Energy Performance of Commercial Buildings with Radiant Heating and Cooling

A Study within the "Optimizing Radiant Systems for Energy Efficiency and Comfort" Project

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Abstract

This report is part of Task 5 within the California Energy Commission (CEC) EPIC project (EPIC-14-009) *Optimizing Radiant Systems for Energy Efficiency and Comfort* managed through the Center for the Built Environment at UC Berkeley. The main goal of this research was to determine the building characteristics of projects with radiant heating and cooling and assess their real world energy use compared to standard benchmarks for building energy performance. The energy use was self-reported through surveys and utility data and is based on whole building site energy use for a minimum of 12 months. System-level efficiency and energy savings opportunities are addressed in another part of the research project.

The report describes the general building characteristics including type, size, location and climate zone of 23 buildings in North America with radiant distribution systems for both heating and cooling the predominant area of the building. The study found that almost all of the 23 buildings outperformed peer buildings and national benchmarks, suggesting that radiant systems are part of the integrated approach that can lead to low energy consumption in commercial buildings. Some operator perspectives from the survey are included to inform design and operation factors regarding radiant systems.

The findings from other parts of the full project are reported separately and will be available on CBE and the CEC EPIC site in late 2017 and in 2018.

Acknowledgments

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Key Words

Radiant Systems, Benchmarking, Energy Use Intensity, Occupant Feedback, Operator Feedback, Commercial Buildings, High-Performance, EnergyStar

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Energy Performance of Commercial Buildings with Radiant Heating and Cooling

Introduction

The *Energy Performance of Commercial Buildings with Radiant Heating and Cooling* report (Energy Report) is part of the larger California Energy Commission (CEC) EPIC project managed through the Center for the Built Environment (CBE) at UC Berkeley: *Optimizing Radiant Systems for Energy Efficiency and Comfort*. The Energy Report, led by New Buildings Institute (NBI) is a part of Task 5, whose main goal is to gather field evidence from buildings to investigate Energy Performance and Occupant Comfort. The findings from the Occupant Comfort Study are reported separately.

While radiant systems have been commonly used for heating, the application of radiant for the cooling side is less common. This report documents the whole building site energy performance of a set of 23 commercial buildings in North America that employ both radiant cooling and radiant heating systems. The research focused on buildings that employ the radiant systems in at least one of three forms: a) Thermally Activated Building Systems (TABS) – the radiant piping system is embedded in the building structure (typically concrete floor slab), 2) Embedded Surface Systems (ESS) – the radiant piping system is embedded within the surface layer (not within the structure), and 3) Radiant ceiling panels (RCP) – where the radiant piping is in metal panels suspended from the ceiling[1]. The objectives of the study of energy performance are three-fold:

1. **Document a variety of building types and sizes** as real world project examples of buildings that are meeting both heating and cooling through radiant systems.
2. **Increase data on the actual energy performance of buildings using radiant** heating and cooling systems.
3. **Benchmark and compare the energy use and related savings** of the research radiant buildings against industry common and best practice buildings.

These outcomes provide a representation of radiant buildings and their overall energy performance, help establish a baseline from which to compare non-radiant buildings, and provide empirical performance data to support other parts of the overall project to estimate the energy savings potential of radiant buildings. The Energy Report findings present the absolute and comparative energy performance of the study set of buildings based on two industry standard energy use and benchmarking metrics:

1. **Energy Use Intensity (EUI)**. Energy use intensity is the most common metric of energy performance and is represented by converting all annual fuel uses to thousands (k) of British Thermal Units (Btu) divided by the total conditioned square feet (ft^2) of the building resulting in the metric of $kBtu/ft^2$. The EUIs of the study dataset are compared to subsets of a) the U.S Energy Information Agency (EIA) Commercial Building Energy Consumption Survey (CBECS 2012) and b) the current Department of Energy (DOE) Building Performance Database (BPD). EUIs are

[1] This study did not investigate differences in energy use based on system type as all analysis was on whole building site energy use.

also shown for NBI's Getting to Zero database of Zero Net Energy buildings to add the context of buildings striving for exceptionally low energy performance.

2. **EnergyStar Score**. EnergyStar is a program of the U.S. Environmental Protection Agency (EPA) resulting in a score and label based on CBECS with adjustments based on actual building characteristics and location.

In addition to analysis using the two energy performance metrics above, we summarized other data collected in the study including HVAC heating and cooling sources, climate zone, LEED status, and other noteworthy building characteristics. We have also included a small sample of feedback from building operators on their real-world experiences with radiant cooling and heating systems. This information can inform other aspects of the larger CEC-CBE study that are investigating design, application and operational factors of current and emerging radiant system designs. A set of case studies, produced in summer 2017, provide project specific outcomes for design, energy and occupant satisfaction results.

Methodology

The study relied on identification of buildings with radiant systems and the ability to obtain data and survey responses from representatives of those buildings. The research team utilized the following sources to find buildings: a) existing datasets of radiant buildings from CBE, b) advanced and zero net energy buildings from NBI, c) review of industry case studies, and d) relationships the project team had with leading design firms. The application and modifications to these initial resources within the study are described below.

Target Building Set

We began with a target building set for the study based on CBE's online database of radiant buildings (http://bit.ly/RadiantBuildingsCBEv2). To this set, we added other potential building candidates from NBI's Getting to Zero (GtZ) database (http://newbuildings.org/resource/getting-to-zero-database/), as well as selections from industry case studies and outreach to building architect and engineering firms involved in design for radiant buildings[2]. At the start of the study, we identified nearly 300 buildings in the initial list of potential candidates.

To meet the applicability to the research, we culled the list of candidate buildings that met certain criteria, including: building type, building size, occupancy size, proportion of building served by radiant, presence of radiant cooling, target types of radiant systems, region, and duration of full occupancy.

Table 1 describes parameters for inclusion in the study set. The goal of this process was to ensure the candidate buildings were predominantly heated and cooled with one or more of the radiant systems shown in Table 1 and that they were types, sizes and climates transferable to the California commercial market and overall research objectives.

