LCA for Low Carbon Construction

Life Cycle Assessment of Mechanical, Electrical, and Plumbing in Commercial Office Buildings

Final Report

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The University of Washington team was comprised of principal investigator Kathrina Simonen, and Co-PI Hyun Woo Lee and graduate research assistant Barbara X. Rodriguez, with key contributions from Monica Huang.

The participation of the Industry Advisory Committee was key to the success of this project. Mechanical and electrical engineers from the Pacific Northwest assisted in defining the systems and establishing the material quantity estimates. For the mechanical and plumbing systems, Ken Dickman, PE with Hermanson Company provided the leading input that enabled the launch of the project and their contribution is greatly appreciated. Additional input was provided by Michael Hedrick, PE, Senior Engineer with McKinstry Facility Services, and Amy Euting, Pre-Construction Manager with Holaday-Parks, INC. For the electrical systems, Chad J. Saxton, Project Manager with Prime Electric provided the leading input, and additional input was provided by Brice Cobean, Project Manager with Valley Electric and Matt Mayer, Chief Estimator from Holmes electric. The UW Research Team assembled the data and (published and unpublished) LCA study results. The Advisory Committee provided invaluable feedback and suggestions and their contributions have provided key insights into the project.

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PARTICIPATION

Advisory Committee

Engineers/Contractors

- Ken Dickman, PE, Hermanson Company
- Michael Hedrick, PE, Senior Engineer McKinstry Facility Services
- Amy Euting, Pre-Construction Manager, Holaday-Parks, INC.
- Chad J. Saxton, Project Manager, Prime Electric
- Brice Cobean, Project Manager, Valley Electric
- Matt Mayer, Chief Estimator, Holmes electric

Research Team/Technical Review

- Jordan Palmeri, Oregon DEQ
- Peter, Canepa, Oregon DEQ
- Kathrina Simonen, UW PI
- Hyun Woo Lee, UW Co-PI
- Barbara Rodriguez Droguett, UW

Materials Quantities Datasets

- Hermanson
- McKinstry
- Holaday-Parks
- Prime Electric
- Valley Electric
- Holmes Electric

Contributions of LCA impact data

- ÖKOBAUDAT (current release 2017-I as of November 27, 2017)
- Quartz Database
- UL Environment EPD Program
- International EPD Program
- IBU EPD Program
- PEP Ecopassport

Published Studies

- CIBSE (2014) Shock & Ore report: The impact of building services on the environment

EXECUTIVE SUMMARY

As an extension of the Life Cycle Assessment (LCA) for Low Carbon Construction project funded in 2016, the objective of this project is to provide estimates of ranges of material quantities consumed and LCA impacts due to mechanical, electrical and plumbing (MEP) systems and interior tenant improvement (TI) fit out (walls, ceilings, lights, finishes and furnishings) for typical commercial office buildings in the Pacific Northwest (PNW).

The Life Cycle Assessment for Low Carbon Construction project had the primary goal to provide guidance to industry professionals looking to integrate carbon into life cycle-based decision making through the establishment of embodied carbon benchmarks of buildings and the creation of an environmental LCA practice guide. The Embodied Carbon Benchmark (ECB) Study identified (1) that the lack of data for MEP and interior TI fit out (L6 and L7 of ECB Report) is a critical source of uncertainty in our understanding of the total embodied carbon in buildings, and (2) that the value of understanding these impacts in particular is high as these components are often the majority of impacts related to building re-use and renovation. This project was selected by Oregon Department of Environmental Quality (ODEQ) for funding based on a refined internal Research Opportunity report V3 dated July 2017.

The research plan for this project followed a four-step approach. The first stage was defined as a 'Characterization Stage', where in conjunction with the Advisory Committee the research team identified representative office buildings and typical MEP systems, including a list of materials and equipment. During the second stage 'Estimation of Material Quantities', the research team quantified unit material quantities for each system type. In the third stage called 'LCA impact data', the research team compiled LCA impacts (cradle-to gate LCA Stage A1-3) from different data sources such as EPD and open databases. The impact data was compiled into a spreadsheet and recorded for Global Warming Potential (GWP), Ozone Depletion Potential (ODP), Acidification Potential (AP), Eutrophication Potential (EP), and Smog Formation Potential (SFP). Finally, in the fourth stage, an open source database was developed as a matrix model to calculate LCA impacts of MEP systems. These results are published as an Excel file to enable others to use this data in their own work. The research team identified four main findings and limitations, which are detailed below:

Finding A: The data presented in the MEP database represent a reasonable order of magnitude and range of variation of estimates of the embodied carbon footprint of MEP in office buildings.

Finding B: LCA data for MEP systems and typical material and equipment types are most commonly available in the forms of open databases, followed by EPDs from European EPD Programs.

Finding C: The total material quantity for MEP of typical commercial office buildings in the PNW ranges are:

Building type	Building model	Electrical (kg/m^2)	Mechanical (kg/m^2)	Plumbing (kg/m^2)	Total Range (kg/m^2)
Standard	Large Standard	3.7	10.0-13.1	2.4	16.1 - 19.1
	Medium Standard	2.5	11.9- 13.8	2.4	16.8- 18.7
	Small Standard	5.8	9.8-11.5	2.7	18.2 – 19.9
	XSmall Standard	1.6	10.3 - 12.8	2.6	14.6 – 17.1
High performance	Large HP	2.5	14.5 -17.9	2.4	19.3 - 22.7
	Medium HP	2.5	12.1- 17.6	2.4	17.1 - 22.6
	Small HP	6.1	12.6- 11.5	2.7	21.4- 20.2
	XSmall HP	5.4	13.2- 13.8	2.6	21.2 - 21.8

XSmall 186-2323 (m^2); Small 929-7432 (m^2); Medium 1858-27871 (m^2); Large 11148-74322 (m^2).

Finding D: The total GWP for MEP systems (excluding refrigerants) of typical commercial office buildings in the PNW ranges are:

Building type	Building model	Electrical ($kgCO_2eq/m^2$)	Mechanical ($kg\ CO_2eq/m^2$)	Plumbing ($kgCO_2eq/m^2$)	Total Range ($kgCO_2eq/m^2$)
Standard	Large Standard	7.1	35.6	6.2	48.9
	Medium Standard	11.7	43.2-48.2	6.4	61.3-66.3
	Small Standard	6.3	27.8-44	7.1	41.2- 57.4
	XSmall Standard	4.6	29.5-35.4	7.2	41.3-47.2
High performance	Large HP	8.6	56.6-60.0	6.2	71.4-74.8
	Medium HP	8.8-9.0	39.8-53.5	6.4	55.1-74.6
	Small HP	15.9	35.8-42.1	7.1	58.9-65.1
	XSmall HP	13.3	45.4-46.4	7.2	65.9-67.0

XSmall 186-2323 (m^2); Small 929-7432 (m^2); Medium 1858-27871 (m^2); Large 11148-74322 (m^2).

Finding E: Refrigerants account for a significant contribution to the total GWP of HVAC system throughout the full life cycle as hydrofluorocarbons (HFCs) have GWP one to nine thousand times greater than that of carbon dioxide. For instance, in this study the original data provided from one of the contractors indicated a refrigerant charge of 0.01 lb/sqft (0.05 kg/sqm) for all types of HVAC systems. According to identified literature there is a 40% loss of refrigerant, equivalent to 0.02 kg/sqm of the original refrigerant charge. If the refrigerant used is R-410 (GWP=1,890 KgCO2e per kg of refrigerant) the total GWP of this 40% loss would be equivalent to 37.8 kgCO2e/sqm across the lifetime of the equipment (15 years in average).

The primary limitations of the above findings are**:**

(1) The available LCA data for MEP systems is scarce, and comes from different geographical regions therefore these may not be representative of North American production making the comparability questionable.

(2) The scope of electrical equipment and materials is limited in this study due to the difficulties to standardize electrical projects. As noted in Figure 1, the list proposed by contractors only include 7 out of 22 items typically described for an electrical project.

(3) The analysis methods and background data used to perform the LCA of the equipment in existing EPDs and LCA reports were not aligned, making it difficult to aggregate between sources.

(4) Only LCA data impacts for product Stage A (A1-A2-A3) known as 'cradle to gate' are considered in this study. Impacts of use, maintenance, and end of life are not considered in this study. The study does include different lifespans of equipment and potential replacement rates.

(5) The database is not a statistically representative sample of current building practices. The research team, in consultation with the Advisory Committee, identified sources of uncertainty and strategies to overcome the uncertainty in estimating the embodied carbon of MEP in buildings.

ABBREVIATIONS

AC	Air conditioning
AHRI	Air Conditioning, Heating, and Refrigeration Institute
AHU	Air handling unit
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
CO_2eq	Carbon dioxide equivalent
DOE	Department of Energy
DOAS	Dedicated outdoor air system
EPD	Environmental Product Declaration
ERV	Energy recovery ventilator
GHG	Greenhouse gas
GWP	Global warming potential
HCFC	Hydrochlorofluorocarbon
HVAC	Heating ventilation air conditioning
HPB	High Performance Building
LCA	Life cycle assessment
LCGWP	Life cycle global warming potential
LCODP	Life cycle ozone depletion potential
QTO	Quantity take offs
MEP	Mechanical, electrical and plumbing
OEESC	Oregon Energy Efficiency Specialty Code
ODP	Ozone depletion potential
PTAC	Packaged Terminal Air Conditioner
PTHP	Packaged Terminal Heat Pump
PFP	Parallel fan powered terminal
kWh	Kilowatt-hour
kW_{th}	Kilowatt (refrigeration capacity=
RTU	Rooftop Unit
SPB	Standard Performance Building
VAV	Variable air volume
VRF	Variable refrigerant flow
WBLCA	Whole building life cycle assessment
WSEC	Washington State Energy Code
WSHP	Water source heat pump

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1 PROJECT OVERVIEW

As an extension of the LCA for Low Carbon Construction project funded in 2016, the objective of this project is to provide estimates of the range of material quantities consumed and LCA impacts due to mechanical, electrical and plumbing (MEP) systems and interior tenant improvement (TI) fit out (walls, ceilings, lights, finishes and furnishings) for typical commercial office buildings in the Pacific Northwest.

The LCA for Low Carbon Construction project had the primary goal to provide guidance to industry professionals looking to integrate carbon into life cycle based decision making through the creation of an environmental LCA practice guide and establishment of embodied carbon benchmarks of buildings. The LCA Practice Guide is used to identify and develop future research projects and resource needs of value to the building industry as we look to integrate embodied carbon into life cycle decision-making.

The Embodied Carbon Benchmark (ECB) Study identified the lack of data for MEP and interior TI fit out (L6 and L7 of ECB Report) as critical sources of uncertainty in our understanding of the total embodied carbon in buildings and identified the value of understanding these impacts in particular as these components are often the majority of impacts related to building re-use and renovation. These projects were selected by Oregon Department of Environmental Quality for funding based on a refined internal Research Opportunity report V3 dated July 2017.

The main objective of this project is to establish reasonable estimates of typical ranges of material quantities consumed and life cycle assessment impacts due to MEP systems and interior TI fit out for typical commercial office buildings in the PNW and characterize the level and sources of uncertainty in our current knowledge. The project identifies pathways and strategies to reduce uncertainties, which will enable the development of more representative material quantities and environmental impacts of MEP systems in the future.

The project brings together MEP experts to identify typical MEP systems in commercial office buildings and their criteria related to estimating material quantities. The Embodied Carbon Benchmark project has five components:

1. Convene advisory committee,
2. Develop systems template,
3. Compile and analyze data,
4. Identify sources of uncertainty, and
5. Document and disseminate results.

2 GENERAL INFORMATION ON THE ASSESSMENT

This report presents an environmental performance assessment of typical MEP systems in sixteen hypothetical commercial office buildings: eight standard buildings in Oregon State, and eight high performance buildings in Washington State.

2.1 Purpose of the assessment

The objective of this project is to provide estimates of the range of material quantities consumed and LCA impacts due to mechanical, electrical and plumbing (MEP) systems.

This report will be used as a technical reference in the building industry and for educational purposes. The intended audience is primarily industry professionals, and academics interested in life cycle assessment.

2.2 Identification of the building models

For this study the research team in conjunction with the advisory committee proposed sixteen hypothetical buildings in order to describe typical MEP systems used in the PNW. The base building that serves as the model for all building categories, is a typical new commercial office (Core &Shell), including large floorplates, open spaces, high ceilings with ample glazing to provide natural light and flexible collaborative spaces. This base building is described for the four building size categories for both standard and high-performance buildings, giving a total of eight independent building models. For each one of the eight building models two typical HVAC systems are described, describing a total of sixteen HVAC systems used as case studies.

