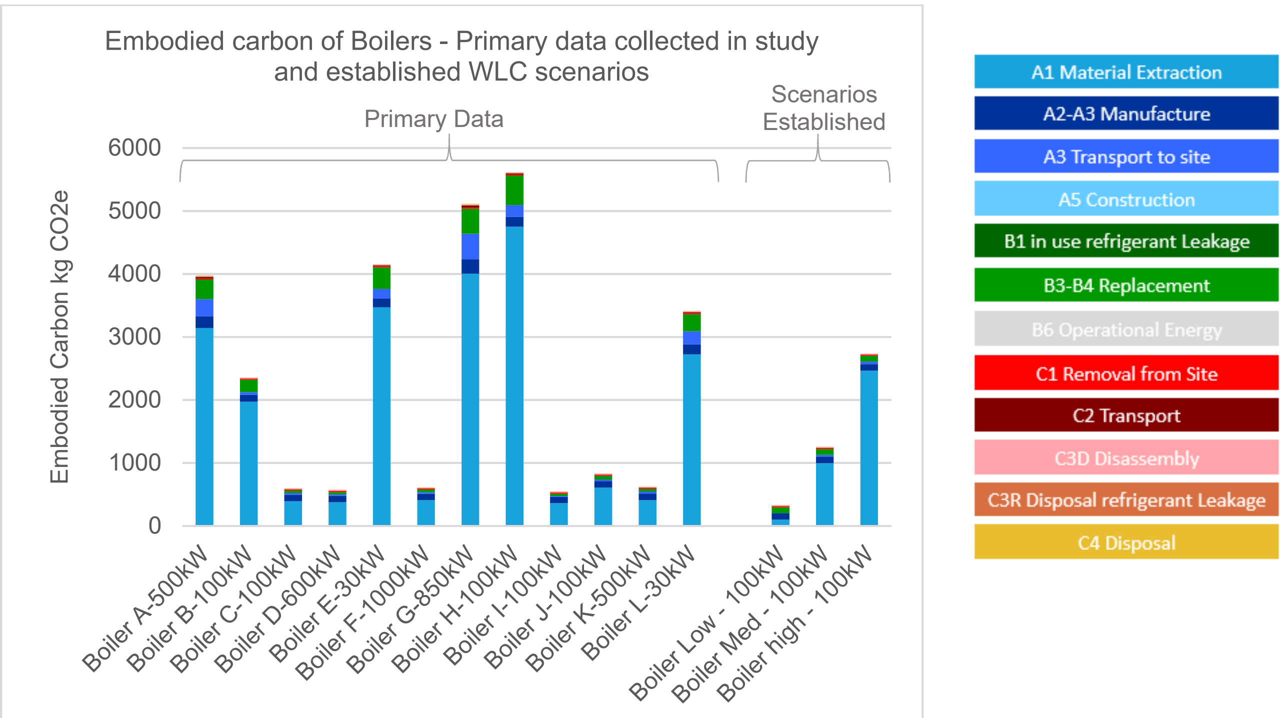


Figure 20: Embodied carbon of boilers - Primary data collected in this study and established WLC scenarios



9.2 CHP

Figure 21: Whole life carbon of CHP - Primary data collected in this study and the established WLC scenarios

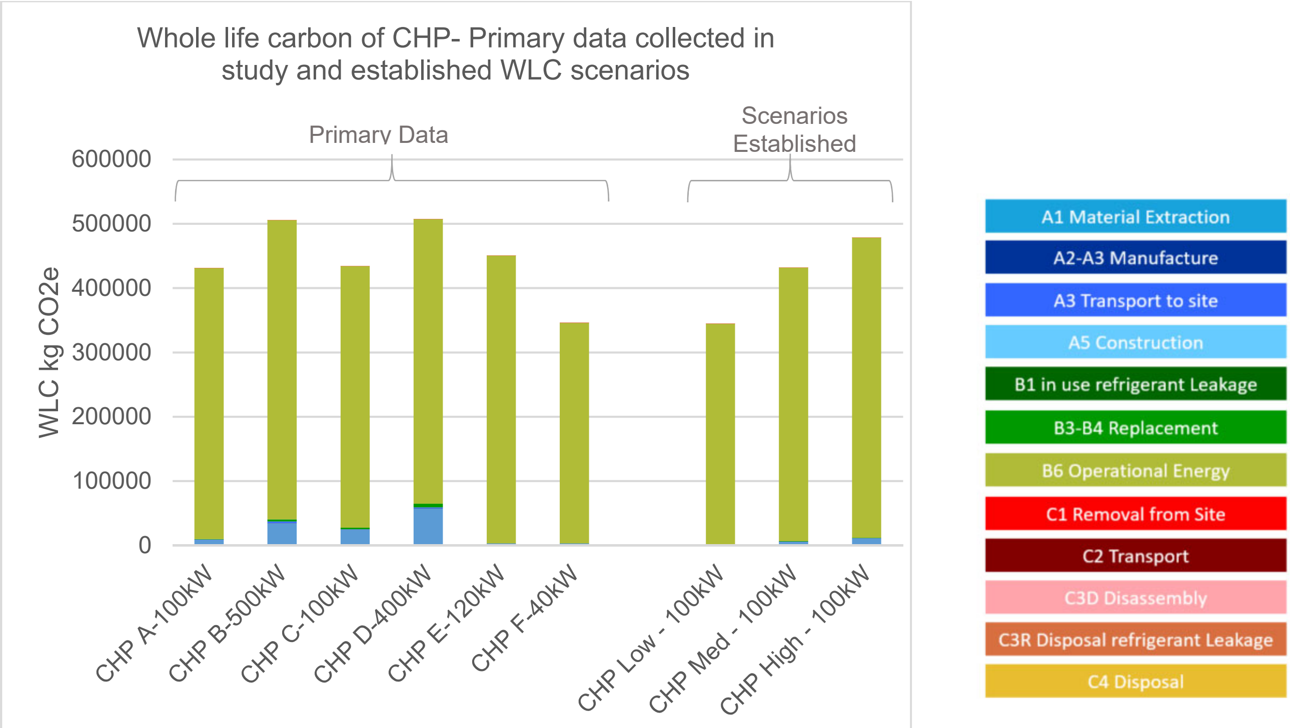
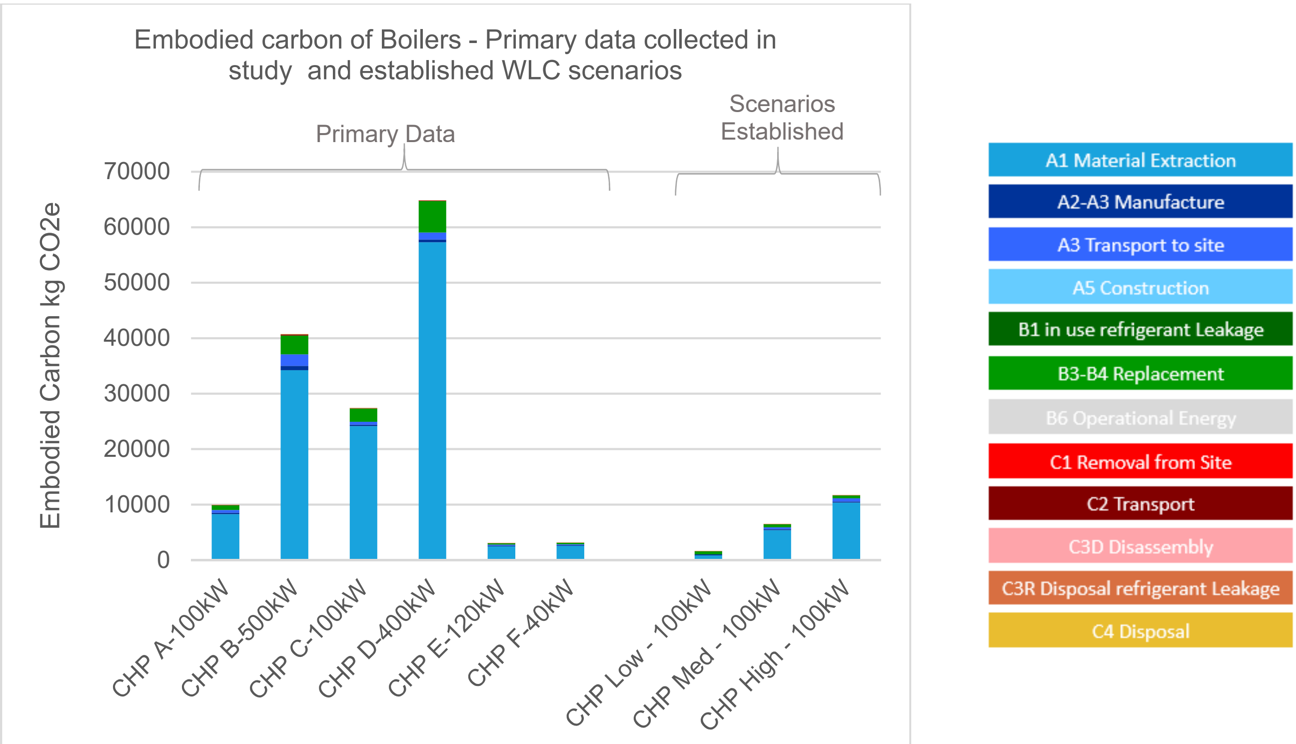