[2] See Appendix for list of sources

Table 1: Radiant criteria used to prioritize buildings for outreach efforts

Category	Criteria Guideline for Study
Building Type	Office, Education, Library, Government, Retail
Building Size	7,500 ft^2 or larger
Region	North America
Radiant Use	Heating and Cooling
Radiant Proportion	Primary system in majority of building
Radiant System Type	TABS, ESS, and/or RCP
Occupancy	12 month minimum

After screening the initial set for these criteria and conducting extensive outreach to determine the applicability of the buildings to the study, the revised set of potential participants was approximately half (146). One significant part of this reduction was the common finding that buildings initially identified as 'radiant' only applied it to a small portion of the building such as a foyer or that it was only used for heating and not applied to cooling.

Data collection

To collect data for each building, we developed two new online surveys to supplement the existing survey from CBE on Building Characteristics (http://www.cbe.berkeley.edu/survey/). Table 2 outlines the two new energy-related surveys. For the energy benchmarking we needed participation from both the building designer and the building operator to gather building characteristics and building energy and operational data. The Energy Consumption and Operational Parameters were linked so that if the respondent had the energy performance data and served as the operations person of the building they could reply to a single survey.

Table 2: Online surveys for data collection

Survey	Completed By	Data Collected
Building Characteristics	Architect or MEP	General info, certifications, systems, windows and shading, controls
Energy Consumption	Owner, Building Manager and/or Building Operator	Energy usage, system types, energy tracking and targets, benchmarking data
Operational Parameters	Building Operator	Set points, controls, reliability, and lessons learned

The outreach phase for this project spanned over a year from December 2015 to February 2017. After initial research to catalog design team information for candidate buildings, NBI and CBE leveraged existing relationships with building designers to facilitate initial communications. These existing relationships were helpful in facilitating the data collection process for buildings and identifying a building operator and getting participation from multiple parties to complete the online surveys.

Data Collection Challenges

We encountered several challenges in the outreach and data collection phase. First, identifying and getting in touch with the building architect or MEP engineer took considerable effort in cases where neither NBI nor CBE had an existing relationship. In many cases, the designer was either unresponsive, too busy to share information, or had left the design firm. The burden to fill out the surveys without having worked directly on the project in question proved too high for design firms in cases where the primary architect or engineer had left the company. Even in cases with strong professional relationships between the study team members and the building design team responses were slow and/or included references to a variety of other parties which took the study team up to dozens of outreach efforts to attempt to find the correct contact.

As we first encountered these challenges, we budgeted gift cards to offer an incentive for designers to participate in the study. The gift cards helped to slightly increase the response rate and, after retiring projects with no responsiveness after multiple attempts, the team had a next phase set of approximately 45 buildings with correct contacts that indicated a willingness to respond to the research surveys.

Of these 45 willing candidates, the resulting study set of 23 represents about a 50% success rate. The additional reduction was due in part to the continued problem of getting through to the appropriate parties for these buildings and the inevitable issue of survey completeness. This proved to be another challenge requiring additional follow up with designers and/or outside research to gather critical pieces of information omitted in the surveys. Examples of missing data include energy data, heating and cooling systems, hours of operation, number of occupants, and contradictory building sizes.

Although the original target was 50 buildings the lack of a large number of available buildings that fulfilled the criteria described above brought the final number of analyzed buildings in this Energy Report down to 23. This represents data from 16% (23/146) of the final building set that met the criteria and is a reasonable research participation result. The data set for these 23 buildings provides the largest dataset of actual radiant heated and cooled building energy performance known to the research team and provides new references to contribute to the estimation of potential savings from the use of radiant heating and cooling.

Data analysis

The data analysis methodology utilized standard energy performance metrics and datasets from which to a) represent the research dataset energy performance and b) compare it to national benchmarks and calculate energy use differences.

Energy Performance Metrics

We report and compare energy consumption for the research buildings and the national benchmarks datasets of actual energy performance as EUI with units of $kBtu/ft^2$. EUI is a widely used metric in the building and energy industry. The main advantage of this metric is that it is easy to calculate and understand. The tradeoff is that EUI does not take into account climate, building type, number of occupants or other factors that affect energy usage. To account for these additional factors and allow for a more robust comparison of building performance, we have calculated EnergyStar scores using the Portfolio Manager Target Finder tool[3].

EnergyStar scores are currently available for a wide range of specific building types but do not cover every building type. For buildings in the dataset that did not precisely align with an EnergyStar building type we used the nearest building type to estimate the building's score. Two buildings in our dataset, a Community and a Visitor Center, did not have a similar building type so do not have a score.

A description of each benchmark is in the Energy Performance Section of this report.

Building Characteristics

The buildings in our research building set had several leading design aspects in common. We observed that efficient HVAC technology, design targets, passive designs, and certifications are common in our building set. The majority of studied buildings were LEED platinum (74%), with two even reaching Living Building Challenge[4] certification and all but one project reached some level of LEED certification. We also found a good diversity in size and building type in the research dataset that reflects a broad range of market applicability. We anonymized and assigned a simple ID number to each building and represent the basic building characteristic findings from the 23 buildings reflecting four building types in Table 3 including location, type, size, and climate zone.

Table 3: Basic building characteristics of studies building set

Building ID	City	State	Type	Size (ft^2)	Year Built / Last Renovation	Climate Zone [5]
1	Fort Collins	CO	Education	95,000	1936 / 2014	5B
2	Portland	OR	Office	10,000	1910 / 2004	4C
3	Vancouver	BC	Library	36,000	1900 / 2010	4C
4	Berkeley	CA	Office	45,000	2009 / None	3C
5	Vaughan	ON	Office	60,000	2004 / None	6A
6	Portland	OR	Office	440,000	2013 / 2013	4C
7	San Jose	CA	Office and Lab	50,000	2011 / None	3C
8	San Francisco	CA	Education	200,000	2013 / 2013	3C
9	Eugene	OR	Education	92,000	2013 / None	4C
10	Port Coquitlam	BC	Community Ctr.	14,500	2006 / None	4C
11	Winnipeg	MB	Office	700,000	2009 / 2009	7A
12	Golden	CO	Office	360,000	2010 / 2012	5B
13	Salem	OR	Office	147,000	1950 / 2012	4C
14	Atlanta	GA	Office	44,000	1986 / 2010	3A
15	Claremont	CA	Education	75,000	2015 / None	3B
16	Portland	OR	Office	205,000	2010 / None	4C
17	Victoria	BC	Office and Lab	16,150	2012 / None	4C
18	Sonoma	CA	Medical Housing	16,000	2014 / None	3C

