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"Embodied and Operational Carbon of Typical Heating, Ventilation and Air Conditioning (HVAC) Systems in Office Buildings in Washington State: A study of buildings registered under LEED v3 2009"

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Abstract. Heating, Ventilation and Air Conditioning (HVAC) systems contribute significantly to operational energy and CO_2e emissions during the service life of office buildings. Over the last decade, stringent energy codes have enabled the introduction of new HVAC technologies to reduce operational CO_2e emissions. However, life cycle carbon emissions of buildings are odivided into operational carbon (OC) and embodied carbon (EC). Operational carbon are the CO_2e emissions generated from the burning of fossil fuels used to heat, cool and power the building space during its service life, while EC encompasses the CO_2e emissions equivalent to producing, procuring, installing, mantaining, repairing and disposing of the materials and components that make up the building. Over the last decade, broad efforts have improved the understanding of the role that HVAC system selection play in overall OC, nevertheless, EC of HVAC has remained unexamined This paper aims to identify typical HVAC systems used in office building design in Washington State and explore the effects of current practice on total energy use, operational and embodied CO_2e. The study sample is composed of twenty office buildings in Washington State registered under the LEED v3 2009 version, from which 15 have obtained LEED certification in the last two years. The projects are registered under the New Construction (NC), Core and Shell (CS), Existing Buildings and Operation and Maintenance (EB:OM) and Commercial Interiors (CI) products and comply with the requirements established in the ASHRAE 90.1-2007 energy standard. The results show that typical HVAC system selection is often a combination of different technologies for ventilation, heating and cooling, and that in general: smaller buildings tend to incorporate high efficiency packaged units while medium and large size buildings typically rely on High Performance Variable Air Volume (HPVAV) systems or hydronic systems such as chilled beams and water source heat pumps (WSHP). The results also indicate that data available through the LEED v3 2009 documentation system on embodied carbon of the mechanical systems is limited and that simplified methods to assess embodied carbon of HVAC are needed in order to integrate EC into whole life assessment of Mechanical Systems.

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1.0 Background

In the face of Climate Change, policy efforts around the world for all new buildings to operate at net zero CO_2e by 2030 have increased in recent years (Laski & Burrows, 2017). Recent ambitions to improve industry practice further contribute to the trend toward net-zero impact, and even net-positive buildings (Lützkendorf, Foliente, Balouktsi, & Wiberg, 2015). Net Zero Carbon buildings (NZC) are defined as 'a highly energy efficient building that produces on-site, or procures, enough carbon-free renewable energy to meet building operations energy consumption annually' (Architecture 2030, 2016). In this context, CO_2e emissions have been widely regarded as a key metric to understand a building's negative impact on the environment and its capacity to incorporate renewable energy sources (Laski & Burrows, 2017). A metric that uses CO_2e emissions instead of site energy intensity (SEI) includes other strategies to mitigate or defer global warming, such as CO_2e sequestration (Wang et al., 2017).

1.1. HVAC Systems in Office Buildings, Operational and Embodied CO2e

In large commercial buildings, HVAC systems represent the largest primary energy end-use (Huang et al., 2015). In developed countries, heating, ventilation, and air-conditioning (HVAC)(Cao, Dai, & Liu, 2016) account for almost half of the total energy use in commercial buildings (Yu, Yan, Sun, Hong, & Zhu, 2016) and approximately 10–20% of total energy consumption, which demonstrates the great energy reduction potential. In the United States buildings rely on electricity to meet a significant portion of its energy demands, especially for lighting and HVAC. In 2007, the emissions attributable to electricity consumption in commercial buildings for lighting, heating, cooling, and operating appliances in the US commercial sector was 79%. This made the sector accountable for 38% of CO2 emissions from fossil fuel combustion. Electricity generators consumed 36% of US energy generated from fossil fuels, and emitted 42% of total CO2 from fossil fuel combustion in 2007(Al-Sallal, 2016).