2.3 General Information on the object of assessment

2.3.1 Functional equivalent

In the context of LCA, a functional equivalent is defined per EN 15978 as "the quantified functional requirements and/or technical requirements for a building or an assembled system (part of works) for use as a basis for comparison"(CEN 2011). This study uses a declared unit defined for this study are defined as one square meter of commercial office building.

2.3.3 Object of assessment scope

The object of assessment scope is the MEP systems including only the equipment and materials within the building site. The scope of the building MEP systems assessed includes only their equipment and materials considered relevant and described by the Advisory Committee. The scope of equipment for each type of system is described in Figure 1 and detailed as follows:

For HVAC the scope of equipment and materials assessed includes only main equipment units, main ducting material, insulation and refrigerants. The scope does not include supplementary equipment such as fittings and hangers. For electrical, supplementary equipment such as fittings and hangers are out of the assessment scope, while the scope of equipment and materials assessed includes only main service; entrance; backup; general lighting; distribution wires; metering; and systems. Electrical service and distribution supplementary components are excluded from the calculations. For plumbing, the scope of equipment and materials assessed includes only water and waste systems. Fixtures and fittings are excluded from the calculations.

Figure 1: Service Omniclass Categories included in the scope of study

Level 2 Title	**Level 3 Title**	**Level 4 Title**	**Included Y/N**
Conveying (OmniClass 21-04 10)			N
Plumbing (OmniClass 21-04 20)	Domestic Water Distribution (21-04 20 10)	Facility Potable-Water Storage Tanks	N
		Domestic Water Equipment	N
		Domestic Water Piping	Y
		Plumbing Fixtures	N
		Domestic Water Distribution Supplementary Components	N
	Sanitary Drainage (21-04 20 20)	Sanitary Sewerage Equipment	N
		Sanitary Sewerage Piping	Y
		Sanitary Drainage Supplementary Components	N
	Building Support Plumbing Systems (21-04 20 30)		N
	General Service Compressed-Air (21-04 20 50)		N
	Process Support Plumbing Systems (21-04 20 60)		N
Heating, Ventilation, and Air Conditioning (OmniClass 21-04 30)	Facility Fuel Systems (21-04 30 10)		N
	Heating Systems (21-04 30 20)	Heat Generation	Y
		Thermal Heat Storage	N
		Decentralized Heating Equipment	Y
		Heating System Supplementary Components	N
	Cooling Systems (21-04 30 30)	Central Cooling	Y
		Evaporative Air-Cooling	Y
		Thermal Cooling Storage	N
		Decentralized Cooling	Y
		Cooling System Supplementary Components	N
	Facility HVAC Distribution Systems (21-04 30 50)	Facility Hydronic Distribution	N
		Facility Steam Distribution	N
		HVAC Air Distribution	Y
		Facility Distribution Systems Supplementary Components	N
	Ventilation (21-04 30 60)	Supply Air	Y
		Return Air	Y
		Exhaust Air	Y
		Outside Air	Y
		Air-to-Air Energy Recovery	Y

		HVAC Air Cleaning	N
		Ventilation Supplementary Components	N
Fire Protection (21-04 40)			N
Electrical (21-04 50)	Facility Power Generation (21-04 50 10)	Packaged Generator Assemblies	Y
		Battery Equipment	Y
		Photovoltaic Collectors	N
		Fuel Cells	N
		Power Filtering and Conditioning	N
		Transfer Switches	N
		Facility Power Generation Supplementary Components	N
	Electrical Service and Distribution (21-04 50 20)	Electrical Service	Y
		Power Distribution	Y
		Facility Grounding	N
		Electrical Service and Distribution Supplementary Components	N
	General Purpose Electrical Power (21-04 50 30)	Branch Wiring System	N
		Wiring Devices	Y
		General Purpose Electrical Power Supplementary Components	N
	Lighting (21-04 50 40)	Lighting Control	Y
		Branch Wiring for Lighting	N
		Lighting Fixtures	Y
		Lighting Supplementary Components	N
	Miscellaneous Electrical Systems (21-04 50 80)	Lightning Protection	N
		Cathodic Protection	N
		Transient Voltage Suppression	N
		Miscellaneous Electrical Systems Supplementary Components	N
Communications (21-04 60)			N
Electronic Safety and Security (21-04 70)			N
Integrated Automation (21-04 80)			N

2.4 System boundaries

The system boundary of the building life cycle in this study includes only product stage (A1, A2, A3) and is described according to the format established in EN 15978 (Fig.2), providing a structured reporting format that is consistent with the LCA data in EPD and open databases.

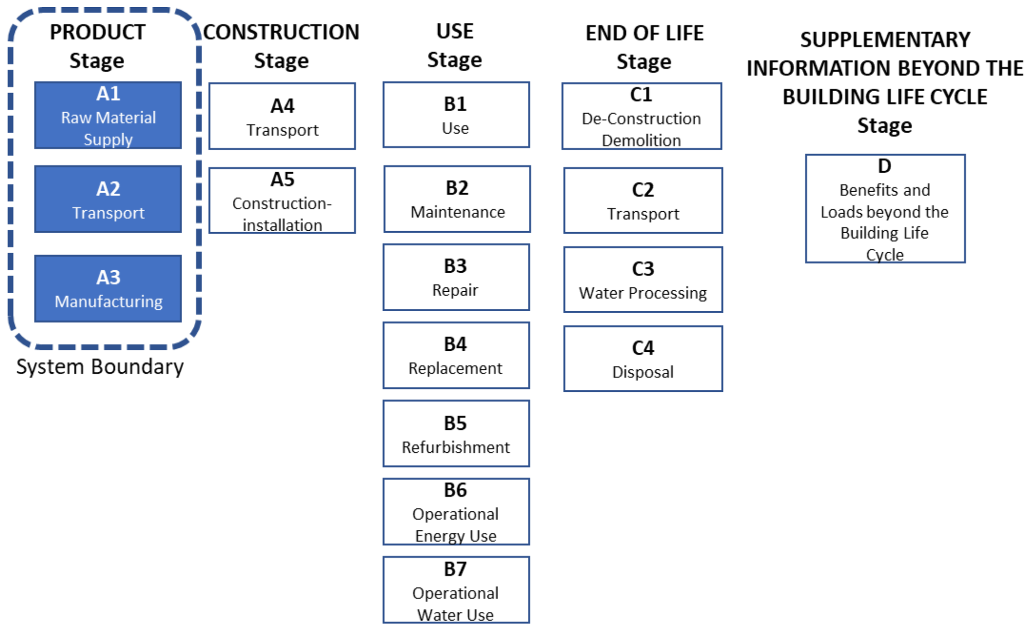


Figure 2: System Boundaries (in blue) according to the stages described in EN15978 (CEN 2011)

3 METHODOLOGY

The research plan for the MEP followed a four-step approach. The first stage was defined as "Characterization Stage", where in conjunction with the Advisory Committee we identified representative office buildings and typical MEP systems, including a list of materials and equipment for each type of system. During the second stage "Estimation of Material Quantities", we quantified unit material quantities for each system type. In the third stage called "LCA Impact Data", we compiled LCA impacts from different data sources such as EPDs, LCA peer reviewed articles and reports, and open databases. The impact data was compiled into a spreadsheet and recorded for Global Warming Potential (GWP), Ozone Depletion Potential (ODP), Acidification Potential (AP), Eutrophication Potential (EP), and Smog Formation Potential (SFP). Finally, in the fourth stage, we developed an open source database as a matrix model to calculate LCA impacts of MEP systems. The results of this study are published online (http://www.carbonleadershipforum.org/)

3.1 Substage 1: Characterization of Hypothetical buildings

a. Research team proposes representative buildings in terms of size.
b. Industry Advisory Committee helps refine representative buildings.

3.2 Substage 2: Estimation of material quantities

a. Building System:
    i. Material quantity estimates determined through direct input from the Advisory Committee.
b. Material Types and Equipment
    ii. Estimate material breakdown and weights by help of the Advisory Committee. Recognize uncertainty in this data. Perform sensitivity analysis.
c. Add the material and equipment quantity estimations using a Finite Aggregation Model.

3.3 Substage 3: Compilation of LCA data

2. Global Warming Potential (GWP), Ozone Depletion Potential (ODP), Acidification Potential (AP), Eutrophication Potential (EP), Smog Formation Potential (SFP): Source data in the following order of priority:
    a. EPDs (local)
    b. EPDs (global)
    c. Open Database: i.e. Quartz database (Thinkstep North America data)
    d. Other sources

   Life span assumptions for components will be taken from industry standard documentation such as the Building Owners and Managers Association International (BOMA) database (Schoen 2010) combined with input from the advisory committee.

3.4 Substage 4: Database Development

e. Publish all QTO data as open source.
f. Develop a matrix model to calculate LCA impacts and publish an Excel file to enable others to update LCA impacts as desired.
g. Summarize data in context of recently completed whole building LCA study of structure and enclosure.

The project scope is limited to evaluating hypothetical buildings by working with an industry advisory committee to assist in defining the systems and establishing material quantity estimates. The data in this study is limited to the material quantity data provided by contractors available to work on this research within the time limitations of the research project (January to June 2018). The data comes from different estimation methods and depends largely on each firm's experience and historical project data.

4 RESULTS

The results of this study are presented and discussed in four sections according to the four methodological steps. First, background information on the building model and typical MEP systems selection is provided. Second, an analysis of the material quantities for each type of MEP system is presented. Third, a brief description of the LCA data from the literature is provided. Finally, an analysis of the total GWP impact for MEP system per building size category is presented.

4.1 Substage 1: Characterization of buildings and MEP systems

The Advisory Committee was convened through personal invitations to well known MEP contractor companies in the PNW. Once the advisory committee was established, the first step was to propose several hypothetical building models that would represent typical commercial office buildings in the PNW. Based on these hypothetical buildings, the advisory committee proposed a series of typical MEP systems and finally listed typical equipment and material types for each system. During this process, the Advisory Committee agreed on the following topics:

1) MEP and HVAC systems design depends largely on state and city local codes. Within the Pacific Northwest, the current 2015 Washington State Energy Code (WSEC) (Washington State 2015) is more stringent than the 2014 Oregon Energy Efficiency Specialty Code (OEESC)(Oregon State 2014). According to the U.S. Department of Energy (DOE) Building Energy Codes Program[1], the OEESC is equivalent to ASHRAE 90.1-2010[2] standard (ASHRAE 2018) while the WSEC is more efficient than ASHRAE 90.1-2013. Therefore, for the purpose of this study, a "Standard Performance Building" (SPB) is defined as a building designed under the Oregon code, while a "High Performance Building " (HPB) building is defined as a building design under the Washington code. It is worth noting, that the 2015 Seattle Energy Code, one of the strictest energy codes nationwide (even more stringent than the WSEC 2015), came into full effect on Jan. 1, 2018 (Seattle Department of Construction and Inspections 2015).

[1] The U.S. Department of Energy (DOE) Building Energy Codes Program reviews adoption of energy codes for residential and commercial buildings. State adoption is reviewed based on the national model energy codes–the International Energy Conservation Code (IECC) for residential buildings and Standard 90.1 for commercial buildings (42 USC 6833) (U.S. DOE 2018).

[2] Standard 90.1 has been a benchmark for commercial building energy codes in the United States and a key basis for codes and standards around the world for more than 35 years. This standard provides the minimum requirements for energy-efficient design of most buildings, except low-rise residential buildings (ASHRAE 2018).

However, for the purpose of this study, High Performance and Standard Performance building categories are defined based on state codes.

2) MEP systems design is a multidisciplinary effort dependent on several building variables such as cost, operational efficiency, noise requirements, space distribution, among which building size plays a key role. Building sizes expressed in total area (gross square footage) shape design requirements and determines types of MEP systems, and therefore in this study four building size categories are established to describe typical MEP systems as shown in Table 1. For each one of these size categories, a base building is defined with the professional judgement of the advisory committee. According to the MEP contractors, the number of stories above ground is not considered a key variable in the MEP system choice. Therefore, a total of eight building models are established, resulting from the combination of four building size categories versus both standard and high-performance buildings as shown in Table 1.

3) MEP systems are inherently different and have diverse levels of equipment complexity and material selection. Plumbing is the least complex of the three systems and is defined primarily in the selection of piping material rather than particular equipment as shown in Table 2. Mechanical systems also known as heating, ventilation and air conditioning (HVAC) and electrical systems are much more complex systems with many intricate components. Mechanical systems are diverse and are available in a broad myriad of combinations in the marketplace. For this study only the two most representative HVAC systems are considered for each building size category under the SPB and HPB categories as shown in Table 2.

For the purposes of this study units are expressed according to the international standard system (IS).