[3] Portfolio Manager Target Finder: https://portfoliomanager.energystar.gov/pm/targetFinder
[4] The Living Building Challenge (LBC) https://living-future.org/lbc/
[5] ASHRAE http://buildingadvisor.com/wp-content/uploads/2014/05/USA-Climate-Zone-Map-ASHRAE.jpg

Building ID	City	State	Type	Size (ft^2)	Year Built / Last Renovation	Climate Zone [5]
19	Vancouver	BC	Visitor Ctr. / Public Assembly	19,400	2011 / None	4C
20	Berkeley	CA	Library	9,400	2013 / None	3C
21	Varennes	QC	Library	24,000	2012 / None	6A
22	Seattle	WA	Office	52,000	2013 / None	4C
23	Clemson	SC	Education	50,300	2012 / None	3A

Climate Zones

Although our criteria included buildings from anywhere in North America, the majority of the final analyzed building set is in temperate marine climate zones, most commonly 4C (42% - Coastal Pacific Northwest, Mixed Marine) and secondly in 3C (21% - Coastal California, Warm-Marine). The remaining buildings span 5 other climate zones including: 3A (warm-humid), 3B (warm-dry), 5B (cool-dry), 6A (cool-humid), and 7A (very cold). Figure 1 shows the distribution of climate zones in the building set.

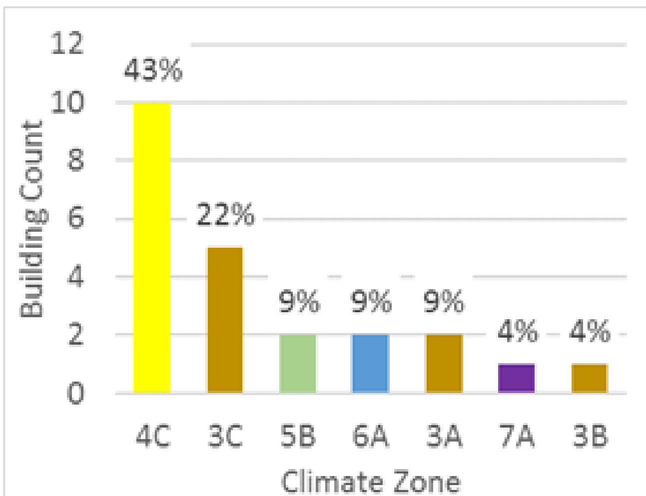

Figure 1: Building count by climate zone of the studied building set

Size

The building sizes are diverse, with buildings greater than 50,000 ft^2 representing 52% of the buildings but 90% of the total square feet in the dataset. Figure 2 further divides this dataset displaying the range of building sizes. The final set has a relatively even distribution, with three size bins each having six buildings. Note that the research set of buildings was limited to those larger than 7,500 ft^2.

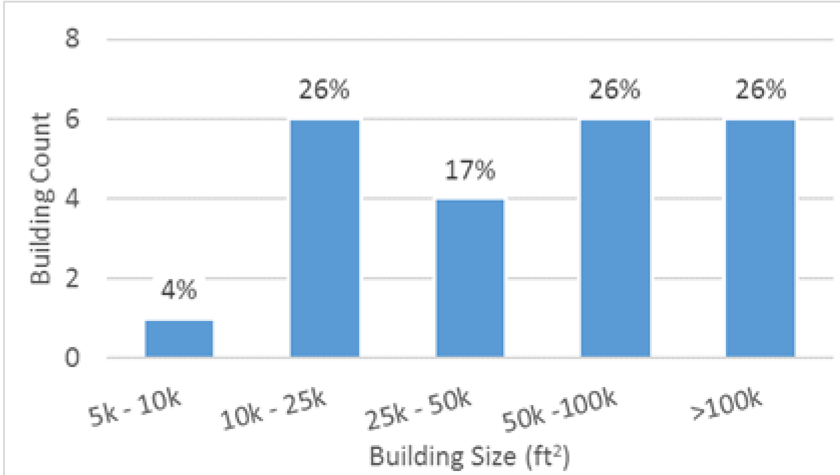

Figure 2: Building size distribution of the studied building set

Types

The study set is distributed between four broad building types as designated by the initial study criteria. Office buildings were the most common, making up nearly half of the final set. Education, library, and other building types make up the rest of the sample as shown in Figure 3. The few buildings that had some mixed uses are categorized by predominant occupancy.

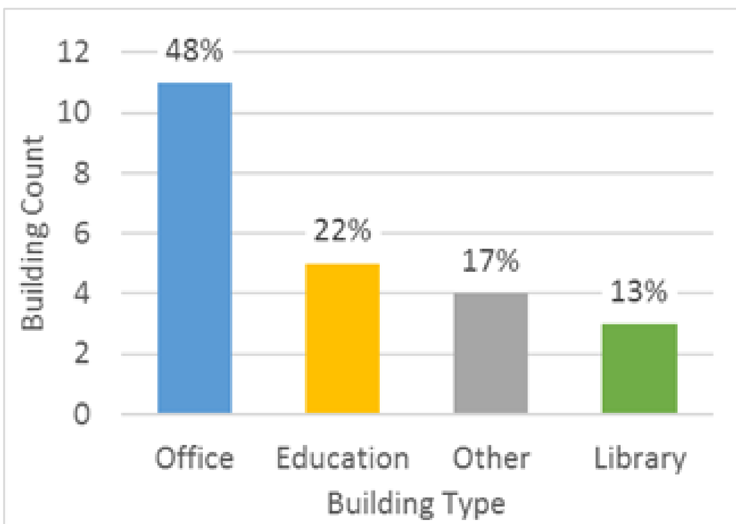

Figure 3: Building type distribution of the studied building set

Heating Ventilation and Air Conditioning (HVAC) Technologies

For heating more than half of the studied buildings (58%) use a ground-source heat pump. Other heating systems used by these projects included air source heat pumps, boilers, or district steam. The use of boilers was both as primary systems and for supplemental heating to assist the ground or air source heat pump. One project (ID: 10) used a gas fired rooftop unit as a backup system, which may explain in part the higher energy usage of that project.