Figure 22: Embodied carbon of CHP - Primary data collected in this study and established WLC scenarios



9.3 ASHP

When establishing the scenarios, the emissions from refrigerant leakage have been adjusted to be in line with published data on refrigerant emissions, rather than using refrigerant emission assumptions received from manufacturers. See Appendix E for details on how these assumptions were established.

Figure 23: Whole life carbon of ASHP - Primary data collected in this study and the established WLC scenarios

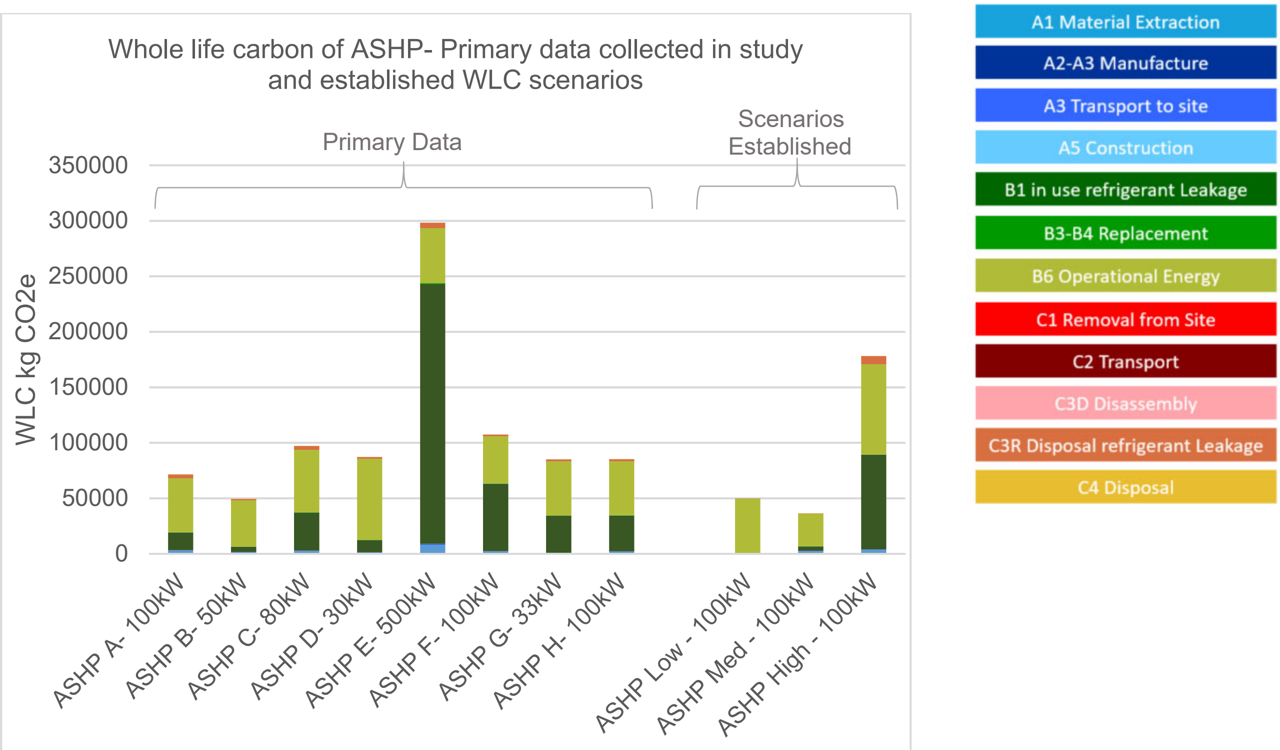


Figure 24: Embodied carbon of ASHP - Primary data collected in this study and established WLC scenarios