However, life cycle carbon emissions of buildings are not only operational. Life cycle CO_2 emissions of buildings are often divided into operational carbon (OC) and embodied carbon (EC). Operational carbon are the CO_2e emissions generated from the burning of fossil fuels used to heat, cool and power the building space during its service life, while EC encompasses the CO_2e emissions equivalent to producing, procuring, installing, mantaining, repairing and disposing of the materials and components that make up the building (Cabeza, Rincón, Vilariño, Pérez, & Castell, 2014). EC assessment plays a critical role in supporting decisions of building retrofit and for considerations of the large environmental impact of post disaster building destruction (Fardhosseini, 2015). Over the last decade, broad efforts have improved the understanding of the role that HVAC system selection play in overall OC, nevertheless, EC of HVAC has remained unexamined. Few studies have looked at the EC of HVAC systems, with only some exceptions quantifyng EC for different components (Chen & Zhang, 2013)(Fong, Lin, Fong, Hanby, & Greenough, 2017) (Rodriguez, Lee, Simonen, & Huang, 2019).

1.2. LEED Rating System and Building Regulation in Washington State

In the United States most state energy codes are based on model codes ANSI/ASHRAE/IES 90.1 (Standard 90.1) or the International Code Council (ICC) International Energy Conservation Code (IECC). The requirements of these codes vary by state and the control requirements can be difficult to implement, yet the assumption is that these codes are implemented and working correctly (Rosenberg, Jones, Hart, Cooper, & Hatten, 2017). The ASHRAE Standard 90.1 developed by the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) and first published in 1976 is one of the leading codes in the U.S in reducing energy demands (Baniassadi, Heusinger, & Sailor, 2018).

The LEED Rating System on the other hand is a voluntary green building rating system developed by the United States Green Building Council (USGBC), and considered widely as one of the most popular green building rating systems around the world (Wu et al., 2017). The LEED Rating system focus is on operational energy and consequently OC, however in the more recent versions of LEED (v4 and v4.1), the concept of "building life- cycle impact reduction" and "building product disclosures and optimizations" have been introduced (Meneghelli, 2018).

In Washington State, several local and state-level policies encourage green building development and energy efficiency. According to Building Energy Codes Program from the U.S. Department of Energy (DOE), the first statewide Washington State Energy Code (WSEC) was adopted in 1986 applicable to all buildings and was based on ANSI/ASHRAE/IES Standard 90A-1980 (U.S. DOE, 2018). The first amendment to the commercial energy standards came in 1991, and from that date progressive modifications for HVAC systems have included increased equipment efficiencies, more restrictive controls, and minimum motor efficiencies (SBCC, 2018). The 2012 WSEC went into effect on July 1, 2013 (WSU Energy Program, 2018). The latest version, the 2015 WSEC is one of the most stringent energy codes in the country and is more efficient than ASHRAE 90.1-2013. Washington is one of the only four states in the country that has adopted a standard with this level of requirements.

Washington is one of the states with the largest number of certified projects in the United States. One of the enablers of a wide adoption of the LEED rating system, was the enactment of Chapter 99, Laws of 2011, that required that "All major facility projects of public agencies receiving any funding in a state capital budget, or projects financed through a financing contract must be designed, constructed, and certified to at least the LEED silver standard". According to the 2017 USGBC annual ranking of LEED Buildings per state, Washington came in 11th place in 2017, with 12,469,420 total square feet of LEED-certified space from 74 certified projects, equating to 1.93 square feet of LEED space per capita (USGBC, 2018a).

2.0 Method

This study aims to respond the following research questions: What are the typical HVAC systems and equipment used in LEED registered buildings in Washington State and what is their contribution to the overall CO2e emissions in the building. In order to respond to these questions, a two-stage research plan is proposed. In the first stage, a systematic review of the project data is developed, the second stage analyses each HVAC system against the different performance indicators commonly used in LEED certification.