For cooling, systems were diverse and often applied as a mixed-mode approach with cooling provided in stages starting with operable windows or natural ventilation. Chillers with cooling towers were the most common cooling source (30%) for the radiant system. Other cooling systems used ground source, air-cooled chillers, or heat recovery chillers.

Energy Performance

The results in this section highlight the overall site energy performance of the 23 sample set of radiant buildings collected through our research. These findings on the energy use of the dataset are then compared to the two metrics previously introduced – Energy Use Intensity and EnergyStar Score.

Site Energy Use of the Research Dataset

The energy use of the 23 buildings in the research is based on metered utility bills and thus reflects the site energy use at the building. The energy use is reported in Table 4 in kBtu/ft^2 (EUI) and the buildings are sorted first by type and then by EUI.

Table 4: Building characteristics and EUI of the research building set sorted by type and EUI

Building ID	City	State	Type	Size (ft^2)	Year Built / Last Renovation	EUI
22	Seattle	WA	Office	52,000	2013 / None	12
6	Portland	OR	Office	440,000	2013 / 2013	32
12	Golden	CO	Office	360,000	2010 / 2012	36
13	Salem	OR	Office	147,000	1950 / 2012	36
16	Portland	OR	Office	205,000	2010 / None	46
2	Portland	OR	Office	10,000	1910 / 2004	48
5	Vaughan	ON	Office	60,000	2004 / None	55
11	Winnipeg	MB	Office	700,000	2009 / 2009	62
4	Berkeley	CA	Office	45,000	2009 / None	144
14	Atlanta	GA	Office	44,000	1986 / 2010	176
7	San Jose	CA	Office and Lab	50,000	2011 / None	37
17	Victoria	BC	Office and Lab	16.150	2012 / None	48
9	Eugene	OR	Education	92,000	2013 / None	27
1	Fort Collins	CO	Education	95,000	1936 / 2014	28
8	San Francisco	CA	Education	200,000	2013 / 2013	37
23	Clemson	SC	Education	50,300	2012 / None	43
15	Claremont	CA	Education	75,000	2015 / None	52
21	Varennes	QC	Library	24,000	2012 / None	15
20	Berkeley	CA	Library	9,400	2013 / None	23
3	Vancouver	BC	Library	36,000	1900 / 2010	154
18	Sonoma	CA	Medical Housing	16,000	2014 / None	32
19	Vancouver	BC	Visitor Ctr. / Public Assembly	19,400	2011 / None	38
10	Port Coquitlam	BC	Community Ctr.	14,500	2006 / None	143

In Figure 4 the energy performance of the research dataset of buildings shows the majority of buildings in the lower end of energy use with a few outliers. The factors driving the higher energy use in these outliers are not known but the reasons usually include longer hours of operation, higher density of occupants, and possible controls issues in addition to design characteristics which may not have optimized the envelope. More relevant is that the majority of the radiant research buildings are under 50 kBtu/ft^2 with few even below 25 kBtu/ft^2. The relationship of these energy performance levels to comparative building sets is discussed in the subsequent section.

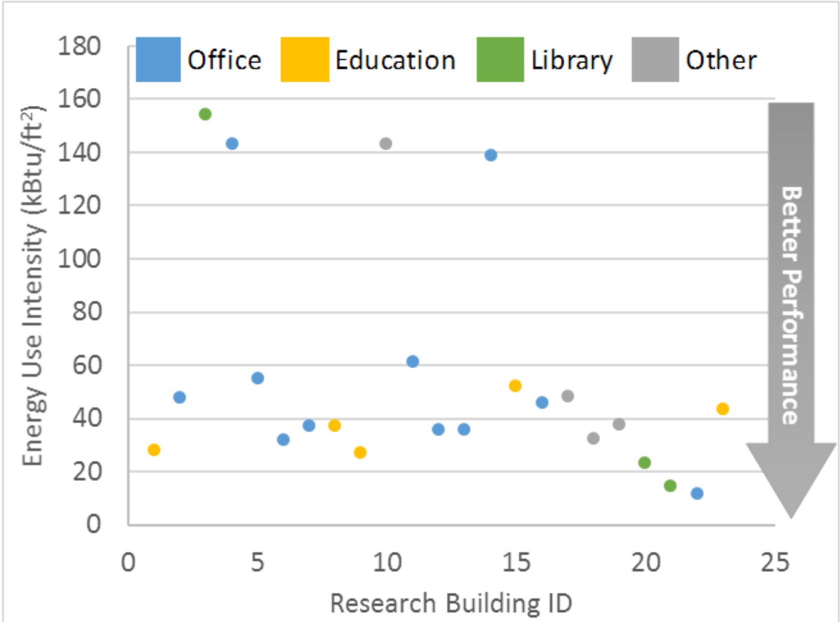

Figure 4: Individual building EUIs of the research building set color-coded by building type. n=23

Comparative Energy Use

The energy use of the research dataset is compared to publicly available data on energy use and energy scores of similar buildings. In this study the following datasets are used in the analysis:

1. **U.S Energy Information Agency (EIA) 2012 *Commercial Building Energy Consumption Survey (CBECS 2012)***[6]. CBECS is the national sample survey on the stock of U.S. commercial buildings, including their energy-related building characteristics and actual energy usage data of 6700 U.S. buildings representative of the approximate the U.S. non-mall building stock of 5.6 million buildings and 87 billion square feet of floor space.
2. **Department of Energy (DOE) *Building Performance Database (BPD)***[7] is the nation's largest dataset of information about the energy-related characteristics of commercial and residential buildings. The BPD combines, cleanses and anonymizes data collected by Federal, State and local governments, utilities, energy efficiency programs, building owners and private companies. The BPD is an ongoing database that merges many datasets including the California Commercial Energy Use Survey (CEUS 2006) as well as self-reported data.
3. **New Building Institute's *Getting to Zero (GtZ) Database*** of Zero Net Energy buildings[8]. The GtZ includes information on measured and modeled energy performance, environmental characteristics, design process, finances, and other aspects of project at or striving to be Zero Net Energy.
4. **The U.S. Environmental Protection Agency (EPA) *EnergyStar Program*** includes a scoring and certification program for commercial buildings based on CBECS with adjustments based on actual building characteristics and location. EnergyStar benchmark methodology has been recently questioned[9] but is the most widely market-adopted energy benchmarks in the U.S. with

[6] CBECS 2012 https://www.eia.gov/consumption/commercial/
[7] DOE BPD https://energy.gov/eere/buildings/building-performance-database
[8] NBI GtZ database http://newbuildings.org/resource/getting-to-zero-database/
[9] Scofield, J. ACEEE proceeding 2014 http://aceee.org/files/proceedings/2014/data/papers/3-725.pdf

more than 28,000 commercial buildings and 5 billon square feet of commercial floor space certified[10]. In addition, the EnergyStar score is used as the basis for city-adopted policies requiring benchmarking that currently is in place in 19 cities impacting over 5 billion square feet of commercial floor space[11].