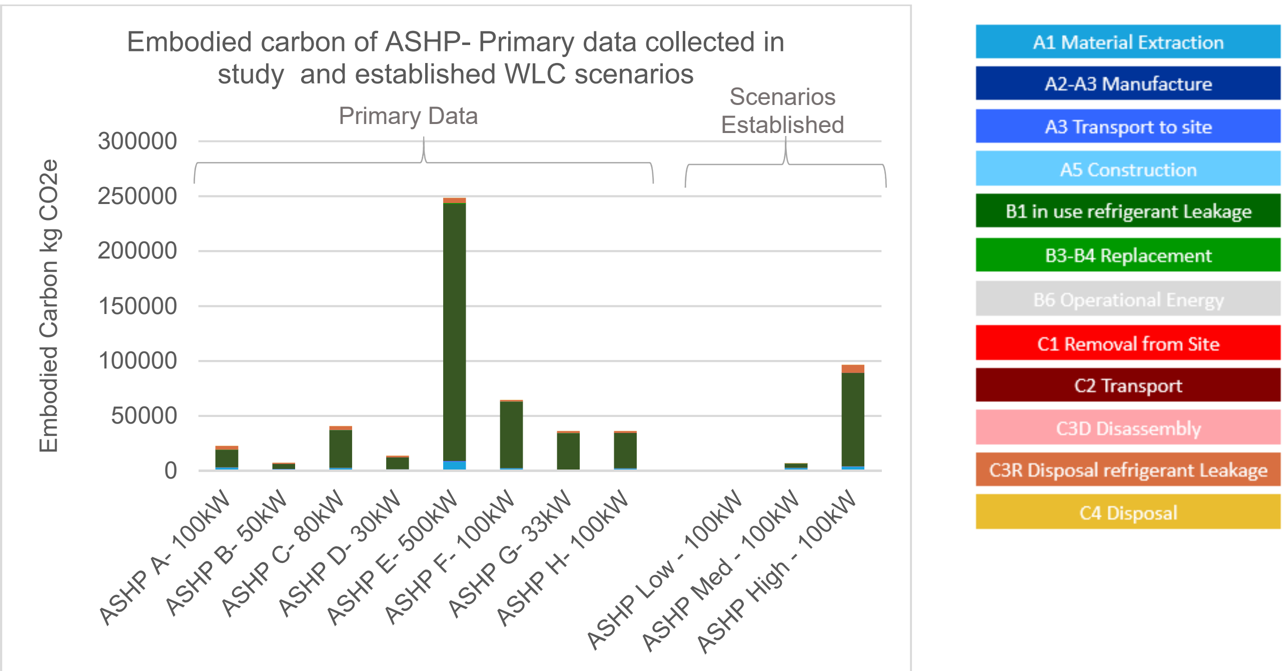
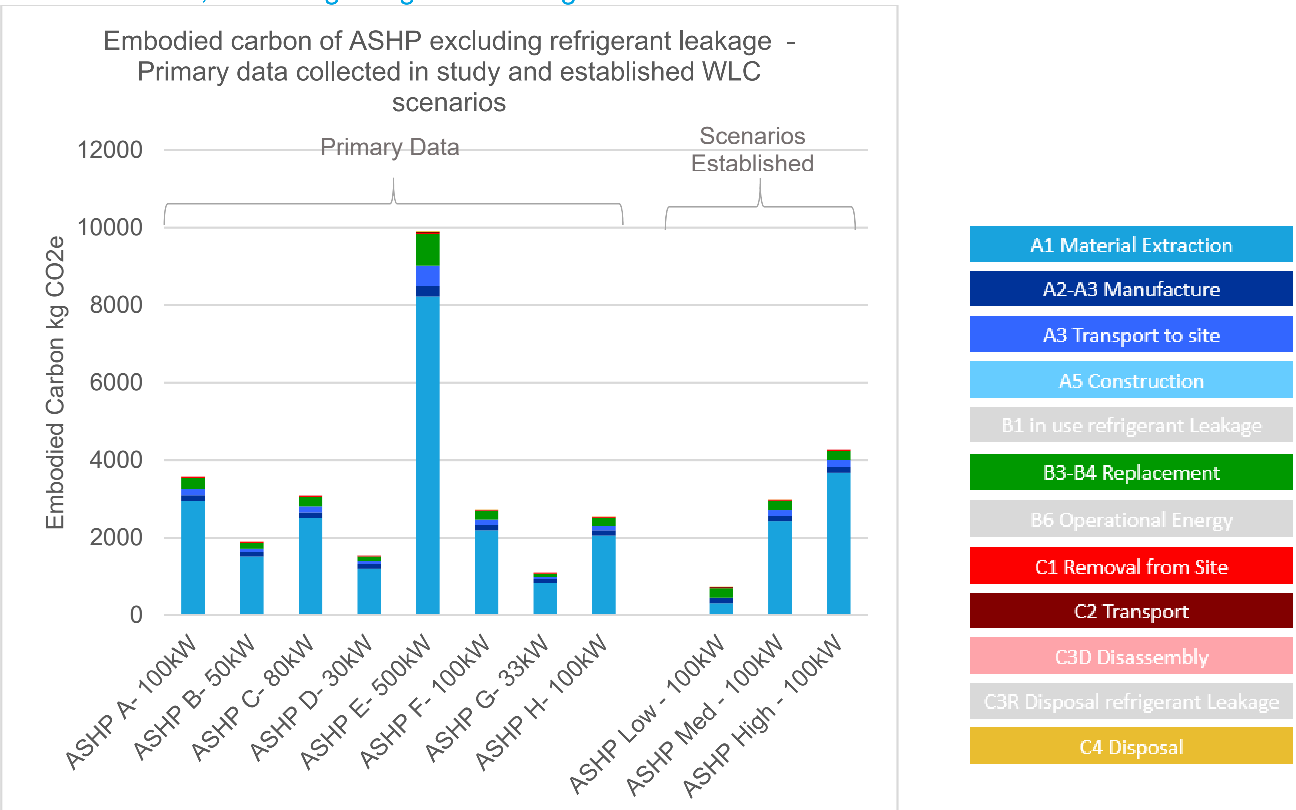


Figure 25: Embodied carbon of ASHP - Primary data collected in this study and established WLC scenarios, excluding refrigerant leakage



9.4 VRF

When establishing the scenarios, the emissions from refrigerant leakage have been adjusted to be in line with published data on refrigerant emissions, rather than using refrigerant emission assumptions received from manufacturers. See Appendix E for details on how these assumptions were established.

Figure 26: Whole life carbon of VRF - Primary data collected in this study and the established WLC scenarios

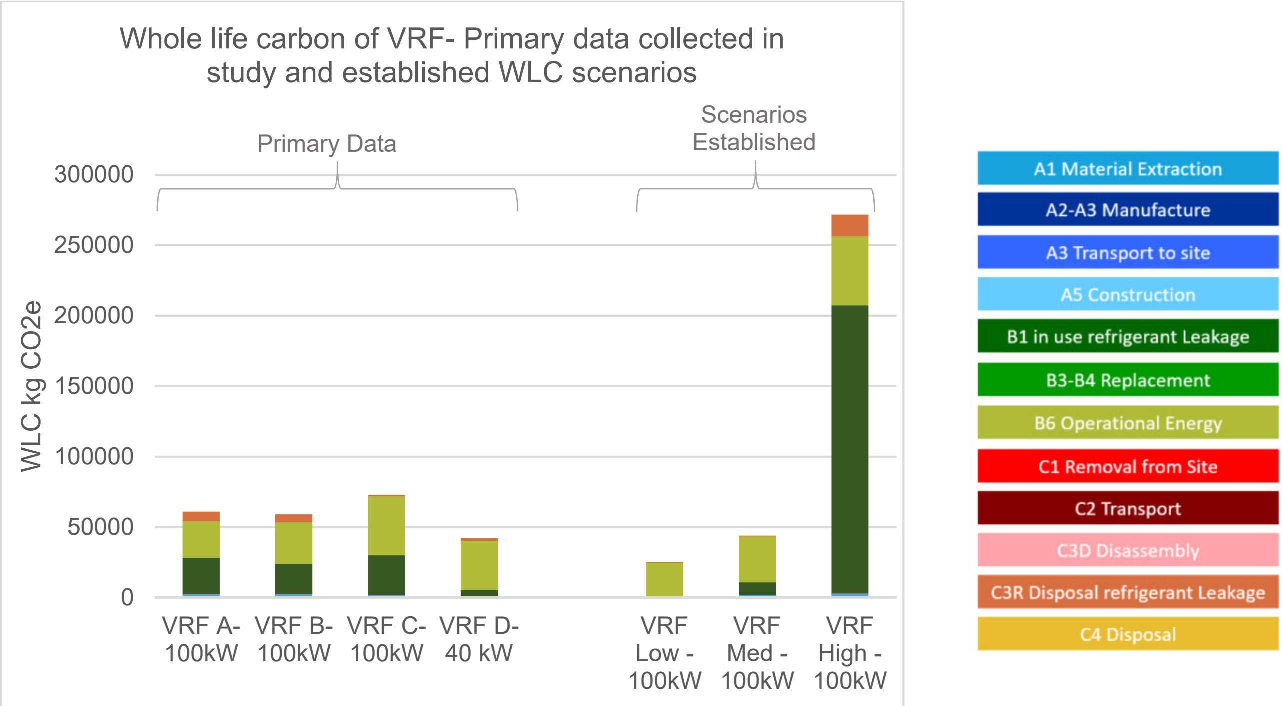


Figure 27: Embodied carbon of VRF - Primary data collected in this study and established WLC scenarios