2.1 Data Gathering Process

The data for this project was obtained via USGBC LEED online system, the official platform for design and construction team members to upload the data for projects undergoing LEED certification process. The data available for each project are credit templates and supporting documentation to demonstrate compliance with each credit. The credit templates offer standardized data for all projects, however the organization of the template varies depending on the LEED product: New Construction (NC), Core and Shell (CS), Existing Buildings, Operation and Maintenance (EB:OM) or Commercial Interiors (CI). The type of supporting documentation in clearly indicated for each project under each credit, however the data is submitted by each project in unstructured content types. The project data was gathered during 12 months from June 2017 to June 2018 directly from the LEED Online website. The data from the website was summarized and recorded into a template for each project, the data recorded in these templates are: System Description Narratives, and Equipment List. During the second stage, specific parameters are organized into a structured database, the parameters included in this database are of five different types and are described in Table 1.

Table 1: Parameter Names in the structured database

Certification Data	**Building Parameters**	**Building Parameters- HVAC Systems**	**Simulation Input Parameters**	**Simulation Output and Performance Parameters**
Project ID	Project Name	System Type	Simulation Program	Total Electricty Proposed [kWh]
Location - city	Total gross floor area GFA [sf]	HVAC&R Equipment Type	Principal heating source	Total Natural Gas Proposed [kBtu]
Project type: Office	Building Base Area [sf]	Refrigerant Qtotal [tons]	Energy Code Used	Total Energy Use [MMBtu/yr]
LEED Project ID	Building size range [sf]	Average refrigerant impact per ton	Weather file	Energy Use Savings [%]
Certification Type	Building Size Category	Total refrigerant impact (ton)	Climate Zone	Electricity Use Intensity Proposed EUI [kWh/sf]
Certified Y/N	Conditioned Areas [sf]	Manufacturer	HDD	Natural Gas Intensity Proposed EUI [kBtu/sf]
Certification Level	Total Office Occupied Areas [sf]	Model Number	CDD	Energy Use Intensity (EUI) [kBtu/sf]
	Unconditioned office Area [sf]	Typical Hours in Operation per Week	Number of hours heating loads not met	Total Energy cost savings [%]
	Number of stories above grade		Number of hours cooling loads not met	Energy Performance Rating (1-100)
	Number of stories below (excluding parking)			CO2-eq emissions (metric t/year)
	HVAC System type			CO2-eq emissions reduction (percent)

2.2 Information about the sample

The twenty buildings analyzed are office buildings registered under the LEED 2009 version 3.0 for either NC, CS, EB:OM, and CI, and 15 have obtained some level of certification over the past two years. All buildings included in the sample are located in the State of Washington, and more specifically in the cities of: Seattle (n=15); Bellevue (n=2); Kirkland(n=1); Olympia (n=1) and Redmond (n=1). Buildings registered under LEED EB:OM (n=4) demonstrate energy performance using historical energy consumption data, while buildings registered under LEED NC, CS, and CI are modeled to estimate energy consumption via building energy simulation programs (i.e. eQuest, EnergysPro, HAP, Trace and IES). Building energy simulation (BES) has been used extensively in the industry in order to estimate energy consumption patterns and to compare of proposed design projects relative to standard designs in early stages of design. BES does not provide predictive accuracy of the

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future energy use of the buildings or HVAC systems and its limitations have been extensively documented in the literature. BES analysis is conducted by first using the software to model the proposed building geometry and the different building parameters such as: climate data, envelope materials, schedules and mechanical, electrical and plumbing systems. The proposed building is then compared to a baseline model designed following the parameters in ASHRAE 90.1 2007. Appendix G guidelines. All projects comply with the 2012 Seattle Energy Code, which is 8 to 12 percent more efficient than ASHRAE 90.1-2010 for all office building sizes (Kennedy, 2014).