The CBECS and BPD subsets are filtered to closely match the radiant building set. Filters include size (7,000 ft^2 to 300,000 ft^2), building type (office, education, and library), and location (pacific region for CBECS; climate zones 3A, 3B, 3C, 4C, 5B for the BPD). To add more context NBI's GtZ Database, considered the highest performance buildings in the market, is filtered for Zero Net Energy (ZNE) buildings with measured energy performance and included as an additional benchmark. Note that CEUS is omitted as a benchmark in this section due a) unavailable data granularity to compute metrics other than average energy use and b) the research dataset includes many buildings outside of California climate zones.

Energy Use Intensity

The EUI of the analyzed buildings is lower (better) than national benchmarks. Table 5 shows the EUIs of the research dataset compared to the three national datasets across the three predominant building types in the research.

As shown in Table 5, the median EUI of the full research dataset of buildings is 38 kBtu/ft^2, while the average EUI (not shown) is 56 kBtu/ft^2. In Table 6, the EUIs of the research set of radiant buildings is represented as a percent lower energy use than the benchmarks. By building type, offices consume 22-27% less and education consume 14-23% less energy than the national benchmark references. Library energy use is the greatest difference with the research dataset consuming 58-66% less energy than the benchmarks. The full dataset uses 31 and 32% less energy than the BPD and CBECs subset databases, respectively.

Table 5: Comparison of EUI (kBtu/ft^2) of research building to national benchmarks

Building Type	Research Set Median EUI	2012 CBECS[12] Subset Median EUI	BPD[13] Subset Median EUI	Net Zero Energy[14] Median EUI
Office	46	59	63	22
Education	37	48	43	18
Library	23	67	55	18
All Buildings	38	56	55	18

[10] EnergyStar 2015 Snapshot www.energystar.gov/sites/default/files/tools/ENERGY%20STAR%202015%20Snapshot_1.pdf
[11] Building Rating and Policy Status at The Institute for Market Transformation http://www.buildingrating.org/
[12] The Commercial Building Energy Consumption Survey (CBECS) http://www.eia.gov/consumption/commercial/
[13] Department of Energy Building Performance Database (BPD) https://bpd.lbl.gov/
[14] Source NBI Getting to Zero Database (GtZ) http://newbuildings.org/resource/getting-to-zero-database/

Table 6: Percent energy use reduction of research buildings compared to national benchmarks

Building Type	Research Set Median EUI	Research Set Percent Energy Use Reduction Compared to: CBECS 2012 Subset Median	Research Set Percent Energy Use Reduction Compared to: BPD Subset Median
Office	46	-22%	-27%
Education	37	-23%	-14%
Library	23	-66%	-58%
All Buildings	38	-32%	-31%

In Figure 5 the research building set is compared alongside the three same benchmarks shown in Table 5. The box plot in Figure 5 bounds the two interquartile ranges for each dataset with each horizontal line representing the 25th, 50th (median) and 75th percentile EUI. The plot shows that the majority (75%) of the radiant research dataset are equal to or better than the best 50% of the benchmark buildings. In addition, the energy use of the median research radiant building is near or below the 25th percentile EUI of the CBECS and the BPD benchmarks. The research dataset energy performance in Figure 5 is also approaching that of the best performing buildings – the GtZ ZNE dataset.

Figure 5: Box plot bounding 25th and 50th percentile EUI of the research set and various benchmarks

Although this limited set of research buildings is not representative of the entire stock of buildings with radiant systems, the research dataset are consistently among the top performers compared to peer buildings of the same size, type, and location. The dataset utilized radiant heating and cooling as one strategy toward aggressive energy performance targets (95% were LEED buildings with 75% seeking platinum LEED) and the strong energy performance outcomes found in this research. This pattern of using radiant systems to accomplish low-energy outcomes is also seen by over half of the ZNE buildings in NBI's GtZ database. The EnergyStar scores of the buildings as discussed in the following section further support this.

EnergyStar Scores

The EnergyStar score benchmarks an individual building against the national building stock normalized for location, type and building characteristics resulting in a score ranging from one (poor) to 100 (best). A score of 50 represents a median performing building, while a score of 95 represents a building in the top 5% of like buildings in terms of performance. To be certified as an 'EnergyStar Building' it must have a score of 75 or greater reflecting that it is in the top quartile of like-type buildings nationally.

Compared to the EnergyStar references, the set of research buildings again shows predominately high-performers compared to this benchmark as seen in Figure 6 across the range of building types and sizes studied. The EnergyStar scores of the radiant buildings indicate that they significantly outperform their peers, with the majority (67%) having an EnergyStar score of 90 or greater, reflecting that their energy performance is in the top 10th percentile of like-type and climate U.S. buildings. These buildings are also significantly better than the median EnergyStar buildings (Score of 50) and certified requirements (Score of 75). However, two of the research buildings are well below the EnergyStar certified levels with one being a dismal score of 1. The reason for the extremely high energy use at these individual buildings would require deeper investigation but could be related to greater occupancy density or operating hours than its peers as well as due to design, operational or technology issues.