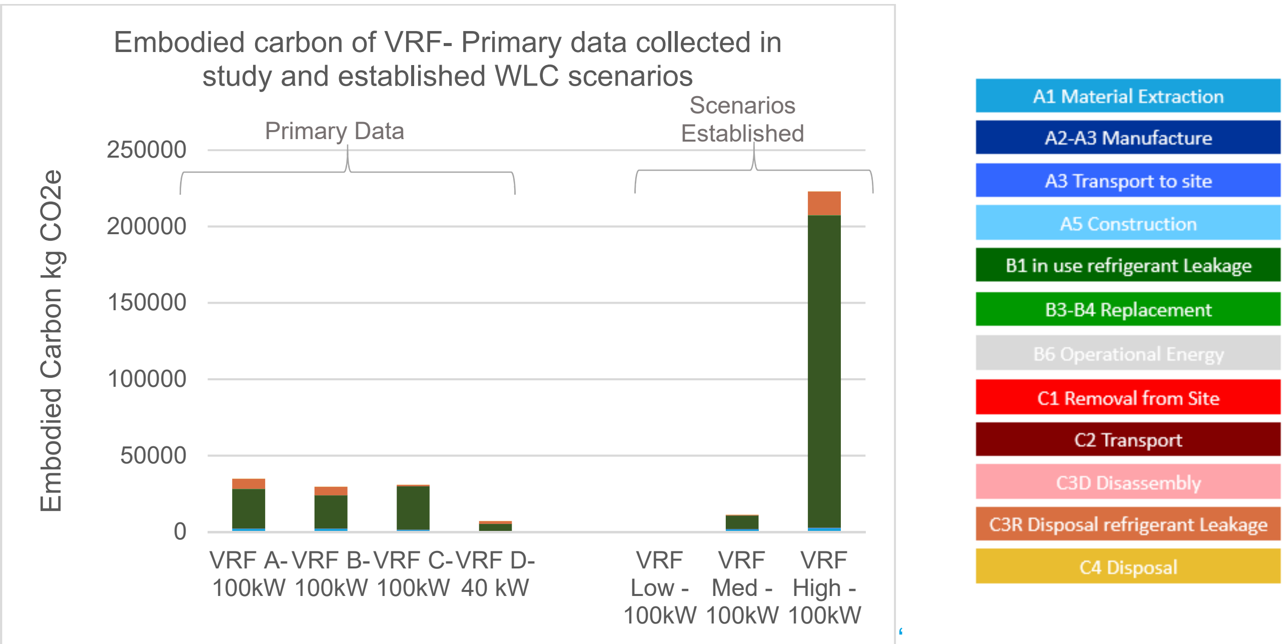
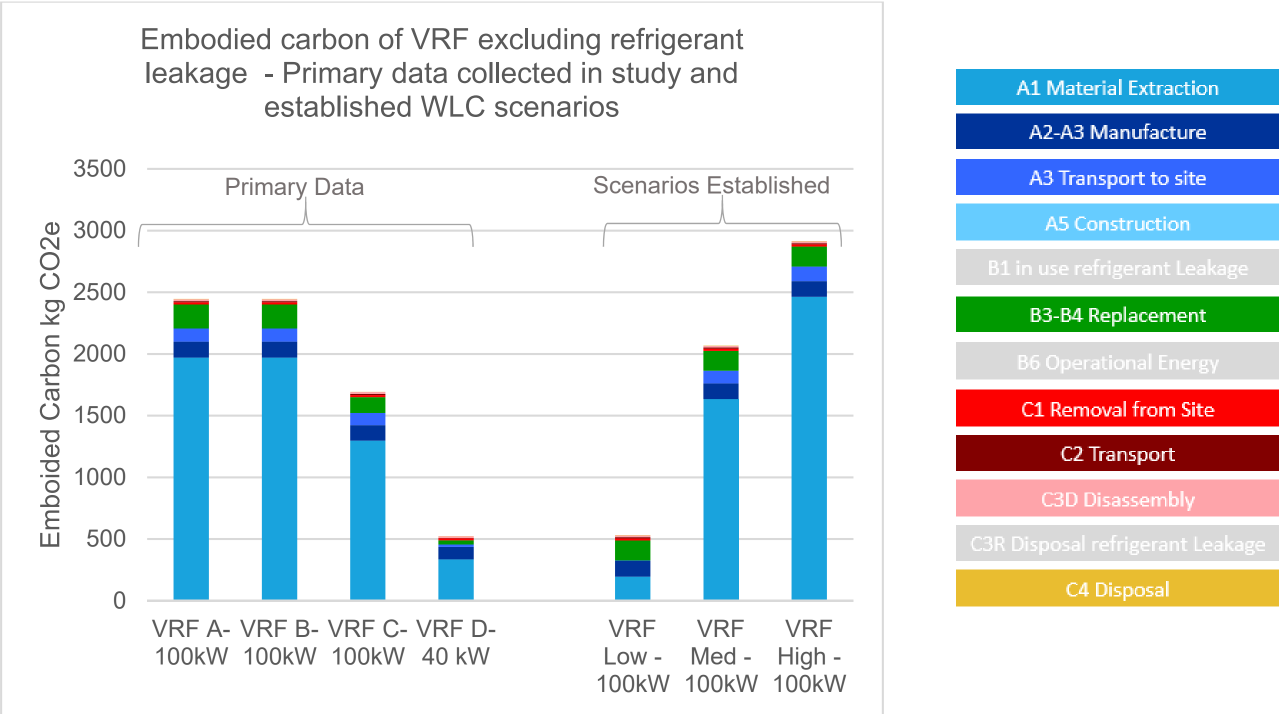


Figure 28: Embodied carbon of VRF - Primary data collected in this study and established WLC scenarios, excluding refrigerant leakage



9.5 SENSE CHECKING WITH PUBLISHED DATABASES

In order to ensure validity of results, WLC calculations were sense checked against results from published databases. This could only be carried out for boilers and ASHP as no published data was found on CHP or VRF.

Published databases

- Oekobaudat (15) - 18 products
- MDEGD_FDES (available through One Click LCA(24)) - 3 products
- Bionova (available through One Click LCA(24)) - 1 product
- Product EPD (25) - 1 product

Material extraction and processing (A1) accounts for the largest proportion of embodied carbon. Table 17 shows how A1 was initially established for the low, medium and high scenarios.

Table 17: Initial assumptions for A1 for the WLC scenarios

Initial assumptions for A1 for the WLC scenarios			
	Low	Medium	High
A1	40% lower than the medium scenario This value is then multiplied by 25%, to account for 75% reused components	Average A1 for products with Capacity close to 100kW	25% more than the medium scenario

Data from published databases was only available for the A1-A4 and D4 stages. Corresponding data from the WLC calculation from primary data collection and the low, medium and high scenarios were established. This was plotted by capacity as shown in Figure 29. The embodied carbon of the scenarios was visually compared between the primary data and the published data sources, and adjusted where necessary.