Due to the large variation of the building parameters across all buildings in the sample, the office buildings were classified according to their size in three categories: Small, Medium, Large as shown in Table 2. Per USGBC requirements, data accessed via LEED Online, describing attributes of individual buildings should not be revealed publicly, all data from the platform must be reported in aggregate, therefore all data used in this study is only presented in aggregate for three building size categories.
In order to obtain data for the EC of the HVAC equipment, this study uses the equipment descriptions submitted in compliance with Credit 4: Enhanced Refrigerant Management under the Energy and Atmosphere Category for LEED-NC and LEED- CS and Credit 5 for LEED EB:OM. Only 16 buildings in the sample complied with the enhanced refrigerant management credit. The equipment weights were calculated using industry technical sheets for each type of equipment. Preliminary estimates of embodied carbon is calculated using global warming potential data from existing databases.

Table 2: Twenty sample buildings classified according to three building size categories

Project ID	Certification type	Certification Level	Building Base Area [sf]	Building size range [sf]	Building Size Category
WS1	LEED-NC v2009	NA	55,000	10,000-80,000	Small
WS2	LEED-NC v2009	Gold			
WS3	LEED-EB:OM v2009	Silver			
WS4	LEED-CS v2009	NA	135,000	80,000-300,000	Medium
WS5	LEED-EB:OM v2009	Silver			
WS6	LEED-CI v2009	Platinum			
WS7	LEED-CS v2009	Gold			
WS8	LEED-CS v2009	Gold			
WS9	LEED-CS v2009	NA			
WS10	LEED-CS v2009	Gold			
WS11	LEED-NC v2009	Platinum			
WS12	LEED-EB:OM v2009	Gold	700,000	300,000-800,000	Large
WS13	LEED-CS v2009	Gold			
WS14	LEED-CS v2009	Gold			
WS15	LEED-EB:OM v2009	Platinum			
WS16	LEED-CS v2009	NA			
WS17	LEED-CS v2009	Gold			
WS18	LEED-CS v2009	Gold			
WS19	LEED-EB:OM v2009	Gold			
WS20	LEED-CS v2009	Gold			

3.0 Results
A subsubsection. The paragraph text follows on from the subsubsection heading but should not be in italic The results of this study are described in two parts. The first part explains the results of the qualitative systematic review of HVAC systems description in LEED online supplementary information. The second part of the results describe the results of the quantitative stage of the research where each EUI and CO2 ranges is described for each building size category and type of HVAC system.

3.1 HVAC Systems descriptions per type of Building Size Category

3.1.1 Typical HVAC Systems in Small Buildings (10,000-80,000)
For most small buildings, the most common type of HVAC system packaged rooftop units (RTUs). In most cases, these RTUs are packaged rooftop heat pumps serving each individual zone in the building. Typical zone numbers in small office buildings range from 10-15 and are typically served by 2.5-15 ton individual RTUs. These RTUs include economizers, power exhaust, and short cycling protection. Another type of system used in small buildings is Variable Refrigerant Flow systems VRF including heat recovery ventilators.

3.1.2 Typical HVAC Systems in Medium Buildings (80,000-300,000)
In both medium and large building size categories High Performance Variable Air Volume Systems (HPVAV) are widely used. HPVAV are characterized by the use of optimized system control strategies, fan-pressure optimization and supply-air-temperature reset (Murphy, 2011). HPVAV also called High Performance Air Systems (HPAS) typically include heat recovery and efficient fans and capacity control(Smith, 2013).
In various buildings in the sample, the centralized system consists of a cooler supporting office by office air handling units (AHU). Each AHU provides conditioned air to all occupied spaces using parallel fan powered terminal units (PFP). Ventilation in primary office space of medium buildings is also provided by roof top units (RTUs).

3.1.3 Typical HVAC Systems in Large Buildings (300,000-800,000)
Ventilation in primary office space of large buildings, is typically achieved by roof top units (RTU) systems. These RTU serve office zones through fan powered and VAV boxes located above the ceiling. Heating in this each zone is served by a series fan powered boxes with electric reheat. Large buildings usually include a central plant that serves the entire facility including different types of use in zones.
In medium and large buildings the first retail floor is usually served by water source heat pumps (WSHPs). For most efficient buildings, the WSHP are served from high temperature chilled water return to reclaim heat that is typically rejected by cooling towers. In the most efficient buildings, these WSHP.