Table 1: Typical Plumbing Systems for Commercial Office Buildings (Standard and High Performance

Office Building Size (sqm)	Base Building (sqm)	Building Size Category	Plumbing system for Standard and High Performance	
			System	Material Type
186 - 2323	650	XSmall	Water	Copper
				PEX
			Waste & Vent	Cast Iron
				PVC
929 - 7432	2322	Small	Water	Copper

			Waste & Vent	Cast Iron
				PVC
1858 - 27871	7432	Medium	Water	Copper
				Stainless Steel
			Waste & Vent	Cast Iron
				PVC
11148 - 74322	25155	Large	Water	Copper
				Stainless Steel
			Waste & Vent	Cast Iron
				PVC

4) In Washington State, under the WSEC2015 prescriptive compliance path, all new commercial buildings are required to include Dedicated Outdoor Air Systems (DOAS)[3]. A DOAS is a system where the ventilation is managed independently of the primary heating and cooling system. DOAS optimizes the operational energy efficiency, by separating ventilation from space conditioning, mechanical systems, and it has been included in the most recent energy efficiency standard. Under the WSEC 2015, a DOAS is required for every HVAC system, regardless of its building size as reflected in Table 2. The WSEC 2015 also requires that the DOAS includes either energy recovery ventilation (ERV) that complies with the minimum energy recovery efficiency or energy recovery bypass requirements where applicable. For complete descriptions of each system see Appendix A.

Table 2: Typical HVAC Systems for Commercial Office Buildings (Standard and High Performance)

Office Building Size (sqm)	Base Building (sqm)	Building Size Category	HVAC system (Standard)	HVAC system (High performance)
186 - 2323	650	XSmall	Packaged rooftop heat pump	DOAS ERV + VRF
			Packaged rooftop AC + Furnace	DOAS ERV + Packaged Rooftop Heat Pump

[3] For office, retail, education, libraries and fire stations, outdoor air shall be provided to each occupied space by a dedicated outdoor air system (DOAS) which delivers 100 percent outdoor air without requiring operation of the heating and cooling system fans for ventilation air delivery (Washington State 2015).

929 - 7432	2322	Small	Packaged rooftop heat pump	DOAS ERV + VRF
			VAV AHU w/ PFP Terminals	DOAS ERV + Packaged Rooftop Heat Pump
1858 - 27871	7432	Medium	VAV AHU w/ PFP Terminals	DOAS + VRF
			WSHP	DOAS + WSHP
11148 - 74322	25155	Large	VAV AHU w/ PFP Terminals	DOAS + Chilled Beam
			WSHP	DOAS + WSHP

5) Electrical systems present additional challenges to their classification under "generic" or "typical" categories. The scope of electrical systems has greatly expanded due to the increasing proliferation of electric systems in building applications. For the purpose of this study, building electrical systems are limited to service entrance; backup; lighting; distribution; metering; and systems, as shown in Table 3. In application, this comprehensive list can expand to more than 20 sub-systems. The limited scope for electrical systems is a limitation of this study.

6) Electrical systems are largely dependent on the local code requirement. For instance, the new provisions of the 2015 Seattle Energy Code require more lighting and control system equipment to achieve. Under the prescriptive path of the code, the maximum admissible lighting power densities (LPD), also known as the installed lighting watts per square foot, decreased by 10 percent below the initial levels established per the code. The new minimum acceptable limit cannot easily be achieved by just choosing LED fixtures and requires including more lighting control devices, which in turn increases the cost and material per sf of the building.

Table 3: Typical Electrical Systems for Commercial Office Buildings (Standard and High Performance)

Office Building Size (sqm)	Base Building (sqm)	HVAC system (Standard)		HVAC system (High performance)	
186 - 2323	650	Basic LTG & Power		Commercial LTG/PWR	
		1.-Service entrance	Utility transformer pole	1.-Service entrance	Utility transformer pole
		2.-Backup systems	Battery backup	2.-Backup systems	Battery backup

		3.Lighting	time clock controlled /Fluorescent	3.Lighting	Enhanced lighting controls/ LED Lighting
		4.Distribution	Aluminum feeder	4.Distribution	Copper feeder wire
		5. Metering	Retail meter center	5. Metering	Energy meters for branch circuit
		6. Systems		6. Systems	Data + other LV
929 - 7432	2322	Commercial LTG/PWR		Commercial LTG/PWR	
		1.-Service entrance	Utility transformer pole	1.-Service Entrance	Utility transformer pole
		2.-Backup systems	Battery backup	2.-Backup Systems	Backup generator
		3.Lighting	time clock controlled /Fluorescent	3.Lighting	time clock controlled /Fluorescent
		4.Distribution	800A 480v Distribution	4.Distribution	Aluminum feeder
		5. Metering		5. Metering	Retail meter center
		6. Systems	Data/WAP (Wireless)	6. Systems	
1858 - 27871	7432	Commercial LTG/PWR		Commercial LTG/PWR	
		1.-Service entrance	Utility transformer pole	1.-Service entrance	Utility transformer pole
		2.-Backup systems	Battery backup	2.-Backup Systems	Battery backup
		3.Lighting	time clock controlled /Fluorescent	3.Lighting	time clock controlled /Fluorescent
		4.Distribution	800A 480v Distribution	4.Distribution	800A 480v distribution
		5. Metering		5. Metering	
		6. Systems	Data/WAP (Wireless)	6. Systems	Data/WAP (Wireless)
11148 - 74322	25155	Commercial LTG/PWR		Commercial LTG/PWR	
		1.-Service entrance	Utility transformer pole	1.-Service entrance	Utility transformer pole

		2.-Backup systems	Battery backup	2.-Backup systems	Battery backup
		3.Lighting	time clock controlled /Fluorescent	3.Lighting	time clock controlled /fluorescent
		4.Distribution	800A 480v Distribution	4.Distribution	800A 480v distribution
		5. Metering		5. Metering	
		6. Systems	Data/WAP (Wireless)	6. Systems	Data/WAP (Wireless)

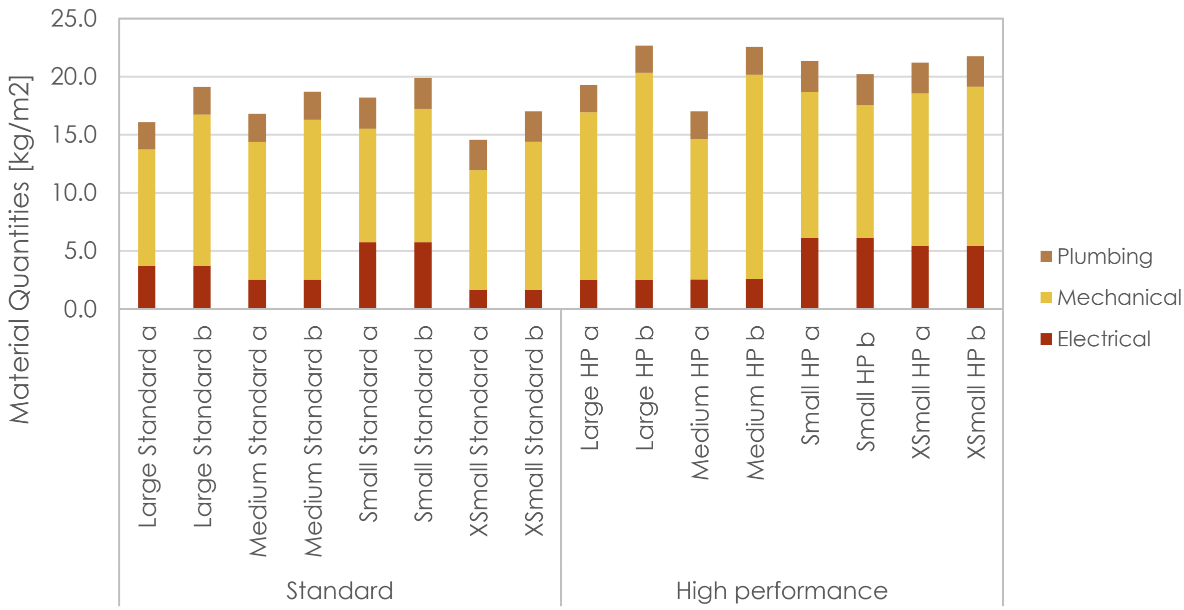
4.2 Substage 2: Estimation of Material Quantities

This analysis reveals that material quantities are higher in HPB compared to SPB across all building size categories. The total material quantity for MEP of typical commercial office buildings in the PNW ranges from 14.6 to 19.9 kg/m^2 for S, and 17.1 to 22.7 kg/m^2 for HPB across sixteen typical building size models. The analysis also reveals that material quantities of mechanical systems are significantly higher than material quantities of electrical and plumbing systems across all building size categories for both and HP buildings. HVAC material quantities can represent up to four times more than electrical and plumbing as shown in Table 4.

Table 4: Material Quantities for Material and Equipment Types in MEP systems in Standard and High Performance Buildings (kg/m^2)

Building type	Building model	Electrical	HVAC	Plumbing	**Grand Total**
Standard	Large Standard a	3.7	10.0	2.4	**16.1**
	Large Standard b	3.7	13.1	2.4	**19.1**
	Medium Standard a	2.5	11.9	2.4	**16.8**
	Medium Standard b	2.5	13.8	2.4	**18.7**
	Small Standard a	5.8	9.8	2.7	**18.2**
	Small Standard b	5.8	11.5	2.7	**19.9**
	XSmall Standard a	1.6	10.3	2.6	**14.6**
	XSmall Standard b	1.6	12.8	2.6	**17.1**
High performance	Large HP a	2.5	14.5	2.4	**19.3**
	Large HP b	2.5	17.9	2.4	**22.7**
	Medium HP a	2.5	12.1	2.4	**17.1**
	Medium HP b	2.6	17.6	2.4	**22.6**
	Small HP a	6.1	12.6	2.7	**21.4**
	Small HP b	6.1	11.5	2.7	**20.2**
	XSmall HP a	5.4	13.2	2.6	**21.2**
	XSmall HP b	5.4	13.8	2.6	**21.8**

Figure 3: Material Quantities for Material and Equipment Types in MEP systems in Standard and High Performance Buildings (kg/m²)



4.2.1 *Material Quantity Results for Heating, Ventilation, and Air Conditioning (HVAC)*

In the scope of this study, material quantities are estimated for material types and equipment types separately per both individual systems in each individual building size category. Material types for all HVAC systems include flexible duct and galvanized sheet metal. Refrigerants and insulation quantities are also included under the material type quantification, however only one HVAC contractor provided an estimation of both material types per m^2. Refrigerants results are shown independently due to the high variability in the values compared to other materials and equipment types and as this impact takes place primarily during the use stage.

Mechanical equipment types for HVAC systems in standard buildings include packaged rooftop heat pumps and boilers, while chilling towers, water source heat pumps and chilled beams are assumed for the high-performance buildings.

Material quantities for standard and high-performance HVAC systems are not directly comparable since these serve different purposes with different energy targets. However, a comparison of the mid-point, resulting from aggregating the different material intensities (kg/m2) provided by three HVAC contractors, shows that HVAC systems with DOAS require larger amounts of galvanized sheet metal for some of the building models, as shown in Figure 4.