Figure 29: Embodied carbon of primary data and published databases compared to capacity of boilers

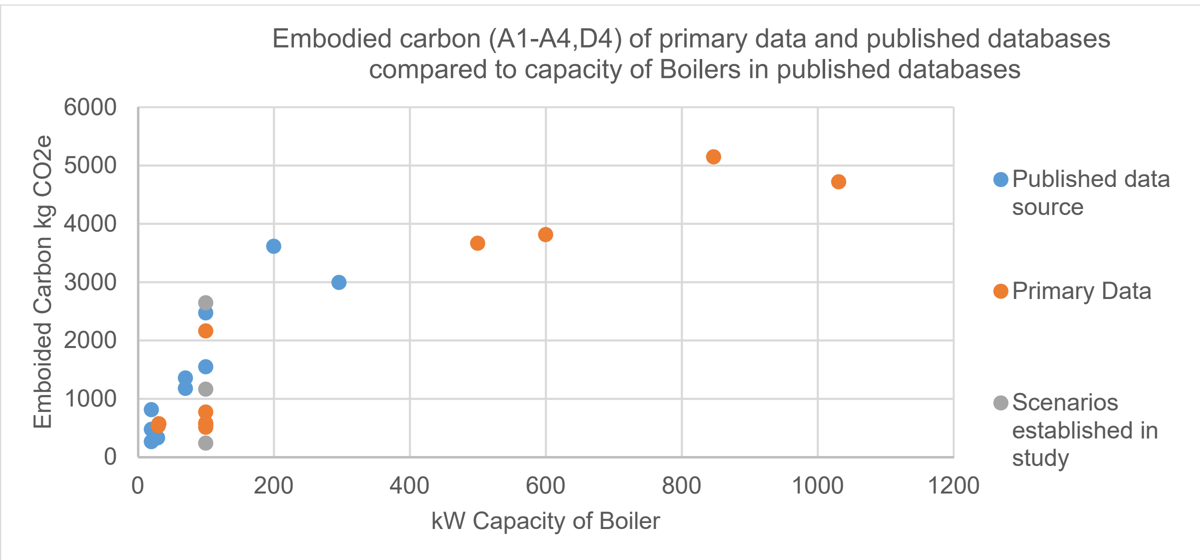
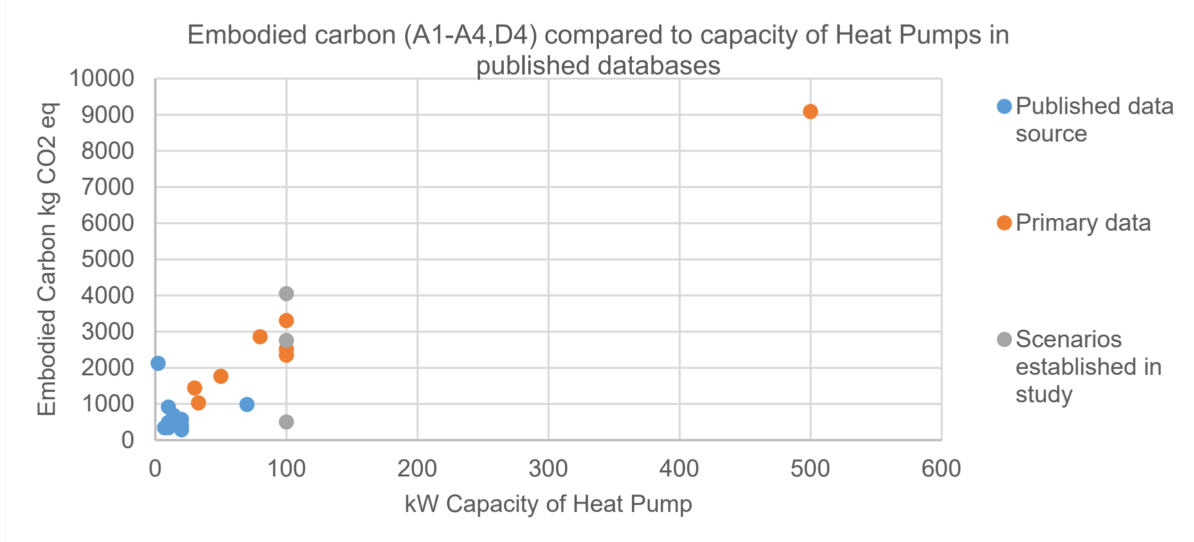


Figure 30: Embodied carbon from primary data and published databases compared to capacity of heat pumps



Note: Refrigerant emissions are not included in Figure 30.

10 APPENDIX D - LIFE CYCLE ANALYSIS

Life cycle assessment (LCA) refers to a multi-step procedure for calculating the lifetime environmental impact of a product or a service. As well as WLC, other impacts can be taken into consideration, such as Ozone Depletion, Human Toxicity, Eutrophication. It can be assessed directly by manufacturers through Environmental product declarations (EPD) or through LCA calculation tools. EPD is a standardised tool used to communicate the environmental performance of products and is compliant with CEN Technical Committee 350 -CEN/TC 350 (26) which enables comparison of products across Europe. An EPD contains information related to energy, pollution and resource depletion impacts. This is currently a voluntary procedure that can show to what extent a manufacturer has considered and reduced the environmental impact of products and can be used to compare products.

Very few EPD's are available for heat generation equipment, and there are few entries in databases. For this reason, carbon calculations were carried out from primary data collected, see Section 2- Methodology for more information.

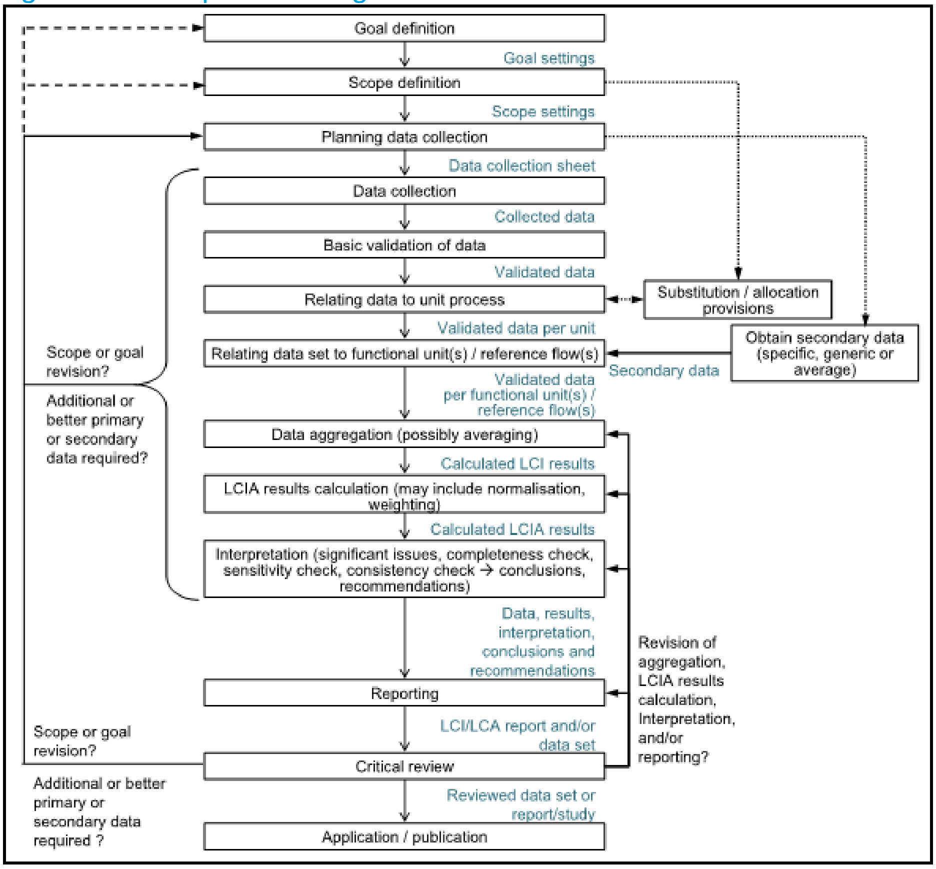
LCA calculations tools are based on data gathered from manufacturers (EPD which don't always cover all lifecycle stages) or industries (generic data based on average), processed according to the chosen system boundaries, functional units, goal, impact category, time period and different modelling approaches such as:

- End of life: If the ability to recycle a product at the end of life has an impact on the LCA
- Replacement scenarios and product lifespan
- Policy concerning small elements scope
- Biogenic Carbon Sequestration[d]

[d] Carbon transformed into the plant tissue from the absorbed CO_2 of a growing biomass. It will be realised into the air again as CO_2 or CH_4 or sequestered permanently in landfills

In order to assess environmental performance, the models are then assessed through characterisation factors to be able to model the data within impact categories according to a chosen impact assessment methodology.
Figure 31, (extracted from ILCD-Handbook-General-guide-for-LCA-Detailed-Guidance (27)) describes the process of a LCA.