3.2 Performance Results per type of HVAC System and Building Size Category (EUI and total CO_2e)
For office buildings in the PNW, in general, HVAC accounts for approximately 45 to 55% of end use consumption within the building. Due to the geographical location of these buildings heating energy is less than in typical office buildings, while ventilation, cooling, pumps and miscellaneous equipment represent larger energy use.

In general, the building's site energy use intensity ranges from 35 to 70 (kBtu/sf-year) for smaller buildings, 20 to 50 (kBtu/sf-year) for medium buildings and from 30 to 60 (kBtu/sf-year) for larger buildings, as shown in Fig. 1. This is in line with the U.S National Median Reference values for the Energy Portafolio Manager (as EUI) for an office building comparable to these building types is 52.9

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kBtu/sf-year(Energy Star, 2018). As shown in Fig 1, system incorporating DOAS contribute to the energy reduction.

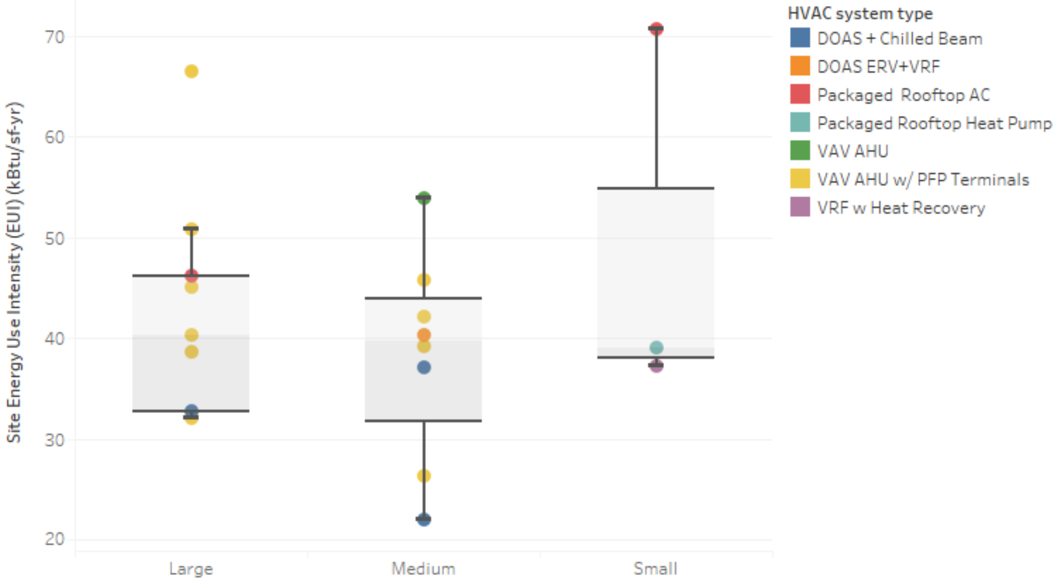

Figure 1: Site Energy Use Intensity (kBtu/sf-year) according to each building size category

The building's CO_2e use intensity ranges from 0.80 to 6.08 (kCO_2e/sqm-yr) for smaller buildings, 0 to 9.15 (kCO_2e/sqm-yr) for medium buildings and from 3.4 to 8 (kCO_2e/sqm-yr) for larger buildings, as shown in Fig. 2. The embodied carbon intensities for each type of building size category vary between 6 and 12 kCO_2e/m^2, however this only considers main refrigerant intensive equipment types and does not consider other types of equipment (i.e. air handling units, cooling towers) nor does consider other types of materials such as ductwork, refrigerants or insulation and their replacement rates.