Figure 4: Material Quantities for Material and Equipment Types of HVAC systems in Standard and High Performance Buildings (kg/m²)

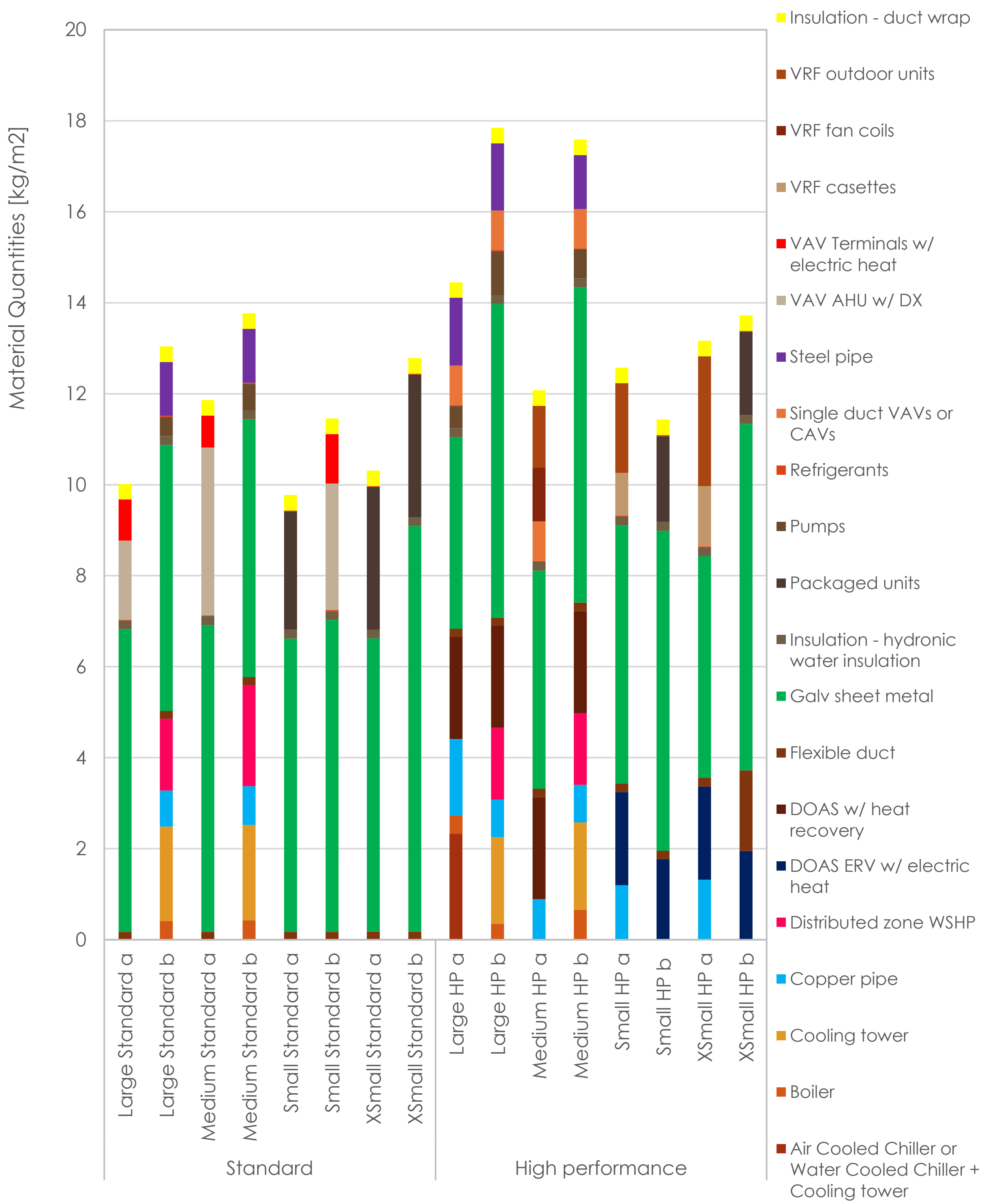


Table 5: Material Quantities for Material and Equipment Types in HVAC systems in Standard and High Performance Buildings (kg/m²)

	Air Cooled Chiller	Boiler	Cooling tower	Copper pipe	Distributed zone WSHP	DOAS ERV w/ electric heat	DOAS w/ heat recovery	Flexible duct	Galv sheet metal	Insulation - hydronic water insulation	Packaged units	Pumps	Refrigerants	Single duct VAVs or CAVs	Steel pipe	VAV AHU w/ DX	VAV Terminals w/ electric heat	VRF casettes	VRF fan coils	VRF outdoor units	Insulation - duct wrap
Large Standard a								0.2	6.7	0.2			0.0			1.7	0.9				0.3
Large Standard b		0.4	2.1	0.8	1.6			0.2	5.8	0.2		0.4	0.0		1.2						0.3
Medium Standard a								0.2	6.7	0.2			0.0			3.7	0.7				0.3
Medium Standard b		0.4	2.1	0.9	2.2			0.2	5.7	0.2		0.6	0.0		1.2						0.3
Small Standard a								0.2	6.4	0.2	2.6		0.0								0.3
Small Standard b								0.2	6.9	0.2			0.0			2.8	1.1				0.3
XSmall Standard a								0.2	6.4	0.2	3.1		0.0								0.3
XSmall Standard b								0.2	8.9	0.2	3.1		0.0								0.3
Large HP a	2.3	0.4		1.7			2.2	0.2	4.2	0.2		0.5	0.0	0.9	1.5						0.3
Large HP b		0.4	1.9	0.8	1.6		2.2	0.2	6.9	0.2		1.0	0.0	0.9	1.5						0.3
Medium HP a				0.9			2.2	0.2	4.8	0.2			0.0	0.9					1.2	1.4	0.3
Medium HP b		0.7	1.9	0.8	1.6		2.2	0.2	6.9	0.2		0.6	0.0	0.9	1.2						0.3
Small HP a				1.2		2.0		0.2	5.7	0.2			0.0					0.9		2.0	0.3
Small HP b						1.8		0.2	7.0	0.2	1.9		0.0								0.3
XSmall HP a				1.3		2.0		0.2	4.9	0.2			0.0					1.3		2.9	0.3
XSmall HP b						1.9		1.8	7.6	0.2	1.8		0.0								0.3

4.2.2 *Material Quantity Results for Electrical Systems*

As indicated in the results for the characterization of the buildings and their systems, electrical systems present additional challenges in terms of their classification under "generic" or "typical" categories. Both electrical contractors mentioned about the difficulties of describing electrical systems in generic terms and expressing the quantities in lb/sf. Nevertheless, the results show an increase of material quantities in high performance buildings, caused by the additional equipment required to comply with the local code. 'Transformer' in particular represents a larger relative mass compared to other building electrical equipment.

Figure 5: Material Quantities for Material and Equipment Types in Electrical systems in Standard and High Performance Buildings (kg/m²)

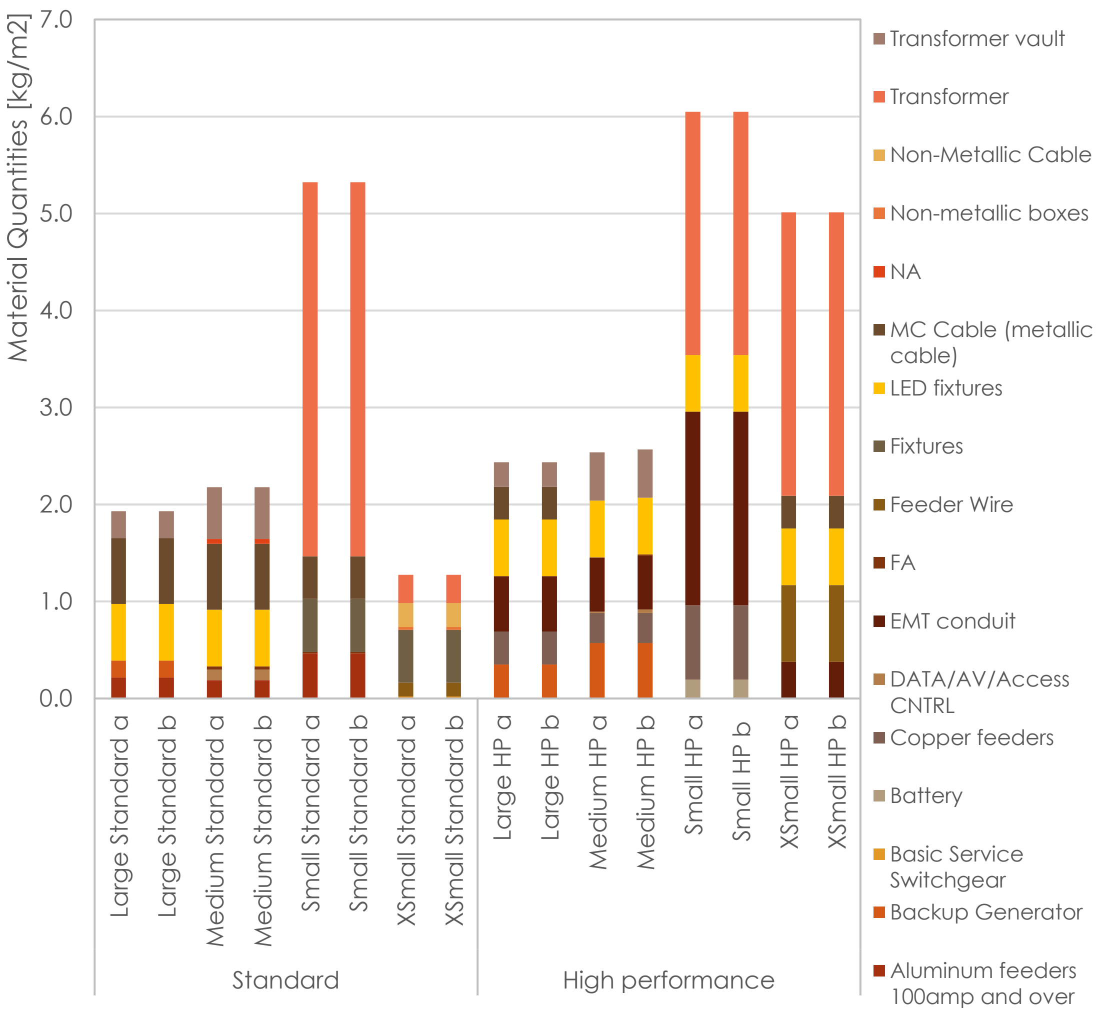


Table 6: Material Quantities for Material and Equipment Types in Electrical systems in Standard and High Performance Buildings (kg/m²)

Bldg model	Aluminum feeders 100amp and over	Backup Generator	Basic Service Switchgear	Battery	Copper feeders	DATA/AV/Access CNTRL	EMT conduit	FA	Feeder Wire	Fixtures	LED fixtures	MC Cable (metallic cable)	NA	Non-metallic boxes	Non-Metallic Cable	Transformer	Transformer vault
Large Standard a	0.2	0.2									0.6	0.7	0.0				0.3
Large Standard b	0.2	0.2									0.6	0.7	0.0				0.3
Medium Standard a	0.2					0.1		0.0			0.6	0.7	0.1				0.5
Medium Standard b	0.2					0.1		0.0			0.6	0.7	0.1				0.5
Small Standard a	0.5							0.0		0.5		0.4	0.0			3.9	
Small Standard b	0.5							0.0		0.5		0.4	0.0			3.9	
XSmall Standard a			0.0						0.1	0.5				0.0	0.2	0.3	
XSmall Standard b			0.0						0.1	0.5				0.0	0.2	0.3	
Large HP a		0.4			0.3		0.6				0.6	0.3	0.0				0.3
Large HP b		0.4			0.3		0.6				0.6	0.3	0.0				0.3
Medium HP a		0.6			0.3	0.0	0.6	0.0			0.6		0.0				0.5
Medium HP b		0.6			0.3	0.0	0.5	0.0			0.6		0.0				0.5
Small HP a				0.2	0.8		2.0				0.6					2.5	
Small HP b				0.2	0.8		2.0				0.6					2.5	
XSmall HP a							0.4		0.8		0.6	0.3				2.9	
XSmall HP b							0.4		0.8		0.6	0.3				2.9	

4.2.3 *Material Quantity Results for Plumbing Systems*

There are no significant differences between plumbing systems for standard and high performance buildings, the material quantity values per m² are the same for both types of buildings as shown in Figure 6.

Plumbing systems material quantities are assessed only focusing on material quantities (instead of material and equipment types as for the mechanical and electrical systems). Cast iron pipe represents the largest weight per m² across waste and vent plumbing systems.

Figure 6: Material Quantities for Material Types in Plumbing System Types in Standard Buildings and High-Performance Buildings (kg/m²)