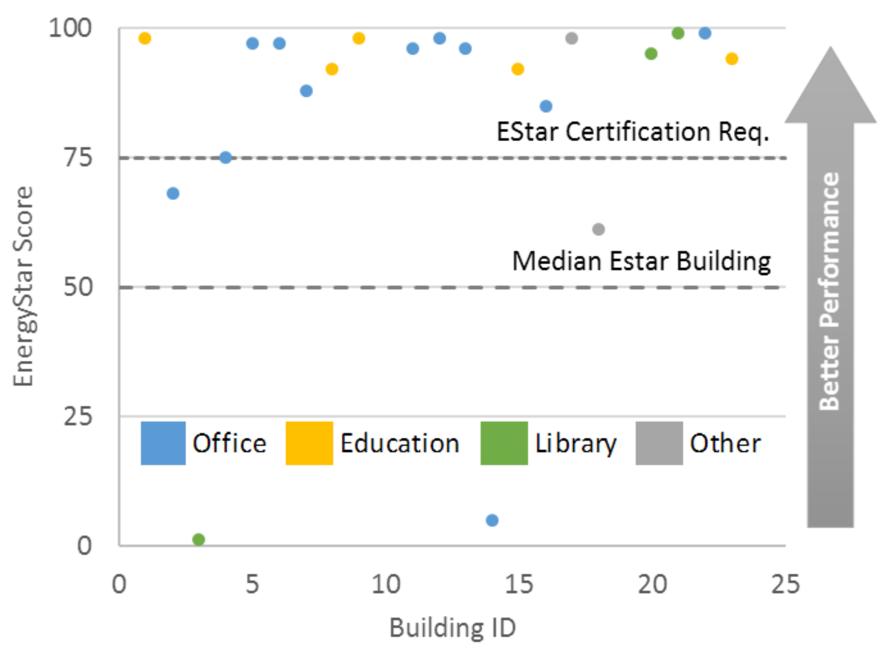

Figure 6: Calculated EnergyStar scores for analyzed buildings. Scaled from 1-100. n=21

Radiant within the Context of Overall Energy Use

The research team clearly recognizes that the energy performance of these buildings cannot be directly attributed solely to the radiant system as there are many factors that influence energy consumption such as the building's envelope, lighting design, plug loads, control systems, occupancy level and operations. While isolating discreet system energy impact is beyond the scope of this study the larger part of this EPIC project will provide greater analysis of radiant-specific energy impact in a lab setting and from energy modeling of system design variations. The role of radiant, for this study, is examined within the context of the larger picture of whole building energy performance outcomes.

High performing dataset. In reviewing the whole building energy performance of this research dataset it is clear that they are generally very high performing buildings and the radiant system is a part of what is normally the largest contributor to energy use – the HVAC system. In California, HVAC represents the highest proportion (32%) of energy use in commercial buildings[15]. Obtaining low-energy outcomes can only be accomplished by addressing the HVAC as a system and involves an integrated design approach wherein the interactive effects of design and technology selections are key to energy performance results.

Examples of integrated impacts. The HVAC system selection can influence and benefit other energy-using design decisions. In the case of selecting a radiant system it usually means limiting the overall design cooling load because there ae physical limitations to how much cooling a radiant system, particularly ESS & TABS, can achieve. This will translate into a better envelope, lower lighting loads, and efforts to reduce plug loads which in turn reduce overall building energy consumption. In addition, the use of radiant systems is most frequently associated with dedicated outside air systems (DOAS) which reduce fan energy needed for ventilation compared to standard forced-air systems. Also the heating and cooling sources associated with radiant are typically more efficient such as those seen in this sample set of buildings. This is partly because large radiant active heat transfer surfaces can effectively cool with higher temperature water, and heat with lower temperature water, which reduces the energy needed from the supply source.

Radiant systems support low-energy targets. While forced-air distribution systems remain the predominant approach to heating and cooling in U.S. commercial buildings[16] radiant systems are more often selected by leading designers striving for low-energy and other 'green' building outcomes. For example, according to NBI's GtZ Database, more than half of the successful net zero energy buildings in North America use a radiant system and a survey of 29 advanced ZNE and near ZNE buildings in CA showed 11 with radiant systems[17]. As stated earlier in this report, 74% of the research buildings were targeting the highest levels of LEED (platinum) and selected radiant distribution systems as part of their approach to optimize energy efficiency. In this context, the radiant system is a documented approach within an integrated efficient total HVAC system to achieve low energy use outcomes as seen in the majority of this study set.

Operations Opinions

Achieving high performance in buildings relies in part on the role of the building operators and control systems. Experienced operators and smart control systems are able to minimize energy use while maintaining occupant comfort. Radiant systems behave differently from traditional forced air systems, and installers and operators must therefore learn to operate them accordingly.

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[15] CEUS 2006

[16] Energy Information Agency CBECS

[17] TRC and PG&E, ACEEE 2016 http://aceee.org/files/proceedings/2016/data/papers/3_636.pdf

In addition to energy data, we a small sample of the building operators responded to the survey questions on management of the radiant systems. Table 7 presents these individuals' perspectives around several topics. These are not a representative sample of either the building operators within the research dataset nor of the market at large by any means but do provide insights to these particular participant's opinions.

Table 7: Highlighted feedback from building operators and designers grouped by recurring themes

General Comments	• We would absolutely use a radiant system again because it is so simple from an O&M perspective. Very few moving parts, good accessibility for the slab pump and manifolds, good comfort, etc. • Very efficient, generally correct temperatures, no fan noise in the office, lower dust and airborne germs circulating than with forced air. • The radiant system is cost effective, energy efficient and provides excellent occupant comfort. • Radiant heating and cooling from ceiling may result in uncomfortable temperatures below desks and horizontal surfaces.
System Response Time	• The slow ramp time of the building to heat or cool is challenging. • Slow response to raise/lower temperatures. • Have had difficulty in changing loop temperature - slow to respond to changes.
Staff Experience	• Allows for precise zone control, but does require staff with more controls experience to manage. • The biggest challenge we've had is operator training - the tendency is for operators to run a radiant system as they would a forced-air system, making dramatic adjustments if there are complaints and expecting quick results. • We had an inexperienced operator set the slab supply water temperature to 8°C to attempt to eliminate overheating complaints, and you can imagine the issues that caused (*implying that low temperature possibly caused condensation among other issues)*. • Operators need to understand that the radiant slab we have is intended for 'average' heating and cooling, and not meant to respond instantaneously or in a precise area.
Recommended changes for next design	• We would simplify the system and provide less control zones. • Just use for heating and allow individual forced air zone control for cooling. • Place 2 slab temperature sensors instead of one as slab temperature sensors tend to fail and are hard to replace. • Possibly provide greater heating capacity - some limits in rate of temperature rise. • Best to break out separate zones for the south and north ends of the building. Our building relies on passive solar heating quite extensively, so our loads were more solar-based rather than internal gains-based.