Figure 31: LCA process diagram



Source: ILCD-Handbook-General-guide-for-LCA-Detailed-Guidance (27)

10.1 CURRENT SOFTWARE USED IN THE INDUSTRY TO CALCULATE LIFE CYCLE ASSESSMENT

Different types of software exist to calculate WLC, commonly differentiated as follows:

- BIM based LCA tools: life cycle assessment incorporated into a BIM software to assess at any stage the whole life carbon footprint. eg: Tally, OneClick, H\BERT
- LCA advanced calculations tools: detailed and specific LCA eg: Gabi, EcoInvent
- LCA medium calculation tools, eg: Impact Estimator of Athena, Equer
- LCA basic calculations tool: Excel models incorporating inputs and outputs.

10.2 BUILDING SERVICES IN LIFE CYCLE ASSESSMENTS

Only two of the LCA tools that were explored as part of this study include building services in their scope.

LCA tool investigated that includes building services in scope

- OneClickLCA, a BIM based LCA calculation tool
- GabiDatabase an LCA advanced calculation

LCA tool investigated that does not includes building services in scope

- H\BERT
- Impact Estimator or Athena
- Tally
- Equer

The reasons why most LCA tools do not include building services are outlined below:

Lack of data: Even OneClickLCA which has the largest available database in the world has very little EPDs on this subject, compared with construction materials.

Difficult to scale: Many systems do not line up linearly, making accurate upscaling very challenging. For example, a 50-floor lift is not the same as a 10-floor lift multiplied by 5.

Not included in rating systems: Few rating systems currently require building services to be included in the LCA scope, meaning there are few incentives. However, BREEAM UK Mat 01 2018 (12) requires building services to be included within the scope of the LCA.

10.3 A SUMMARY OF ONECLICKLCA

The methodology, availability of data and assumptions of OneClickLCA (24) were investigated as they include building services in their scope.

Table 18: OneClickLCA

How building services are broken down	Scope of products available
Electricity cabling	• Electrification components and systems - 330 products
Heating system	• Heating, ventilation, and air conditioning (HVAC) components and systems -176 products
Solar heat exchanger system	
Sprinkler system	
Pipes-system, hot and cold-water supply	• Plumbing and pipes – 158 products
Ventilation system	• Ventilation System – unknown number of data

OneClick LCA has an inbuilt compensation methodology if a product is not available in the database.

- **Option 1: Using similar resources and scaling.** When the building services product of the system is available, but the correct size and capacity is not available
- **Option 2: Building services based on building area**. Generic products of components that can be applied on a per m^2 floor area such as cabling and pipes. This is useful for early stage analysis.
- **Option 3: Estimate by weight of material type.** If data is not available in the database and there are also no relevant alternatives and generic resources. The system environmental profile can be created based on its material composition and weight.

11 APPENDIX E- REFRIGERENT EMISSIONS

Chiller and heat pumps utilise the refrigeration cycle (vapour compression cycle) to extract heat or coolth. Integral to this process is a refrigerant, a suitable fluid which evaporates and condenses at suitable temperatures required. Refrigerant leakage occurs at various stages in the product life cycle, this includes; manufacture of equipment, annual leakage and leakage through decommissioning.

Addressing refrigerant emissions is considered significant to global warming and reducing the impacts of climate change and is addressed in the Montreal Protocol. In the majority of refrigerants, 72%, fluorinated gases (F-gases) are used for refrigeration, air conditioning and heating (28).

Refrigerant leakage occurs at the manufacturing stage of the HVAC equipment, continuously in operation and at end of life when the product is decommissioned. Refrigerant must be topped up annually due to leakage. This is important because if a heat pump does not have the required levels of refrigerant, this reduces the COP of the heat pump thus increasing carbon emissions in operation.

Historically refrigerant have a high Global Warming Potential (GWP);

- Chlorofluorocarbons (CFCs) were used, but these were banned in 1996 as they had high ozone depleting potential (ODP) e.g. R12 with a GWP of 10,900
- Hydrochlorofluorocarbons(HCFC's) were then introduced as they had no ODP, however they had very high GWP and were banned in 2000 eg R22
- Hydrofluorocarbons (HFC) - are currently being used but are being phased out e.g. R410a, R407c R134a
- Hydrofluoroolefins (HRO) are now being introduced (these get broken down by sunlight) e.g. r1234ze, r600a

The GWP of refrigerants that are currently used in heat pumps varies widely, R410a is commonly used and has a GWP of 2088. Under EU legislation from 2022 refrigerants with a GWP of over 150 will be banned in new HVAC equipment.

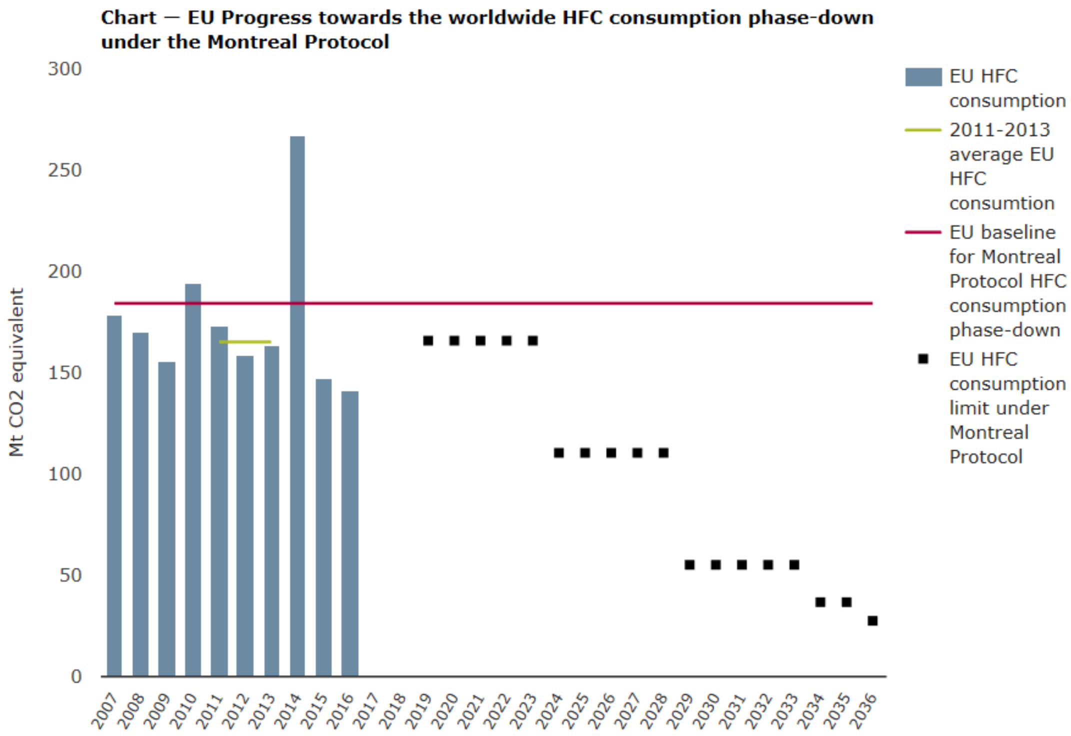
11.1 POLICIES THAT ARE IN PLACE TO REDUCE REFRIGERANT EMISSIONS

The European F-gas regulation that came into force in 2015 aims to reduce refrigeration emissions in Europe and is aligned with the Montreal Protocol; .