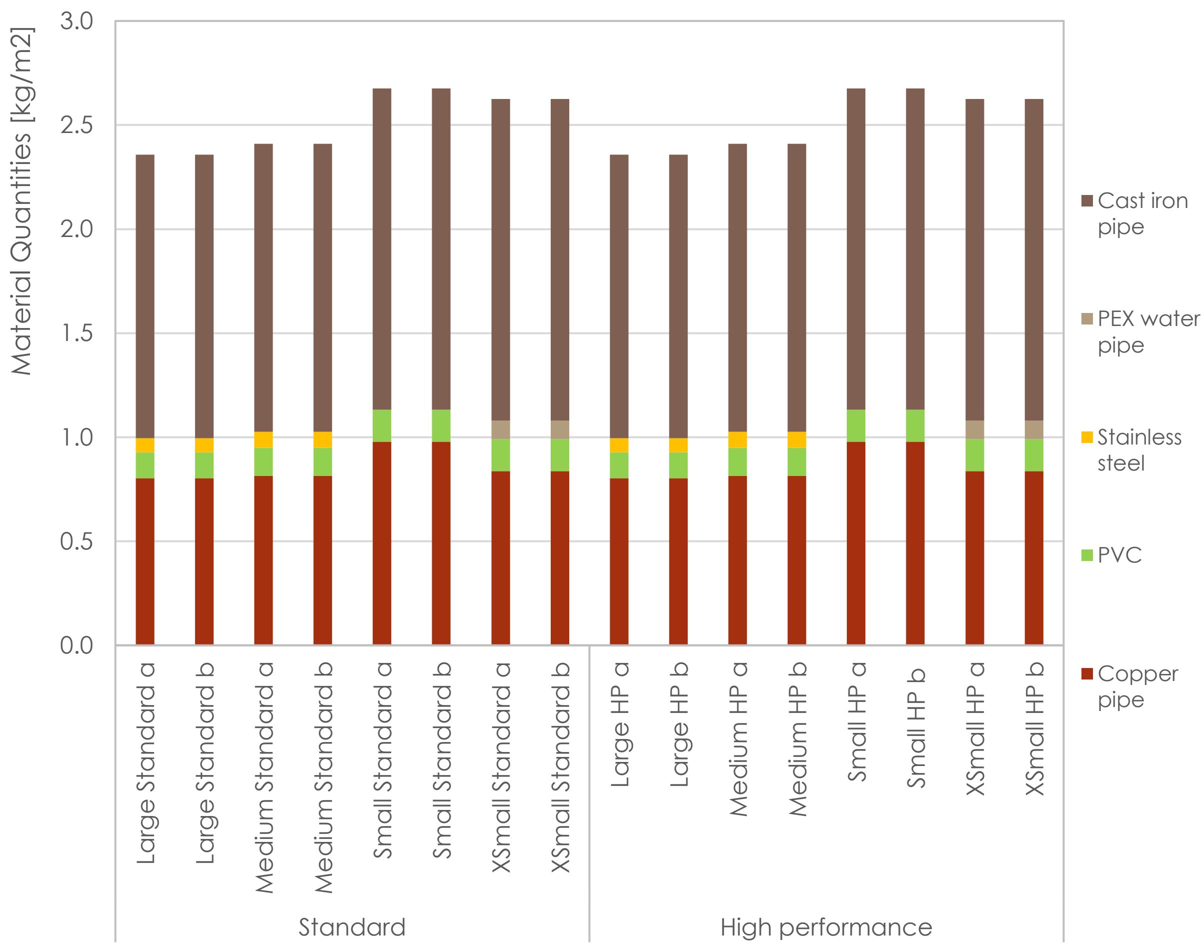


Table 7: Material Quantities for Material Types in Plumbing System Types in Standard Buildings and High-Performance Buildings (kg/m2)

Building model	Copper pipe	PVC	Stainless steel	PEX water pipe	Cast iron pipe	Grand Total
Large Standard a	0.8	0.1	0.1		1.4	2.4
Large Standard b	0.8	0.1	0.1		1.4	2.4
Medium Standard a	0.8	0.1	0.1		1.4	2.4
Medium Standard b	0.8	0.1	0.1		1.4	2.4
Small Standard a	1.0	0.2			1.5	2.7
Small Standard b	1.0	0.2			1.5	2.7
XSmall Standard a	0.8	0.2		0.1	1.5	2.6
XSmall Standard b	0.8	0.2		0.1	1.5	2.6
Large HP a	0.8	0.1	0.1		1.4	2.4
Large HP b	0.8	0.1	0.1		1.4	2.4
Medium HP a	0.8	0.1	0.1		1.4	2.4
Medium HP b	0.8	0.1	0.1		1.4	2.4
Small HP a	1.0	0.2			1.5	2.7
Small HP b	1.0	0.2			1.5	2.7
XSmall HP a	0.8	0.2		0.1	1.5	2.6
XSmall HP b	0.8	0.2		0.1	1.5	2.6

4.3 Substage 3: Compilation of LCA data

LCA results of manufacturing typical HVAC equipment and material are commonly available through open databases and journal articles. The ÖKOBAUDAT , the German mandatory data source within the Bewertungssystem Nachhaltiges Bauen (BNB),offers the largest amount of data for mechanical components (210 out of 1186 datasets are mechanical systems LCA data) . All ÖKOBAUDAT datasets are compliant with EN 15804 and have been generated based on GaBi background data.

There are only a few valid EPD for HVAC equipment in existing EPD programs. The PEP Ecopassport program, the International EPD System and the IBU have the largest number of English EPD for HVAC equipment. In the US, the UL EPD program holds two EPDs for centrifugal chillers and 39 EPDs for insulation types.

Table 8.- LCA data for equipment types in standard and high performance HVAC systems

Equipment	LCA source data	LCA source name	Name of product in the LCA source
1. Packaged units	Database	ÖKOBAUDAT	Electric heat pump (air-water) 10 kW; 1 piece (315lb)
2. DOAS ERV w/ electric heat *	Database	ÖKOBAUDAT	Ventilation centralized per 30000 m3/h, 168kg.
3. VRF outdoor units *	Database	ÖKOBAUDAT	Ventilation centralized with heat recovery per 10000 m3/h; 1 piece, 704kg
4. VRF casettes*	Database	PEP Ecopassport	Caisson de ventilation simple flux collective ou tertiaire
5. VAV AHU w/ DX	Database	PEP Ecopassport	Bidirectional ventilation unit for tertiary buildings Bidirectional
6. VAV Terminals w/ electric heat*	EPD	PEP Ecopassport	Caisson de ventilation simple flux collective ou tertiaire
7. Cooling tower	Database	ÖKOBAUDAT	Ventilation centralized per 10000 m3/h, 168kg
8. Boiler	Database	ÖKOBAUDAT	Gas condensing boiler 120-400 kW (upright unit); 1 piece
9. DOAS w/ heat recovery*	Database	ÖKOBAUDAT	Ventilation centralized with heat recovery per 10000 m3/h; 1 piece, 704kg
10. Single duct VAVs or CAVs*	Database	ÖKOBAUDAT	Ventilation centralized per 10000 m3/h, 68kg
11. VRF fan coils	Database	PEP Ecopassport	Caisson de ventilation simple flux collective ou tertiaire
12. Distributed zone WSHP	Database	ÖKOBAUDAT	Electric heat pump (air-water) 10 kW; 1 piece (315lb)
13. Air cooled chiller or Water cooled chiller + Cooling tower	EPD	UL	Centravac chiller Portfolio
14. Pumps	Database	ÖKOBAUDAT	Electric heat pump (air-water) 10 kW; 1 piece (315lb)

*Equipment used as proxy for typical equipment

Table 9.- LCA data for material types in SPB and HPB HVAC systems

Material types	LCA source data	LCA source name	Name of product in the LCA source
1. Galvanized sheet metal	Database	QUARTZ	Galvanized steel ducts
2. Cooper pipe	Database	QUARTZ	Copper Piping
3. Stainless steel	Database	ÖKOBAUDAT	Steel Pipe
4. Flexible duct	EPD	UL	Aluminum Cold-Rolled Sheet and plate (functional unit converted from 1 ton to 1 kg)
5. Steel pipe	Database	ÖKOBAUDAT	Steel Pipe
6. Insulation – duct wrap	EPD	UL	Armaflex® Class 1
7. Insulation – hydronic water insulation	EPD	UL	FIBERGLAS™ PIPE INSULATION
8. Refrigerant**	LEED Reference Guide- Standard Industry Data		

** Different type of LCA data source

Table 10.- LCA data for equipment types in SPB and HPB electrical systems

Equipment	LCA source data	LCA source name	Name of product in the LCA source
1. Non-metallic boxes	Database	QUARTZ	Solvent Weld Soil and Waste Pipe
2. LED fixtures	EPD	PEP Ecopassport	Hublots LED Chartres Essentiel ON/OFF
3. Fixtures	Database	ÖKOBAUDAT	Fluorescent lamp T8-18W; 1 piece (en
4. Battery 20W Unit	Database	ÖKOBAUDAT	Lithium iron phosphate (LiFePO4) battery (per 1kWh storage); 1kWh storage capacity (en)
5. Battery	Database	ÖKOBAUDAT	Lithium iron phosphate (LiFePO4) battery (per 1kWh storage); 1kWh storage capacity (en)
6. Occupancy sensors	EPD	PEP Ecopassport	Wattstopper® - Dual Technology Wall Switch Occupancy Sensors
7. Daylight sensors	EPD	PEP Ecopassport	Wattstopper® - Dual Technology Wall Switch Occupancy Sensors

8. MC Cable (metallic cable)	Database	ÖKOBAUDAT	Cable 1-wire; 1 piece 1.0 m (Length), 0.02 kg/m (linear density)
9. Copper feeders	Database	ÖKOBAUDAT	Cable 1-wire; 1 piece 1.0 m (Length), 0.02 kg/m (linear density)
10. Metal boxes	Database	ÖKOBAUDAT	Cable 1-wire; 1 piece 1.0 m (Length), 0.02 kg/m (linear density)
11. Code minimum time clock, 0.68 lbs/EA	Database	ÖKOBAUDAT	Cable 1-wire; 1 piece 1.0 m (Length), 0.02 kg/m (linear density)
12. Data/WAP (Wireless)	Database	ÖKOBAUDAT	Electronic control gear; 1 piece (en) en de
13. DATA/AV/Access CNTRL	Database	ÖKOBAUDAT	Cable 1-wire; 1 piece 1.0 m (Length), 0.02 kg/m (linear density)
14. Feeder Wire	Database	ÖKOBAUDAT	Cable 1-wire; 1 piece 1.0 m (Length), 0.02 kg/m (linear density)
15. Aluminum feeders 100amp and over	Database	ÖKOBAUDAT	Cable 1-wire; 1 piece 1.0 m (Length), 0.02 kg/m (linear density)
16. FA	Database	ÖKOBAUDAT	Cable 1-wire; 1 piece 1.0 m (Length), 0.02 kg/m (linear density)
17. Basic Service Switchgear	Database	ÖKOBAUDAT	Rocker lightswitch; 1 piece
18. D-Rings 0.15 lbs/EA	Database	ÖKOBAUDAT	Rocker lightswitch; 1 piece
19. Transformer	Database	ÖKOBAUDAT	Rocker lightswitch; 1 piece
20. Transformer Vault	Database	ÖKOBAUDAT	Rocker lightswitch; 1 piece
21. Backup Generator	Database	ÖKOBAUDAT	Rocker lightswitch; 1 piece
22. Non-Metallic Cable	Database	ÖKOBAUDAT	Cable CAT 7; 1 piece (en)
23. EMT Conduit	Database	QUARTZ	Steel conduit/ Electric rigid steel conduit
24. Energy meters, 0.59 lbs/EA	EPD	PEP	Wattstopper® - Digital light management room controller with 0-10V dimming

*Equipment used as proxy for typical equipment

Table 11.- LCA data for material types in plumbing systems

Equipment	LCA source data	LCA source name	Name of product in the LCA source

1.Cast iron pipe	Database	QUARTZ	USA
2.PEX water pipe	Database	QUARTZ	PEX Water Pipe
3.PVC	Database	QUARTZ	Solvent weld soil and waste pipe
4.Cooper pipe	Database	QUARTZ	Copper piping
5.Stainless steel	Database	ÖKOBAUDAT	Steel pipe

4.3.1 *Note on Data quality*

For this study, the data was assessed based on three indicators: reliability, temporal correlation and completeness. Based on these criteria, the ÖKOBAUDAT is used as the main LCA data source, followed by the Quartz database. EPDs are used only for MEP items that are not listed under the ÖKOBAUDAT. Data from selected journal articles were used only when EPD were not available and are considered the data of lowest quality.

4.3.2 *Note on life expectancy of the Equipment*

According to the Building Owners and Managers Association International (BOMA) the following Tables 10 and 11 average useful life years of the equipment considered for this study:

Table 12: Average Useful Life Years per Type of HVAC Equipment (Schoen 2010)

Equipment	Average Useful Life Years
1.Packaged units	18
2.DOAS ERV w/ electric heat *	25
3.VRF outdoor units *	15
4.VRF casettes*	17
5.VAV AHU w/ DX	25
6.VAV Terminals w/ electric heat*	17
7.Cooling tower	10
8.Boiler	18
9.DOAS w/ heat recovery*	12
10. Single duct VAVs or CAVs*	25
11. VRF fan coils	20
12. Distributed zone WSHP	15
13. Air Cooled Chiller or Water Cooled Chiller + Cooling tower	20
14. Pumps	15

Table 13: Average Useful Life Years per Type of Electrical Equipment (Schoen 2010)

Equipment	Average Useful Life Years
1. Non-metallic boxes	NA
2. LED fixtures	20
3. Fixtures	20
4. Battery 20W Unit	5
5. Battery	5
6. Occupancy sensors	10
7. Daylight sensors	10
8. MC Cable (metallic cable)	40
9. Copper feeders	40
10. Metal boxes	20
11. Code minimum time clock, 0.68 lbs/EA	NA
12. Data/WAP (Wireless)	NA
13. DATA/AV/Access CNTRL	NA
14. Feeder Wire	40
15. Aluminum feeders 100amp and over	NA
16. FA	NA
17. Basic Service Switchgear	25
18. D-Rings 0.15 lbs/EA	NA
19. Transformer	30
20. Transformer Vault	30
21. Backup Generator	20
22. Non-Metallic Cable	40
23. EMT Conduit	40
24. Energy meters, 0.59 lbs/EA	20

Table 14.- Average Useful Life Years per Type of Plumbing Materials (Schoen 2010)

Material Type	Average Useful Life Years
1. Cast iron pipe	30
2. PEX water pipe	30
3. PVC	30
4. Cooper pipe	30
5. Stainless Steel	NA

4.4 Substage 4: LCA Matrix, LCA data multiplied by material quantities

During the final stage of this project, the LCA results are calculated by multiplying the life cycle data with the material quantities from the second substage. Table 13 shows the global warming potential (GWP) for all building systems for the 16 building models.