Summary

The *Energy Performance of Commercial Buildings with Radiant Heating and Cooling* report outlines the goals, methods, and findings of the energy portion of Task 5 within the broader scope of the CEC EPIC project, *Optimizing Radiant Systems for Energy Efficiency and Comfort.* The primary goals of this research are to report actual energy usage of existing buildings that have both radiant heating and cooling systems and to compare the research buildings with other benchmarks of energy performance. The energy data presented provides real-world examples of radiant buildings and their energy outcomes and will aid in establishing a baseline from which to estimate potential energy savings from increased adoption of radiant systems in new construction.

The energy performance of 23 commercial buildings is shown both as kBtu/ft^2 (the Energy Use Intensity or EUI) and as an EnergyStar score, which further contextualizes the energy usage by providing a simple 1-100 score that is widely used in commercial real estate and energy assessment. In addition to energy data, the building characteristics of the research buildings offer insights to the applicability of radiant systems. A small set of feedback from building operators is included to provide a sense of the operational benefits and challenges faced by building operators in these existing buildings.

Building Characteristics

The research buildings varied in size, climate zone, and type. Most buildings (43%) were in climate zone 4C represented by Coastal Pacific Northwest, Mixed Marine and secondly in 3C (22%) in the Coastal California, Warm-Marine climate. Offices made up the largest portion of building types (nearly 50%) followed by education and library. The number of buildings in the study distributed by size was split evenly above and below 50,000 ft^2 with buildings greater than 50,000 ft^2 representing 52% of the buildings but nearly 90% of the total square feet in the dataset.

Energy Performance

The energy performance of the 23 analyzed buildings was predominantly very efficient with a few outliers using 2-3 times more energy than their study set peers. Figure 7 shows the spread of the EUI for the research dataset of buildings. The majority of buildings (70%) are below 50 kBtu/ft^2 and 14% of them are below 25 kBtu/ft^2 – a threshold often used to define the best energy performance for these buildings types and used to target zero net energy performance whereby the inclusion of onsite renewables may be able to offset the full buildings site energy use[18].

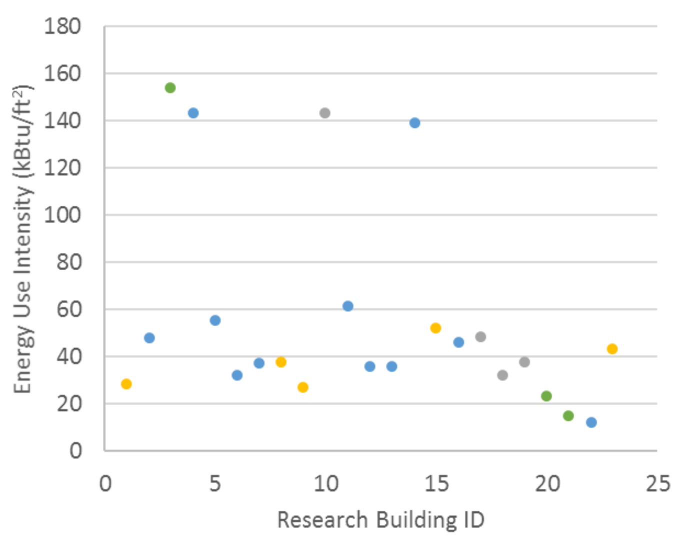

Figure 7: Total site building energy use of the research building dataset n=23

[18] NREL Realizing High-Performance Buildings http://www.nrel.gov/docs/fy15osti/62530.pdf

Comparative Energy Use

Energy Use Intensity (EUI). The median EUI for these buildings was below (better than) both national benchmarks, CBECS and the BPD, as seen in Figure 8. The analysis also shows clearly that the majority (75%) of the radiant research dataset are equal to or better than the best 50% of the benchmark buildings. The median EUI of the full research dataset (38 kBtu/ft^2) is 31% and 32% less energy intensive than the BPD and CBECs subset databases respectively. By building type, offices used 22-27% less and education used 14-23% less energy than the national benchmark references. Library energy use is the greatest difference with the research dataset using 58-66% less energy than the benchmarks.

Figure 8: Box plot bounding 25th and 50th percentile EUIs of the research set and various benchmarks

EnergyStar Scores. The EnergyStar scores of the radiant buildings also indicate that they outperform their peers. 67% of the research dataset buildings have EnergyStar scores above 90 which indicates that they are in the top 10% of buildings relative to their peers. Further, all but four buildings (81%) had EnergyStar scores at or above 75, meaning that they quality for EnergyStar certification and almost all of the research buildings are significantly better than the median EnergyStar buildings (Score of 50).

Zero Net Energy Buildings. The research dataset energy performance is also approaching and mirroring that of the best performing buildings in North America (NBI GtZ ZNE dataset) with the best performing research buildings having comparable EUIs in the 20s. In addition, the study noted that two independent study datasets found the majority of ZNE buildings use radiant systems, which suggests that leading designers have identified radiant systems as a part of their solution to get to low-energy results.

Radiant Systems Support Low-Energy Results

It is not a single system that creates improved energy outcomes, but rather an integrated approach addressing a wide range of building factors including design, technology, operational and occupancy factors, but each system matters. An integrated design approach relies on interactive affects and the selection of radiant systems can be a driver to reduce the overall building cooling load that needs to be served and thus influence improved envelope, window selection and ratios, lighting and plug loads. All but one of the research dataset targeted a LEED certification and 74% aimed for the highest level of LEED platinum. HVAC is the largest energy use in typical buildings and in this research set the design firms chose radiant systems as a key component to meet their heating and cooling needs and low-energy targets. The research dataset shows consistency regarding low-energy targets, the use of radiant systems, and comparatively low-energy outcomes.

Operator Perspective

Based on the small sample of feedback operators often praised radiant systems for energy performance and air quality, but also mentioned issues arising from the lack of operator experience with radiant systems. Operators often controlled radiant systems as they would a forced air system and most operators noted the relatively slow response time to set point changes.