Figure 32 shows future projections for the HFC consumption. The regulation limits the total amount of the most important F-gases that can be sold in the EU from 2015 onwards and phasing down in steps to one-fifth of 2014 sales in 2030. It bans the use of F-gases in many new types of equipment and it prevents emissions of F-gases from existing equipment by requiring checks, proper servicing and recovery of the gases at the end of the equipment's life (29). As part of this regulation from 2022 only refrigerants with a GWP of 150 or lower will be allowed in new HVAC equipment.

The Kigali Amendment (to the Montreal Protocol) which will phase down HFCs across the world came into force on 1st January 2019. It's a global version of the European F-gas regulation and assigns refrigerant manufacturers a quota of GWP that reduces over time.

Figure 32: EU progress towards HFC consumption phase down



Source: Emissions and supply of fluorinated greenhouse gases (28)

11.2 REFRIGERENT LEAKAGE THAT OCCURS IN HVAC EQUIPMENT

Refrigerant leakage occurs at the manufacturing stage of the HVAC plant, continuously in operation and at end of life when the product is decommissioned. There is a wide range of estimates when it comes to refrigeration leakage. This section will explore the published data available and outline assumptions used in this study.

11.2.1 Refrigerant leakage – Annual leakage and end of life recovery rates

Table 19 outlines refrigerant leakage found in various global refrigerant leakage studies.

Table 19: Refrigerant leakage from various published studies

Reference	Type of plant	Annual leak rate		End of life recovery rate	date of paper
TM56 Resource efficiency of building services (16)	Air-cooled chiller	Lower	1%	90%	2014
		Upper	5%	70%	2014
	Water-cooled chiller	Lower	1%	90%	2014
		Upper	5%	80%	2014
	Rooftop	Lower	1%	70%	2014
		Upper	5%	80%	2014
	Split system	Lower	2%	90%	2014
		Upper	8%	50%	2014
	VRF system	Lower	1%	90%	2014
		Upper	10%	80%	2014
Methods of calculating Total Equivalent Warming Impact (30)	Chillers	Lower	5%	70%-95%	2012
		Typical	7%		
		Upper	9%		
	Roof top packaged systems	Lower	4%		
		Typical	5%		
		Upper	9%		
	Split systems (single and multi)	Lower	3%		
		Typical	4%		
		Upper	9%		
BREEAM 2018 (12)	Unitary split	Typical	15%	95%	2018
	Small scale chillers	Typical	10%		
	heat pumps	Typical	6%		
Impacts of Leakage from Refrigerants in Heat Pumps (31)	heat pumps	Lower	n/a	85%	
		Typical	3.80%	80%	2014
		Upper	n/a	75%	
Cold Hard Facts 3 (32)	Small AC :sealed-	Theoretical leak rate	2.5%	85% (95% set as the max technical recovery rate)	2016
	HW heat pump: domestic-	Service rate	2%		2016
	Small AC: Split:	Theoretical leak rate	3.5%	80% (95% set as the max technical recovery rate)	2016
	Single split: nonducted-	Service rate	2%		2016
	Medium AC	Theoretical leak rate	2.7%	80% (95% set as the	2016

Reference	Type of plant	Annual leak rate		End of life recovery rate	date of paper
	Split system: ducted	Service rate	2%	max technical recovery rate)	2016
	VRV/VRF split system	Service rate	2%		2016
	Multi split	Service rate	2%		2016
	Large AC	Theoretical leak rate	4.5%	85% (95% set as the max. technical recovery rate)	2016
	Large AC <350 kWr	Service rate	4%		2016
	Large AC >350 & <500 kWr	Service rate	4%		2016
March (1991) as cited in BNCR36: Direct Emission of Refrigerant Gases (33)	Heat pumps	Lower	3%		1991
		Upper	10%		
Haydock et al (2003) as cited in BNCR36: Direct Emission of Refrigerant Gases (33)	Heat pumps	Lower	3%		2003
		Upper	5%		
ETSU (1997) as cited in BNCR36: Direct Emission of Refrigerant Gases (33)	Heat pumps	Typical	4%		2007
Evaluation of the leakage rates of 11,000 refrigeration systems in Hungary (34) cited by Schwarz (35)	Stationary refrigeration and air conditioning equipment >3 kg.	Average	10%		2010
Assumptions used by Schwarz (35)	Heat pumps	Typical	3.5%	75%	2011
Guidance from manufacturer A	Heat pumps	Typical	<1%	98%	2018
Guidance from manufacturer B	multi split (VRF)	Typical	2%	99%	2018
Guidance from manufacturer C	Heat pumps	Typical	5%	95%	2018
Guidance from manufacturer D	Multi split (VRF)	Typical	2%	85%	2018

11.3 ASSUMPTIONS ON REFRIGERANT LEAKAGE USED IN THIS STUDY

A low, medium and high refrigerant leakage scenario was used in this study. The refrigerant leakage rates from various papers, outlined in Table 19 were reviews, and leakage rates chosen based on how recent the study was and the sample size. In most studies VRF has a higher leak rate than heat pumps (chillers), (16).

Table 20: Assumptions on refrigerant leakage used in this study

	Scenario	Annual leakage	End of life recovery rate
ASHP	Low	1%	99%
	Med	3.8%	98%
	High	6%	90%
VRF	Low	1%	99%
	Med	6%	90%
	High	10%	85%

11.4 REFRIGERANTS WITH LOW GWP

Refrigerants with a low GWP must be found for HVAC purposes. As well as having low GWP and zero ODP, the refrigerant must have thermodynamic properties matched to the refrigeration application, chemical stability within the refrigeration system, low toxicity and nonflamable status (36). Many low GWP refrigerants are classed in the refrigeration industry as “low-flammability” which means it is difficult to ignite but will burn. This classification is not currently legally recognised. A likely outcome in practice, is that there will be a restriction on the allowable amount of refrigerant that can be used per unit of room volume (as is already the case for hydrocarbon refrigerants) (7).

Another common issue with low GWP refrigerants is that a larger volume of refrigerant is required for the same capacity of heating than with a traditional refrigerant. For example R1234yf required more than twice the volume of R410a to provide the same heating capacity (36). A consequence of this is that a larger compressor is needed, increasing the volume of material required to produce the heat pumps, and requiring a major re-design of the heat pump by the manufacturer.

Table 21: Low Global Warming Potential refrigerants

Refrigerant type	GWP	Issues
CO_2	1	- asphyxiation
R1234ze /*R1234yf*	6 - R1234ze 4 - R1234yf	- Hailed as a replacement for R134a - Approximately 20% less refrigeration capacity compared with R134a but with significantly lower pressures - Non-flammable under ADR, however is classified as A2L under ASHRAE classification (37.)
Ammonia	0	- Toxicity
Butane (r600a)	3	

Other considerations using refrigerants with a low GWP

- Most low GWP refrigerants are toxic thus require refrigerant leak detection
- The pressures needed are quite high, thus the low GWP refrigerants have higher leakage
- The COP is typically lower with refrigerants that have lower GWP. This means that the heat-generation equipment needs to be larger (thus more embodied energy) and they will require more operational energy

11.5 REFRIGERANT GWP REDUCTIONS OVER TIME

The Department of Energy and Climate change study into the Impacts from leakage in refrigerants, forecast the refrigerant market share over the next 30 years, see Figure 33.