Table 15: Global Warming Potential (GWP) for electrical, HVAC (excluding refrigerants) and plumbing system types in SPB and HPB (kg CO_2eq/m[2])

Building type	Building model	Electrical	HVAC	Plumbing	Grand Total (kg CO_2e/m[2])
Standard	Large Standard a	7.1	35.6	6.2	48.9
	Large Standard b	7.1	35.6	6.2	55.0
	Medium Standard a	11.7	48.2	6.4	66.3
	Medium Standard b	11.7	43.2	6.4	61.3
	Small Standard a	6.3	27.8	7.1	41.2
	Small Standard b	6.3	44.0	7.1	57.4
	XSmall Standard a	4.6	29.5	7.2	41.3
	XSmall Standard b	4.6	35.4	7.2	47.2
High performance	Large HP a	8.6	60.0	6.2	74.8
	Large HP b	8.6	56.6	6.2	71.4
	Medium HP a	8.8	39.8	6.4	55.1
	Medium HP b	9.0	59.2	6.4	74.6
	Small HP a	15.9	42.1	7.1	65.1
	Small HP b	15.9	35.8	7.1	58.9
	XSmall HP a	13.3	45.4	7.2	65.9
	XSmall HP b	13.3	46.4	7.2	67.0

The results of this stage illustrate that HVAC adds the largest contribution to the total GWP of each building due to the high level of material weight and the great GWP of some of the HVAC components, as shown in Fig. 7. The second largest contribution to GWP are electrical systems, followed by plumbing across all building size categories. In conclusion, the trends of embodied carbon for both S and HP buildings in downward order are HVAC, electrical and plumbing.

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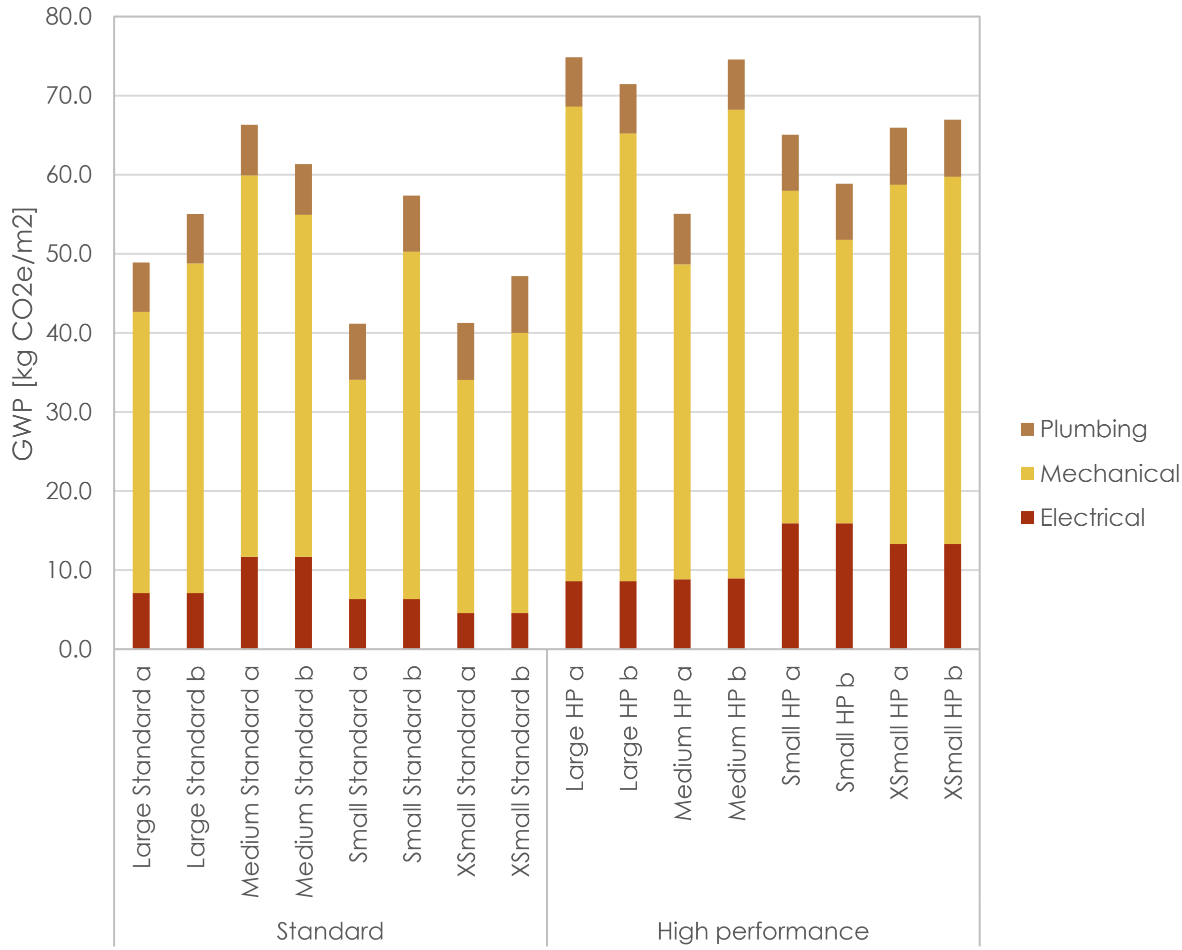
Figure 7: Global Warming Potential (GWP) for Mechanical (excluding refrigerants) Electrical and Plumbing System Types in Standard Buildings and High-Performance Buildings (kg CO_2eq/m²)



4.4.1 GWP results for Heating, Ventilation, and Air Conditioning (HVAC)

As seen in Table 10, embodied carbon in SPB ranges from 27.8 to 48.2 kg CO_2e/m² for standard HVAC systems and 30.6 to 60.0 kg CO_2e/m² for high performance systems as shown in Table 10.

The significant contribution of HVAC components becomes increasingly higher with the addition of refrigerants, which contribute up to 1,890 kg CO_2 eq/kg of refrigerant(USGBC 2013). Refrigeration and HVAC systems contribute to GHG emissions due to operational energy consumption and use of refrigerant fluids that have high global warming potential (GWP)(Bovea et al. 2007). According to Goetzler et al., stationary HVAC systems around the world account for nearly 700 million metric tons of direct and indirect CO2-equivalent emissions (MMTCO2e) annually. Indirect emissions from electricity generation account for approximately 74% of this total, with direct emissions of HFC and hydrochlorofluorocarbon (HCFC) refrigerants accounting for 7% and 19%, respectively (Goetzler et al. 2016). HFCs are commonly used refrigerants and are one of the seven top GHGs (Kyoto Protocol, 1997), having a warming effect on the atmosphere up to 23,000 times greater than CO2 (Bortolini et al. 2015).

In this study, the GWP of refrigerants in the HVAC systems was calculated separately from the rest of the equipment, since the material quantity of refrigerants in HVAC system was provided by only one of the contractors from the advisory committee. Additionally refrigerant use is typically considered a use stage impact. GWP contribution of typical refrigerants such as R-410 or R-22 is more than double the typical embodied carbon of equipment. For instance, assuming a 10% loss at the end of the life cycle, and 2% leakage rate during the life time (15 years) of the equipment, the result is a 40% loss of refrigerant, equivalent to 0.02 kg/sqm of the original refrigerant charge. If the refrigerant used is R-410 (GWP=1,890 kg CO_2e per kg of refrigerant) the total GWP of this 40% loss would be equivalent to 37.8 kg CO_2e across the lifetime of the equipment. It is worth noting, that if no refrigerant is captured at the end of the lifecycle, there would be a 100% loss and the impact would be equivalent 92.6 kg CO_2e, which represents twice the quantity of embodied carbon in HVAC equipment and materials for most of the systems (27.8 to 48.2 kg CO_2e/sqm for SPB and 30.6 to 60 kg CO_2e/sqm for HPB).

The industry standard for refrigerant quantity calculation is the formula provided for enhanced refrigeration management in LEED v4 2009 (USGBC 2013). In this calculation shown in equation (1), Life Cycle Global Warming Potential (LCGWP) and Life Cycle Ozone Depletion Potential (LCODP) are calculated for a weighted average of all multiple types of HVAC equipment in the building across a period of 10 years. LCGWP is calculated using equation (2) where Global Warming Potential of Refrigerant (GWPr) is multiplied by the result of a leakage rate of (2.0% default value) for each year of equipment life (10 years default) and End-of-life Refrigerant Loss (10% default value). This study is based on the impacts reported under the LEED Rating System for HFC-410A (R410A), one of the most common types of refrigerants used in commercial HVAC (GWP of 1,890 kg CO2 eq/kg of refrigerant).

(1) Σ [(LCGWP + LCODP × 10^5) x Qunit ≤ 100] / Qtotal

(2) LCGWP = [GWPr × (Lr × Life + Mr) × Rc] / Life

Where:
GWPr: Global Warming Potential of Refrigerant (0 to 12,000 lb CO2/lbr)

Lr: Refrigerant Leakage Rate (2.0%)

Life: Equipment Life (10 years; default based on equipment type, unless otherwise demonstrated)

Mr: End-of-life Refrigerant Loss (10%)

Rc: Refrigerant Charge (0.5 to 5.0 lbs of refrigerant per ton of gross AHRI rated cooling capacity)

Q unit = Gross AHRI rated cooling capacity of an individual HVAC or refrigeration unit (tons)

Q total = Total gross AHRI rated cooling capacity of all HVAC or refrigeration

USGBC indicates several trade-offs also between the concerns on refrigerants and the reduction of operational energy. Many products that are currently available, or will become available in the near-term, provide GWP reductions of 50-75% or more compared to the most commonly used refrigerants(Goetzler et al. 2016). Alternatives to CFC and HCFC refrigerants, such as HFC-410A (R410A), have a lower GWP when directly released, but their use may require more energy, which also affects climate. Conversely, variable refrigerant flow (VRF) systems may improve energy efficiency but have a higher refrigerant charge (USGBC 2013).

Figure 8: Global Warming Potential (GWP) for HVAC system types (excluding refrigerants) in SPB and HPB (kg CO_2eq/m^2)

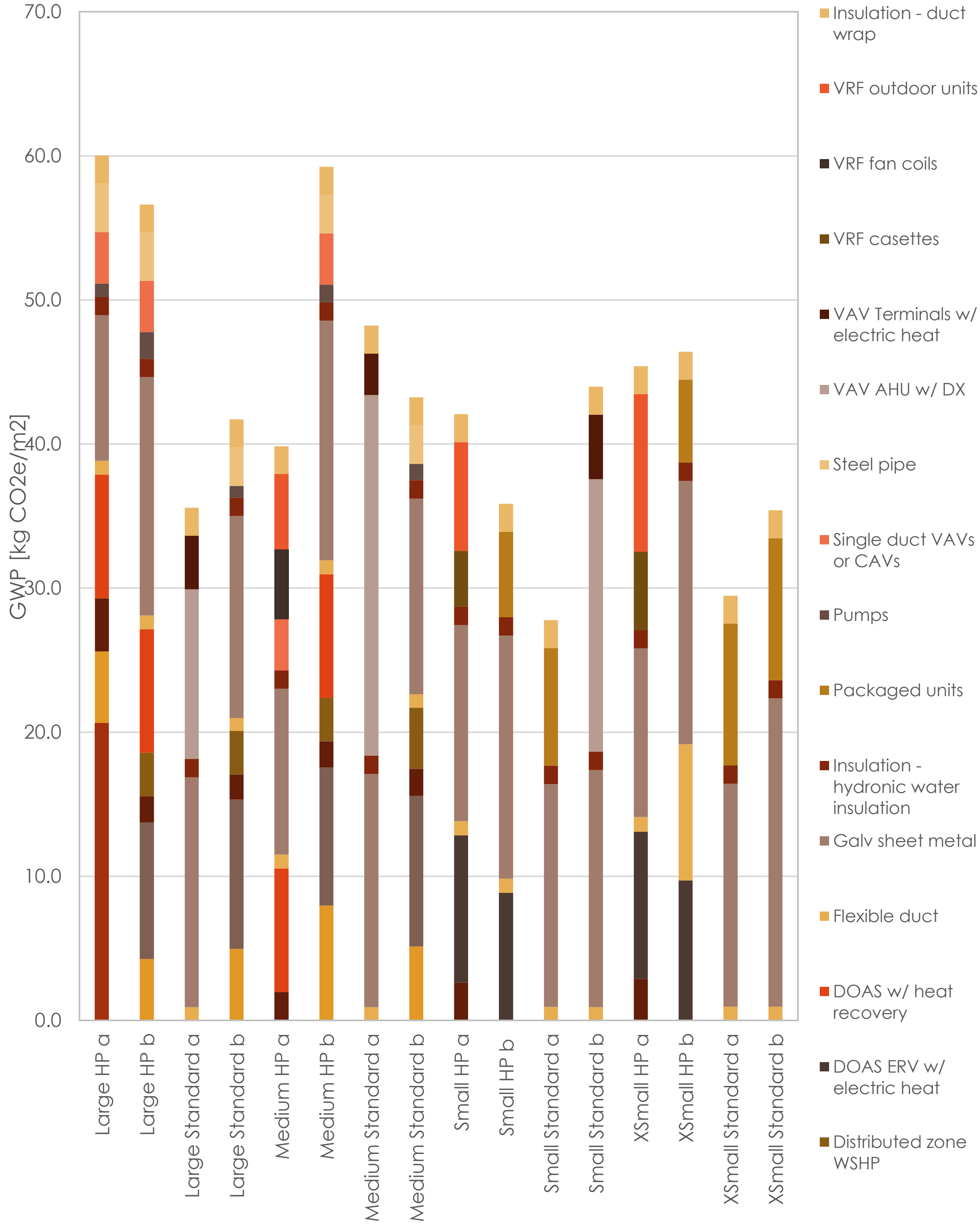


Table 16: Global Warming Potential (GWP) for HVAC system types in SPB and HPB (kg CO_2eq/m^2)