Next Steps

This study provides the largest dataset of radiant heated and cooled building's measured energy performance known to the research team and provides new references to contribute to the estimation of potential savings from the use of radiant heating and cooling. A separate study of occupant comfort within Task 5 will present results from occupant surveys in these, and other, radiant buildings.

The findings of this Energy Report will contribute to the larger CEC EPIC project on radiant systems, led by UC Berkeley Center for the Built Environment, addressing optimum system design and operational characteristics for next generation radiant systems. Results and guidance from these studies will support the improved performance, and potential for increased adoption of, radiant systems in California as a path to meet state goals for low energy use in commercial buildings.

Appendix

This appendix provides the data sources and calculation basis from which we established the findings in the *EPIC Energy Use of Commercial Buildings with Radiant Heating and Cooling*.

Data Sources

These sources were used to identify buildings that met the study criteria.

- UC Berkeley Center for the Built Environment database of Radiant Buildings[19]
  http://bit.ly/RadiantBuildingsCBEv2
- New Buildings Institute Getting to Zero database of North America Zero Net Energy Buildings
  http://newbuildings.org/resource/getting-to-zero-database/
- Case Studies of leading buildings:
  - PG&E Zero Net Energy Volume I and II
  - ASHRAE High Performance Magazine
  - International Living Future Institute
  - AIA Top Ten
  - NBI Getting to Zero Case and High Performance Building Case Studies
- Outreach to architecture and engineering firms involved in radiant buildings:
  - Integral Group, Oakland and San Francisco CA, Vancouver BC
  - Arup
  - EHDD Architecture
  - Transsolar
  - Opsis Architecture
  - Perkins+Will Architects
  - SERA Architects
  - Stantec
  - HOK
  - AECOM

Benchmark Sources

We compared the study set of buildings to these datasets of actual energy performance.

1. Energy Information Agency Commercial Buildings Energy Consumption Survey – CBECS
   http://www.eia.gov/consumption/commercial/
2. LBNL-DOE Buildings Performance Database – BPD 0 https://bpd.lbl.gov/
3. U.S. Environmental Protection Agency EnergyStar Portfolio Manager Scores
   https://portfoliomanager.energystar.gov/pm/targetFinder?execution=e1s1
4. New Buildings Institute Getting to Zero database of North America Zero Net Energy Buildings
   http://newbuildings.org/resource/getting-to-zero-database/

[19] CBE was a smaller dataset at the time of the study. Additional buildings found through the research have been added to the CBE dataset and the list and map at the link is frequently updated and expanded.

Surveys Used in the Study

These are the two questionnaires used in the energy research. We gathered responses through online links and/or phone interviews. The survey content extends beyond this report focus on energy use and includes design and operational questions that are informing other tasks within the larger EPIC study of radiant heating and cooling in commercial buildings.

- Building Characteristics Survey
  https://berkeley.qualtrics.com/SE/?SID=SV_5nhRtS3b7mZRrmd
- Energy Use and Operations Survey
  https://berkeley.qualtrics.com/SE/?SID=SV_6EHQwnkwt6ukIND

EnergyStar Calculation Parameters

The data in Table 8 is from two online surveys conducted as a part of the research project - the Building Characteristics survey and the Energy Data Survey identified above. The scores were derived from one of two sources: a) provided to the research team through the survey or b) calculated by the research team via the Portfolio Manager Target Finder tool[20] in cases where the survey participant (designer or operator) did not have or provide an EnergyStar score. The parameters needed to establish an EnergyStar score are represented in the columns in Table 8.

Table 8: Building dataset and EnergyStar score calculation inputs

Building ID	City	State	Type	Size (ft^2)	EUI ($kBtu/ft^2$)	EStar Score	# of Staff/ Occupants	Number of Computers	Weekly Operating Hours	Source of EStar Score
4	Berkeley	CA	Office	45,000	143.5	75				Provided in Survey
6	Portland	OR	Office	440,000	32	97				Provided in Survey
11	Winnipeg	MB	Office	65,000	61.6	96				Provided in Survey
13	Salem	OR	Office	147,000	36	96				Provided in Survey
16	Portland	OR	Office	205,000	46	85				Provided in Survey
10	Port Coquitlam	BC	Community Ctr.	14,500	143	NA				Not Applicable, Building Type
19	Vancouver	BC	Visitor Ctr. / Public Assembly	19,400	37.7	NA				Not Applicable, Building Type
1	Fort Collins	CO	Education	95,000	28	98	250	225	56	Calculated via Target Finder
2	Portland	OR	Office	10,000	48	68	37	39	65	Calculated via Target Finder
3	Vancouver	BC	Library	36,000	154	1	75	Default	Default	Calculated via Target Finder
5	Vaughan	ON	Office	60,000	55.4	97	80	Default	Default	Calculated via Target Finder
8	San Francisco	CA	Education	200,000	37.3	92	2650	Default	Default	Calculated via Target Finder

[20] https://portfoliomanager.energystar.gov/pm/targetFinder?execution=e1s1

Building ID	City	State	Type	Size (ft2)	EUI (kBtu/ft^2)	EStar Score	# of Staff/ Occupants	Number of Computers	Weekly Operating Hours	Source of EStar Score
9	Eugene	OR	Education	92,000	26.9	98	400	Default	Default	Calculated via Target Finder
12	Golden	CO	Office	360,000	36	98	1000	2000	60	Calculated via Target Finder
15	Claremont	CA	Education	75,000	52	92	150	50	150	Calculated via Target Finder
17	Victoria	BC	Office and Lab	16.150	48.2	98	68	150	45	Calculated via Target Finder
18	Sonoma	CA	Medical Housing	16,000	32.1	61	10	Default	Default	Calculated via Target Finder
20	Berkeley	CA	Library	9,400	23.1	95	100	Default	Default	Calculated via Target Finder
21	Varennes	QC	Library	24,000	14.5	99	Default	Default	Default	Calculated via Target Finder
22	Seattle	WA	Office	52,000	12	99	Default	Default	Default	Calculated via Target Finder
23	Clemson	SC	Education	50,300	43.3	94	400	350	60	Calculated via Target Finder
7	San Jose	CA	Office and Lab	50,000	37.5	88	211	211	40	Calculated via Target Finder
14	Atlanta	GA	Office	44,000	139	5	190	200	60	Calculated via Target Finder