Figure 33: Future refrigerant mix forecast

Refrigerant Market Share	2005/06	2010/11	2015/16	2020/21	2030/31	2050/51
404A	4%	2%	0%	0%	0%	0%
407C	44%	30%	20%	10%	0%	0%
410A	50%	66%	75%	50%	15%	0%
134a	2%	2%	0%	0%	0%	0%
HCs	0%	0%	2%	16%	43%	50%
CO_2	0%	0%	0%	4%	13%	25%
HFOs	0%	0%	3%	20%	30%	25%

Table 22: Central Assumption for Refrigerant Mix to 2050

Source:Impacts of leakage from refrigerents (31)

11.6 ASSUMPTIONS ON GWP OF REFRIGERANTS USED IN THIS STUDY

Table 22 shows the assumptions on GWP that were chosen for this study.

Table 22: GWP assumptions used in this study

	Scenario	GWP
GWP	Low	1
	Med	150
	High	2088

12 APPENDIX F- SENSITIVITY ANALYSIS

Sensitivity analysis was carried out to understand the effect of certain assumptions on the conclusions of this study. To carry out the sensitivity analysis, the medium scenario for each heat generation equipment was tested. See Table 23-26 for results.

Table 23: Sensitivity of WLC to lifespan of equipment

		Half the consumption used in the study	Assumption used in study	Twice the consumption used in the study
		10 years	20 years	40 years
WLC kgCO2e/ year	Boiler	14,144	14,081	14,050
	CHP	21,918	21,593	21,430
	ASHP	2,948	2,793	2,716
	VRF	2,314	2,192	2,132
Embodied Carbon as a proportion of WLC	Boiler	0.89%	0.45%	0.22%
	CHP	2.97%	1.51%	0.76%
	ASHP	17.08%	12.48%	9.99%
	VRF	29.58%	25.67%	23.55%
% reduction in WLC of a ASHP compared to a Boiler		79%	80%	81%
% reduction in WLC of a VRF compared to a Boiler		84%	84%	85%
% reduction in WLC of a ASHP compared to a CHP		87%	87%	87%
% reduction in WLC of a VRF compared to a CHP		89%	90%	90%
% reduction in WLC of a CHP compared to a Boiler		-55%	-53%	-53%

Table 24: Sensitivity of WLC to energy consumption of the fabrication factory

	Lowest figure from manufacturers	Average figure from manufacturers- (Assumption used in study)	Highest figure from manufacturers	Percentage difference in WLC
	WLC kgCO2e			
Boiler	281,580	281,628	281,695	0.04%
CHP	431,806	431,855	431,923	0.03%
ASHP	55,812	55,861	55,930	0.21%
VRF	43,800	43,848	43,918	0.27%

Table 25: Sensitivity of WLC to % material wasted in manufacture

	Half the assumption used in the study	Assumption used in the study	Ten times the assumption used in the study	Percentage difference in WLC
	0.5% by material weight	1% by material weight	10% by material weight	
	WLC kgCO2e			
Boiler	281,623	281,628	281,718	0.03%
CHP	431,828	431,855	432,338	0.12%
ASHP	55,849	55,861	56,079	0.41%
VRF	43,840	43,848	43,995	0.35%

Table 26: Sensitivity of WLC to emissions related to transport

	Half the assumption used in the study	Assumption used in the study	Twice the assumption used in the study	Percentage difference in WLC
	WLC kgCO2e			
Boiler	281,613	281,628	281,660	0.02%
CHP	431,673	431,855	432,217	0.13%
ASHP	55,784	55,861	56,015	0.41%
VRF	43,793	43,848	43,959	0.38%

13 APPENDIX G- EMBOIDED CARBON IN BUILDING SERVICES

Various papers were reviewed to understand the proportion of embodied carbon that relates to building services. A summary of the data is outlined in Figure 34 and Table 27.

Figure 34: Percentage of embodied carbon associated with Building Services

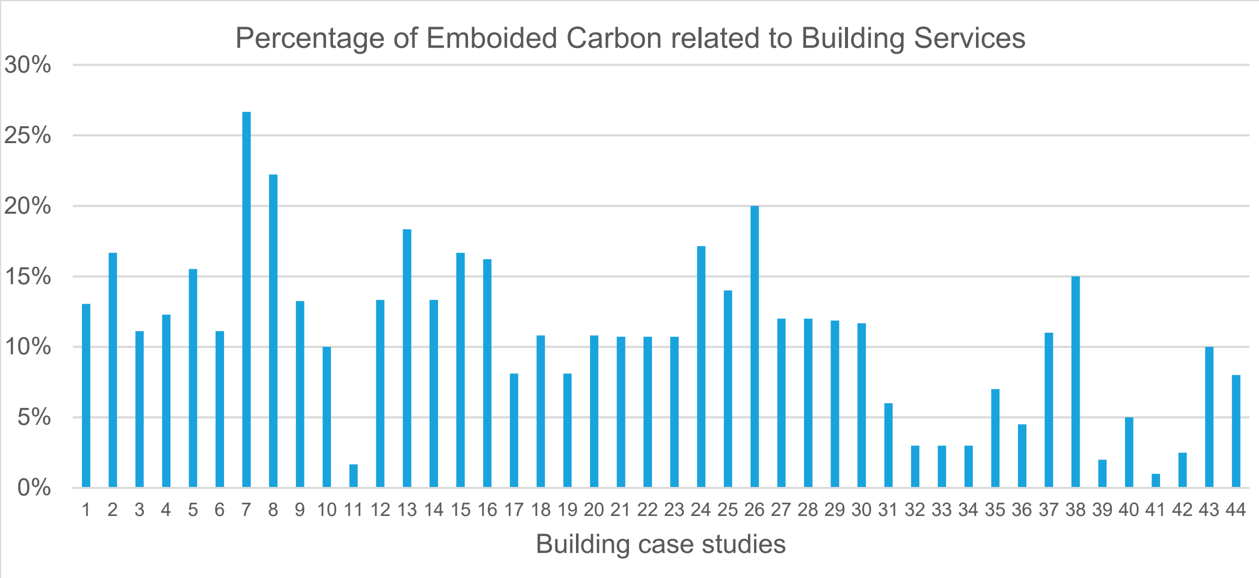


Table 27: Percentage of embodied carbon associated with Building Services

Example	Reference	Percentage
1	Summary of embodied carbon studies for new office building by Davis Langdon referenced in (38)	13%
2		17%
3		11%
4		12%
5		16%
6		11%
7		27%
8		22%
9		13%
10		10%
11		2%
12		13%
13		18%
14		13%
15		17%
16		16%
17		8%
18		11%
19		8%
20		11%
21		11%
22		11%
23		11%
24		17%
25		14%
26		20%
27		12%
28		12%
29		12%
30		12%
31	Case Study for an office without air conditioning (39)	6%
32	Analysis of three low rise, naturally ventilated, heated-only offices in South West England (40)	3%
33	Analysis of three low rise, naturally ventilated, heated-only offices in South West England (40)	3%
34	Analysis of three low rise, naturally ventilated, heated-only offices in South West England (40)	3%
35	Office building (21)	7%
36	Ropemaker place by Sturgis / British Land referenced in (41)	5%
37	One kingdom street adapted from Target Zero / dcarbon8 referenced in (41)	11%
38	One kingdom street adapted from Target Zero / dcarbon8 referenced in (41)	15%

Example	Reference	Percentage
39	Embodied carbon studies from Sustainable Concrete Architecture adapted from Bennett referenced in (41)	2%
40	Embodied carbon studies from Sustainable Concrete Architecture adapted from Bennett referenced in (41)	5%
41	Embodied carbon results by Eaton & Amoto referenced in (41)	1%
42	Embodied carbon results by Eaton & Amoto referenced in (41)	3%
43	WRAP MEDIUM RISE OFFICE STUDY (41)	10%
44	Farringdon Station redevelopment Embodied carbon results by Hammond and Jones referenced in (41)	8%
	Minimum	1.00%
	Maximum	26.67%
	Mean	10.93%
	Median	11.06%