Bldg model	Air Cooled Chiller or Water Cooled Chiller + Cooling tower	Boiler	Cooling tower	Copper pipe	Distributed zone WSHP	DOAS ERV w/ electric heat	DOAS w/ heat recovery	Flexible duct	Galv sheet metal	Insulation - hydronic water insulation	Packaged units	Pumps	Single duct VAVs or CAVs	Steel pipe	VAV AHU w/ DX	VAV Terminals w/ electric heat	VRF casettes	VRF fan coils	VRF outdoor units	Insulation - duct wrap
Large Standard a								0.9	16.0	1.3					11.8	3.7				1.9
Large Standard b		5.0	4.2	1.7	3.0			0.9	14.0	1.3		0.8		2.7						1.9
Medium Standard a								0.9	16.2	1.3					25.0	2.9				1.9
Medium Standard b		5.1	4.2	1.9	4.2			0.9	13.6	1.3		1.1		2.7						1.9
Small Standard a								0.9	15.5	1.3	8.2									1.9
Small Standard b								0.9	16.5	1.3					18.9	4.5				1.9
XSmall Standard a								1.0	15.5	1.3	9.8									1.9
XSmall Standard b								1.0	21.4	1.3	9.8									1.9
Large HP a	20.6	5.0		3.7			8.6	1.0	10.1	1.3		0.9	3.6	3.4						1.9
Large HP b		4.3	3.8	1.8	3.0		8.6	1.0	16.5	1.3		1.9	3.6	3.3						1.9
Medium HP a				2.0			8.6	1.0	11.5	1.3			3.6					4.8	5.2	1.9
Medium HP b		8.0	3.9	1.8	3.0		8.6	1.0	16.6	1.3		1.2	3.6	2.7						1.9
Small HP a				2.6		4.1		1.0	13.6	1.3							3.9		7.6	1.9
Small HP b						3.6		1.0	16.9	1.3	5.9									1.9
XSmall HP a				2.9		4.1		1.0	11.7	1.3							5.4		10.9	1.9
XSmall HP b						3.9		9.4	18.3	1.3	5.8									1.9

4.4.2 *GWP results for electrical systems*

Figure 9: Global Warming Potential (GWP) for Electrical System Types in SPB and HPB (kg CO_2eq/m^2)

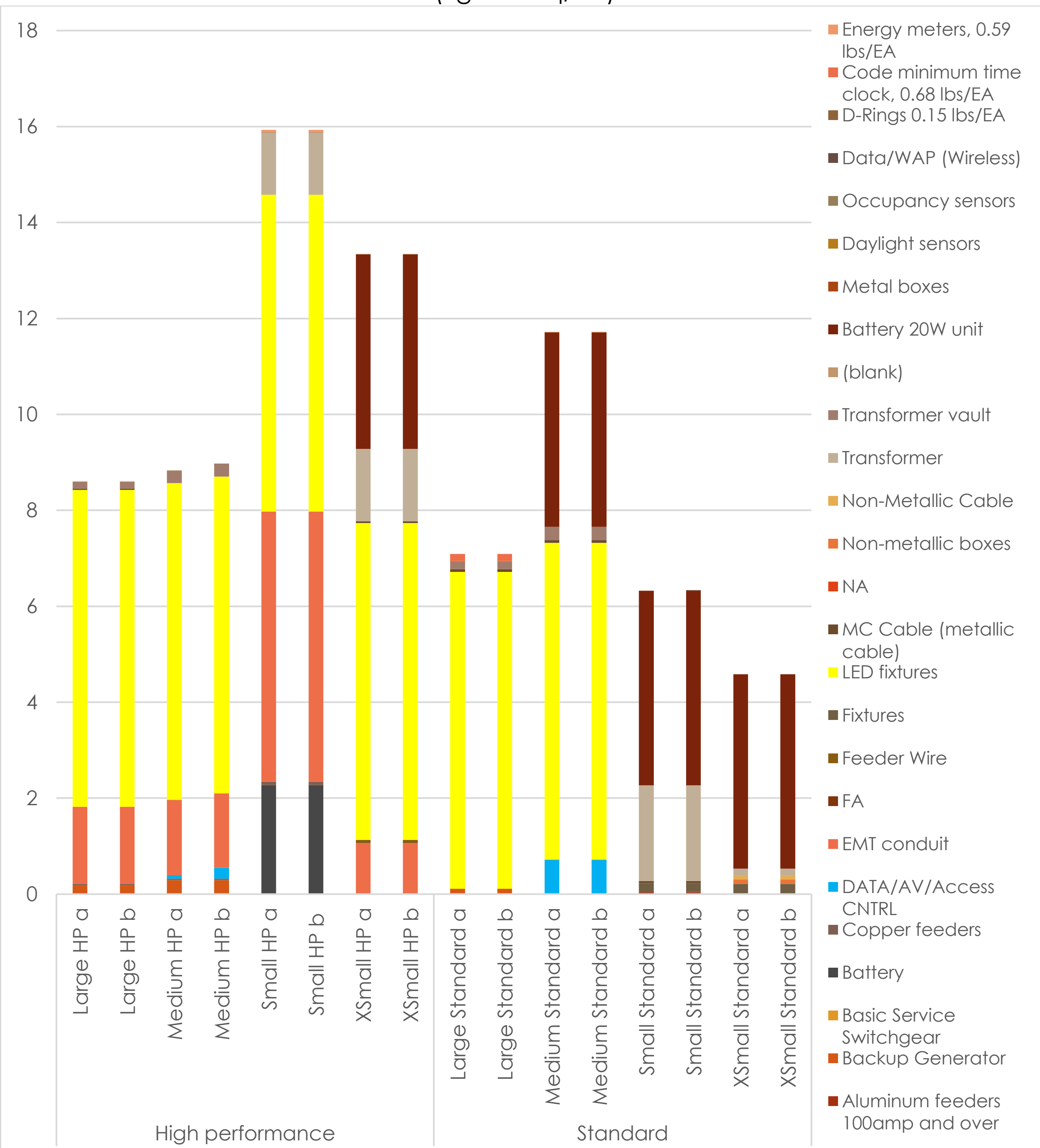


Table 17: Global Warming Potential (GWP) for Electrical System Types in SPB and HPB (kg CO_2eq/m^2)

Bldg Model	Aluminum feeders 100amp	Backup Generator	Battery	Copper feeders	DATA/AV/Access CNTRL	EMT conduit	Feeder Wire	Fixtures	LED fixtures	MC Cable (metallic cable)	Non-metallic boxes	Non-Metallic Cable	Transformer	Transformer vault	Battery 20W unit	Daylight sensors	Occupancy sensors	D-Rings 0.15 lbs/EA	Code minimum time clock,	Energy meters, 0.59 lbs/EA
Large HP a		0.2		0.0		1.6			6.6	0.0				0.1		0.0	0.0			
Large HP b		0.2		0.0		1.6			6.6	0.0				0.1		0.0	0.0			
Medium HP a		0.3		0.0	0.1	1.6			6.6					0.3		0.0	0.0			
Medium HP b		0.3		0.0	0.2	1.5			6.6					0.3		0.0	0.0			
Small HP a			2.3	0.1		5.6			6.6				1.3			0.0	0.0			0.0
Small HP b			2.3	0.1		5.6			6.6				1.3			0.0	0.0			0.0
XSmall HP a						1.1	0.1		6.6	0.0			1.5		4.1		0.0			
XSmall HP b						1.1	0.1		6.6	0.0			1.5		4.1		0.0			
Standard	0.1	0.2			1.4		0.0	0.8	26.4	0.3	0.2	0.1	4.3	0.8	24.3	0.0		0.0	0.3	
Large Standard a	0.0	0.1							6.6	0.1				0.1		0.0			0.1	
Large Standard b	0.0	0.1							6.6	0.1				0.1		0.0			0.1	
Medium Standard a	0.0				0.7				6.6	0.1				0.3	4.1	0.0		0.0	0.0	
Medium Standard b	0.0				0.7				6.6	0.1				0.3	4.1	0.0		0.0	0.0	
Small Standard a	0.0							0.2		0.0			2.0		4.1			0.0		
Small Standard b	0.0							0.2		0.0			2.0		4.1			0.0		
XSmall Standard a							0.0	0.2			0.1	0.1	0.2		4.1			0.0		
XSmall Standard b							0.0	0.2			0.1	0.1	0.2		4.1			0.0		

4.4.3 *GWP Results for Plumbing Systems*

Figure 10: Global Warming Potential (GWP) for Plumbing System Types in SPB and HPB (kg CO_2eq/m²)

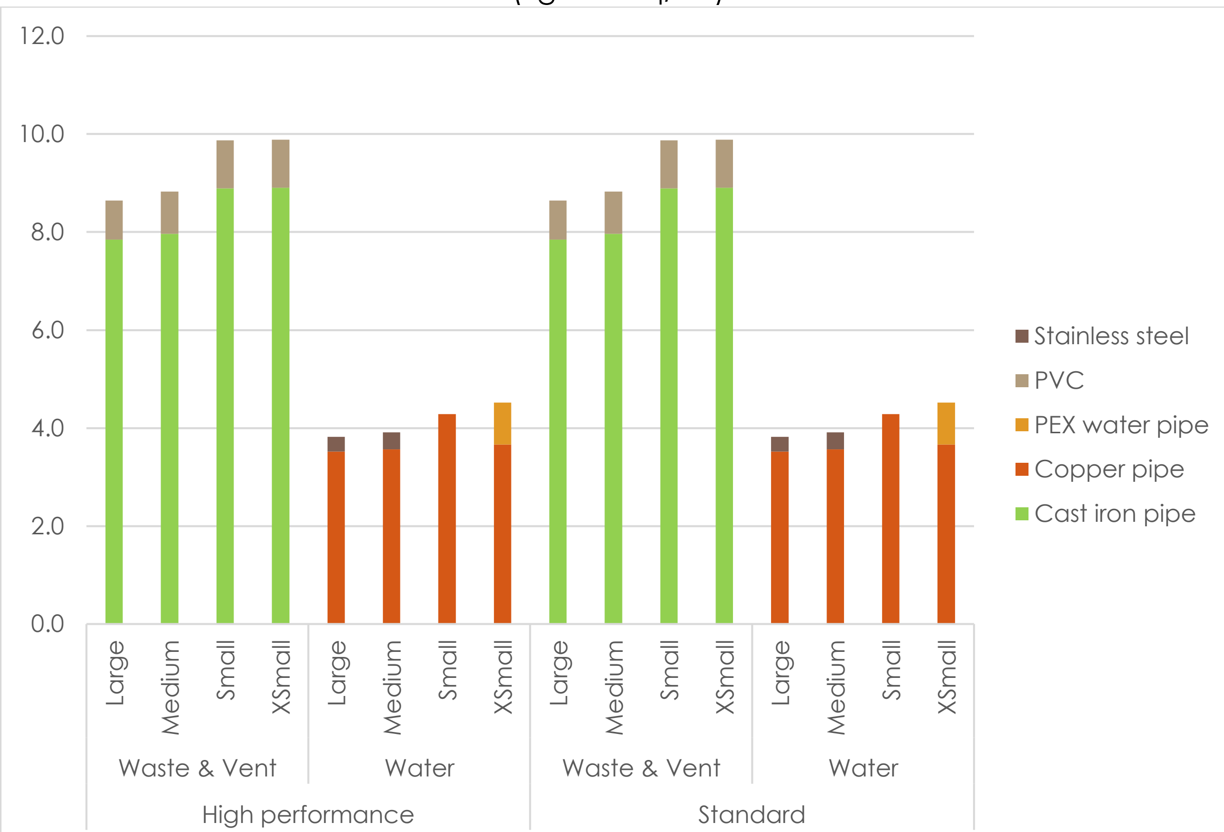


Table 18: Global Warming Potential (GWP) for Plumbing System Types in SPB and HPB (kg CO_2eq/m²)