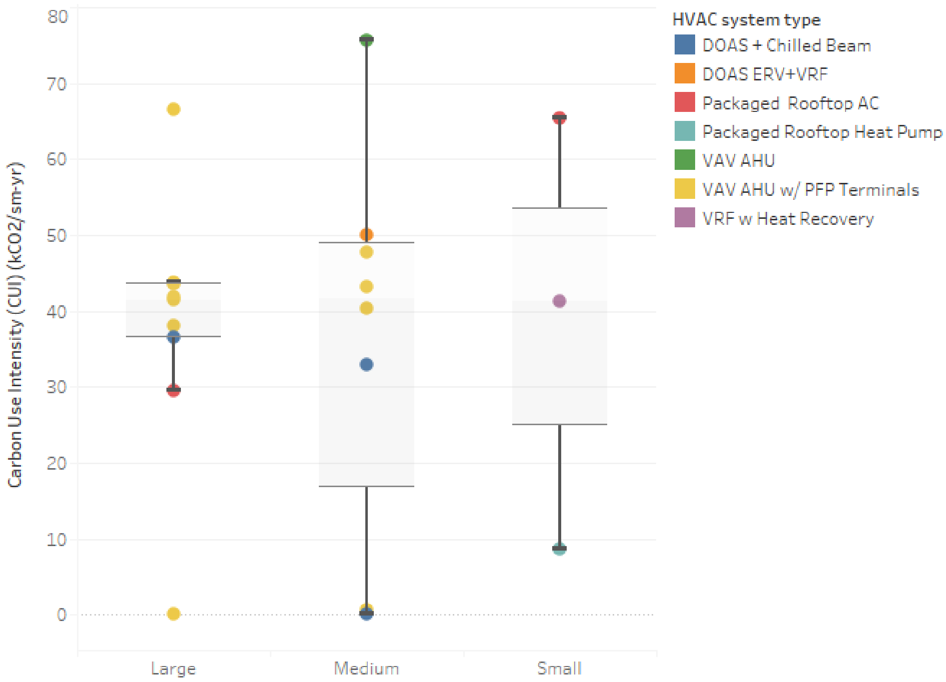

Figure 2: Operational CO_2e Intensity (kCO_2e/m^2-year) according to each building size category

Table 3: Embodied CO_2e Intensity (kCO_2e/m^2) according to each building size category

Building Size Category	Embodied CO_2e Intensity (kCO_2e/m^2) *
Large	8- 11
Medium	6-12
Small	9-10

*Scope: Main refrigerant intensive equipment types and does not consider other types of equipment (i.e. air handling units, cooling towers) nor does consider other types of materials such as ductwork, refrigerants or insulation and their replacement rates.

4.0 Conclusions

In this study, the HVAC systems of twenty buildings registered under LEED v3 where analyzed. The twenty buildings are office buildings located in Washington State and registered under the LEED 2009 version 3.0 for either NC, CS, EB:OM, and CI. Fifteen buildings have obtained some level of certification over the past two years. Buildings registered under LEED EB:OM (n=4) demonstrate energy performance using historical energy consumption data, while buildings registered under LEED NC, CS, and CI are modelled to estimate energy consumption via building energy simulation programs comparing the proposed to a baseline model designed following the parameters in ASHRAE 90.1 2007. Appendix G guidelines. The office buildings were classified according to their size in three categories: Small, medium, and large.

The results show that typical HVAC system selection is often a combination of different technologies for ventilation, heating and cooling, and that in general: smaller buildings tend to incorporate high efficiency packaged units while medium and large size buildings typically rely on High Performance Variable Air Volume (HPVAV) systems. Medium and large size buildings tend to incorporate more novel systems such as chilled beams and water source heat pumps (WSHP). Large buildings implement central plants and typically incorporate Dedicated Outdoor Air System (DOAS), which contributes significantly to reduce energy consumption for ventilation.

The building's operational CO_2e intensity ranges from 0.80 to 8 (kCO_2e/m^2-yr) for larger buildings in contrast to the initial embodied carbon intensities for each type of building size category that vary between 6 and 12 (kCO_2e/m^2). However the embodied carbon calculations only consider main refrigerant intensive equipment types and does not consider other important types of equipment for HVAC nor does consider other types of materials such as ductwork, refrigerants or insulation and their replacement rates. Further work is required to assess the different varieties of HVAC equipment, their material types and renovation rates across the building life cycle.

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