Row Labels	**Cast iron pipe**	**Copper pipe**	**PEX water pipe**	**PVC**	**Stainless steel**	**Grand Total**
Waste & Vent HP						
Large HP a & b	7.8			0.8		8.6
Medium HP a & b	8.0			0.9		8.8
Small HP a & b	8.9			1.0		9.9
XSmall HP a & b	8.9			1.0		9.9
Water HP						
Large HP a & b		3.5			0.3	3.8

Medium HP a & b		3.6			0.3	3.9
Small HP a & b		4.3				4.3
XSmall HP a & b		3.7	0.9			4.5
Waste & Vent SP						
Large SP a & b	7.8			0.8		8.6
Medium SP a & b	8.0			0.9		8.8
Small SP a & b	8.9			1.0		9.9
XSmall SP a & b	8.9			1.0		9.9
Water						
Large SP a & b		3.5			0.3	3.8
Medium SP a & b		3.6			0.3	3.9
Small SP a & b		4.3				4.3
XSmall SP a & b		3.7	0.9			4.5

5 DISCUSSION

5.1 Limitations

The inherent limitations of this study should be acknowledged in all publications of the data, including the website. A summary of the limitations per research stage are as follows:

5.1.1 *Limitations on the characterization of generic buildings and systems*

(1) The database of generic office buildings does not represent a statistical sample of buildings in the region, and is weighted to larger, more prominent buildings than those that make up the complete building stock in the PNW.

(2) The MEP systems described for generic office buildings used for this study are not statistically representative of current building MEP design choices and instead should be considered simplified models of typical systems used in standard and high-performance buildings in the PNW. The building size categories and the systems were described by the Advisory Committee based on their professional judgement.

5.1.2 *Limitations on calculating material quantities of typical MEP systems*

(1) Calculation of MEP system equipment in weight per area is not a standard practice for most MEP contractors. In order to provide the data required for this study, most contractors sized the equipment assuming particular design requirements and then calculated the weight per unit of equipment, finally they estimated a total for the entire building.

5.1.3 Limitations on compiling LCA data of buildings

(1) The available LCA data for MEP systems is scarce and comes from different geographical regions; therefore it is not directly comparable.
(2) The available LCA data is limited to only some types of MEP equipment and materials. In order to complete this study, EPD and openly available LCA data from standard equipment was used to represent other equipment of similar material composition and weight.
(3) Most LCA data sources use different units for some of the impacts in this study and hence represented a limitation to the aggregation of final impacts. For instance, Total Ozone depletion potential (ODP) is measured in the [kg CFC11-eq.] ÖKOBAUDAT database, while the North American, UL Environment and the Quartz database use [kg R11 eq.]. The same limitation arises in the comparison of Eutrophication Potential (EP), and Smog Formation Potential (SFP) impacts across sources.
(4) This study uses only LCA data for MEP equipment for life cycle stage A.
(5) This study uses only LCA data available in English EPD, databases and published journals.

5.2 Sources of Uncertainty

This study presents several sources of uncertainty in the four substages which are explained herein by each research stage.

5.2.1 Sources of uncertainty on the characterization of generic buildings and systems

(1) The building characterization method followed by the contractors presents several sources of uncertainties. In order to describe building systems across building size categories, several assumptions were made by each individual contractor based on previous system design choices in past projects. These assumptions were not shared with the research team and/or between contractors. Each individual contractor made their own assumptions on design requirements such as building occupancy, climate data, noise requirements, building envelope, structure and design layout for each floor.
(2) The equipment list and material quantities described in this study are limited to the main components and should be considered a simplification of real systems. For instance, in the case of plumbing systems fittings, hangers and typical rainwater capturing systems are not considered. The exact proportion of equipment incorporated into the study vs the actual list of equipment for each system varies across the different MEP systems.

5.2.2 *Sources of uncertainty on calculating material quantities of typical MEP systems*

(1) The material quantities estimation method performed by the Advisory Committee presents several sources of uncertainties. In order to obtain pounds of equipment per square foot of building, several assumptions were made. Some of these assumptions include considering equal capacity of MEP equipment across all building scales. For example, in a 2,000 to 25,000 sf office, the equipment list includes two packaged rooftop heat pumps, each of which weighs 2,000 lb/unit. Those exact same units (also 2,000 lb/unit) would be used for a 10,000-80,000 sf office, but ten units total. This method assumes that the packaged rooftop heat pumps are identical across building sizes, while in reality, mechanical equipment varies in size and capacity, depending on the design requirements.

(2) Each individual contractor used their own material quantity estimation data for MEP materials and equipment based on historical quantity and cost data from past projects. This data gathering effort was different for each contractor and the research team did not have access to this confidential data.

5.2.3 *Sources of uncertainty on compiling LCA data of buildings*

(1) The LCA data used for this study are not aligned since different background data software, and assumptions are used across all different sources. LCA methods used for different LCA data may not be consistent since different life cycle stages and calculation methodologies are used. In MEP systems, in particular, functional/declared units and reference flows contain significant variability. For example, under ÖKOBAUDAT database (German), reference flows for mechanical equipment are typically described 'per unit' or 'piece of equipment', while EPD use 'one ton of cooling capacity' (based on an average case 1000-ton centrifugal chiller mode). The conversion of cooling capacity units to kg, adds a significant level of uncertainty to the impact calculation since different number of equipment units with varying levels of capacity and operational weight can serve the same purpose.

(2) MEP equipment uses different names and description across geographical regions. Using and aggregating LCA data from different geographical locations adds uncertainty.

5.2.4 *Sources of uncertainty on calculating LCA impacts*

(3) LCA data is not available for all types of equipment, many uncertainties remain in relation to specific types of equipment. In order to calculate an estimated value, this study used the same LCA data for different equipment types based on similarities in material composition and weight. The number of equipment for

which other product LCA impact data is used, can be tracked in the LCA tab of the spreadsheet matrix.

5.3 Future research

5.3.1 Research needed for characterization of buildings

(1) Select statistically representative samples of actual commercial office buildings to assess typical MEP systems.
(2) Develop LCA studies for typical case studies, describing a complete list of MEP equipment and materials, specific to each case.

5.3.2 Research needed for calculating material quantities of typical MEP systems

(1) Calculate case specific material quantities for each particular commercial office case study in order to obtain a more accurate estimation and specific weights of equipment.
(2) Develop a survey targeted to building owners and building managers to estimate total refrigerant quantities, leakages during operation and end of life scenarios. This data cannot be provided by mechanical contractors and is highly variable across studies even within the same building size category.

5.3.3 Research needed for LCA data of MEP system of buildings

(1) Develop a North American LCA dataset for MEP equipment and materials integrating results from EPDs, open databases and local studies.

5.3.4 Research needed for calculating LCA impacts of MEP systems

(1) Develop comprehensive LCA studies of typical MEP system in chosen case studies taking into account complete list of equipment, and case specific material quantity takeoffs. This comprehensive LCA studies could contribute to the refinement of the simplified method described in this study.

6 CONCLUSION

With support from an Advisory Committee, the goal of this research was to offer a reasonable estimate of embodied carbon and life cycle impacts during the manufacturing stage of MEP systems in commercial office buildings in the PNW. The first stage of this research show that MEP systems are inherently different and present differing levels of equipment complexity that allow for different opportunities for standardization and aggregation. Plumbing is the least complex of the three systems and is defined primarily in the selection of piping material rather than particular equipment. HVAC is a much more complex system, and for this study only the two most representative mechanical systems were considered for each building size category under the SPB and HPB categories. Electrical systems present the largest challenges to their classification under "generic" or "typical" categories, since the scope of electrical systems has significantly increased due to the growing proliferation of electric systems in building applications.

The second stage of this research revealed that material quantities are higher in HPB buildings compared to SPB buildings across all building size categories. The total material quantity for MEP of typical commercial office buildings in the PNW ranges from 14.6 to 19.9 kg/m2 for SPB, and 17.1 to 22.7 kg/m2 for HPB buildings across sixteen typical building size models. The analysis also reveals that material quantities of mechanical systems are significantly higher than material quantities of electrical and plumbing systems across all building size categories for both SPB and HPB. HVAC material quantities can represent up to four times more than electrical and plumbing. In conclusion, the trends of material quantities for both SPB and HPB in downward order are HVAC, electrical and plumbing.

The results of the third stage of this research showed that HVAC adds the largest contribution to the total GWP of each building due to the high material weight and the great GWP of some of the HVAC components. The second largest contribution to GWP are electrical systems, followed by plumbing across all building size categories. The total GWP, for MEP systems of typical commercial office buildings in the PNW ranges from 41.2 to 66.3 kg CO_2 eq/m^2 for SPB, and 53.6 to 74.8 kg CO_2 eq/m^2 for HPB across sixteen typical building size models. In conclusion, the trends of embodied carbon for both and HP buildings in downward order are HVAC, electrical and plumbing. The significant contribution of HVAC components becomes increasingly higher with the addition of refrigerants, which can contribute up to 1,890 kg CO2 eq per kg of refrigerant for types such as R-410. Assuming a 10% loss at the end of the life cycle, and 2% leakage rate during the life time (15 years) of the equipment. The result is a 40% loss of refrigerant, equivalent to 0.02 kg/sqm of the original refrigerant charge. If the refrigerant used is R-410 the total GWP of a 40% loss would be equivalent to 37.8 kgCO2e across the 15 year lifetime of the equipment.

The method described in this study represents a simplified approach to life cycle assessment, that can assist design teams to assess the overall environmental impact of MEP systems in early stages of design.

Further LCA studies focusing on MEP would greatly benefit from a more complete list of MEP equipment and materials, specific to each system and also from a more accurate assessment of total refrigerant use for each building type. More comprehensive LCA data for MEP material types specific and equipment for North America is urgently needed.

7 REFERENCES

ASHRAE. 2018. "ANSI/ASHRAE/IES Standard 90.1-2016 -- Energy Standard for Buildings Except Low-Rise Residential Buildings." Accessed May 30. https://www.ashrae.org/technical-resources/bookstore/standard-90-1.

Bortolini, Marco, Mauro Gamberi, Rita Gamberini, Alessandro Graziani, Francesco Lolli, and Alberto Regattieri. 2015. "Retrofitting of R404a Commercial Refrigeration Systems Using R410a and R407f Refrigerants." *International Journal of Refrigeration* 55 (July). Elsevier: 142–52. doi:10.1016/J.IJREFRIG.2015.02.015.

Bovea, María D., Ramón Cabello, and Daría Querol. 2007. "Comparative Life Cycle Assessment of Commonly Used Refrigerants in Commercial Refrigeration Systems." *The International Journal of Life Cycle Assessment* 12 (5): 299–307. doi:10.1065/lca2007.06.346.

CEN. 2011. "EN 15978 Sustainability of Construction Works - Assessment of Environmental Performance of Buildings - Calculation Method." Vol. 436.

Goetzler, W, M Guernsey, J Young, J Fuhrman, and O Abdelaziz. 2016. "The Future of Air Conditioning for Buildings." www.osti.gov/home/.

Oregon State. 2014. *2014 Oregon Energy Efficiency Specialty Code- Ch 5 Commercial Energy Efficiency*. www.bcd.oregon.gov.

Schoen, Lawrence J. 2010. "Preventive Maintenance Guidebook: Best Practices to Maintain Efficient and Sustainable Buildings." Washington D.C.

Seattle Department of Construction and Inspections. 2015. "Energy Code - Overview." *Seattle Department of Construction and Inspections*. http://www.seattle.gov/dpd/codesrules/codes/energy/overview/.

U.S. DOE. 2018. "State Code Adoption Tracking Analysis | Building Energy Codes Program." *Building Energy Codes Program*. https://www.energycodes.gov/state-code-adoption-tracking-analysis.

USGBC. 2013. "LEED v4 Reference Guide for Building Design and Construction (BD+C)."

Washington State. 2015. *2015 Washington State Energy Code Chapter 51-11C*. http://www.energy.wsu.edu/Documents/ga_2015WSEC_C_final.pdf.

APPENDIX A:

BACKGROUND DATA ON MEP SYSTEMS IN COMMERCIAL OFFICE BUILDINGS