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Publication Date
2017-04-19

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April 2017

ABSTRACT/SUMMARY

Radiant cooling and heating systems provide an opportunity to achieve significant energy savings, peak demand reduction, load shifting, and thermal comfort improvements compared to conventional all-air systems, and as a result, application of these systems has increased in recent years. However, due to the relatively new and unfamiliar nature of radiant system technology compared to other traditional HVAC systems, there is a lack of energy, cost, and occupant satisfaction data to provide real world examples of energy efficient, affordable, and comfortable buildings using radiant systems. The overarching goal of this research is to make a first step to fill that information gap. This paper specifically (1) describes a new expanded database with over 400 buildings using radiant cooling and heating systems, (2) presents the CBE online radiant systems world map that displays all buildings from the database, and (3) summarizes the results and trends from this radiant map dataset, which focuses primarily on North America (United States and Canada). To collect the data, we used existing publications on case studies, articles from websites & architectural magazines and information provided from building professionals. Thus, the radiant map dataset is not a representative sample of all radiant buildings in North America, as by nature of the methods used to identify buildings, it is weighted towards higher profile and higher performance buildings, about which information was readily available in the public domain. Our analysis of the dataset provides the following general findings: (1) the West Coast has a larger amount of buildings compared to the East Coast, (2) the most common radiant technology is an embedded floor system in a thermal diffusion layer, (3) almost 60% of the buildings have a LEED Certification, (3) the largest number of buildings are located in ASHRAE climate zone 5, (4) the most common building category is higher education type and (5) 2013 is the year with the highest number of new radiant buildings in the dataset. This dataset is publicly available here: http://bit.ly/RadiantBuildingsCBEv2.

ACKNOWLEDGMENTS

We would like to thank Università IUAV di Venezia, Venice, Italy, for their support of Riccardo Talami while he was a visiting Graduate Student Researcher at the Center for the Built Environment, University of California, Berkeley. Partial funding was also provided by the California Energy Commission (CEC) Electric Program Investment Charge (EPIC) (EPN-14-009) "Optimizing Radiant Systems for Energy Efficiency and Comfort," and the Center for the Built Environment, University of California, Berkeley.

INTRODUCTION

Energy consumption of buildings in developed countries represents 32% of the global worldwide primary energy use and 10% of total direct energy-related CO_2 emissions [IEA 2012]. In the United States, specifically, building primary energy consumption is 40% of the national total energy use [EIA 2016]. A projection of future trends made by the Energy Administration Information (EIA) shows that from 2009 through 2035, the total primary energy consumption increase is expected as 17% [EIA 2010]. HVAC energy consumption for space heating and cooling, among all the building services, is 48% of the building total energy consumption, and 20% of the final national energy use [D&R International, LTD 2011].

Radiant systems are defined as exchanging more than 50% of total heat transfer with the conditioned space through radiation (large heat transfer area), circulating a lower and higher temperature fluid in heating and cooling mode, respectively; that is to say working with the water temperature close to the temperature desired in the room [ASHRAE Handbook 2016, Babiak et al. 2007]. Radiant cooling and heating systems have the potential to reduce energy consumption of buildings and to increase occupants' thermal comfort, providing also quiet and clean operation, and space savings [Olesen 2002].

Previous research has shown that the application of radiant cooling and heating systems can increase energy efficiency in buildings and provide equal or improved occupant thermal comfort compared to traditional all-air systems [Karmann et al. 2016], and further that radiant technology reduces the amount of HVAC energy consumption up to 67% when coupled with DOAS [Moore 2008] showing also an interesting combination with renewable or waste energy resources (e.g., heat pumps driven by geothermal source). Sastry and Rumsey (2014) reported on a side-by side comparison between a VAV system and a hydronic slab system, an energy saving percentage of more than 30% and 63% satisfaction rate for thermal comfort for the radiant system compared to a 45% for the VAV system.

Hydronic radiant technology has successfully been used in Europe for more than 20 years as an energy efficient system, as a matter of fact Olesen [2002] claims that in Germany, Austria and Denmark, 30% to 50% of new residential buildings have radiant floor heating. In Korea and Northern China the spread of water-based floor systems is significant with a percentage of 95% and 85% respectively and in Japan the growth is showing an increase of approximately 10% annually, as reported from the Japan Floor Heating association [Olesen 2010].

The situation in North America is completely different and shows a significant geographical disparity between Europe and Asia. Although the percentage of hydronic-based systems is lower, the New Buildings Institute (NBI) analyzed a growing adoption of radiant systems technology and an increasing popularity in a report on 160 zero-net energy buildings [NBI 2014].

Different types of radiant systems and conditioning modes are used around the world: Olesen [2012] claims that thermally activated building systems (TABS) are widely distributed in central Europe (Germany, Austria, Netherlands, etc.) but not yet in The United States and Asia. The same applies to radiant space cooling application, which are still relatively rare in North America [Tian and Love 2009]. The limitations of radiant systems' spread have been analyzed in recent years [Moore et al. 2006], showing a complexity on sizing [Bauman et al. 2013, Feng et al. 2013], and a limited experience and lack of familiarity [Tian and Love 2009] by U.S engineers and architects, and lower acceptance of higher initial costs by the US building industry when compared to Europe

The background of this study is a project started in 2014 by mapping buildings using radiant systems and the goals were: a) provide resources to building stakeholders, focusing on world regions where these technologies are less popular (USA and Canada); b) connect designers; c) contribute to on-going research by connecting researchers with a large set of implemented cases in order to facilitate further studies (field measurements and post-occupancy studies) [Karmann et al. 2014].

The major aim of this research is to gain a better understanding of the actual status of the radiant systems technology in North America through a descriptive analysis of the market trends, by helping spread knowledge of these systems. To achieve this purpose, we collected data about buildings conditioned by radiant heating and cooling systems, we developed a comprehensive radiant systems database and we analyzed the data. In addition, we updated the CBE radiant systems map.

METHODOLOGY

Data selection

We collected data of buildings using radiant systems focusing on two main different levels of detail: general information about the building and its features, specific information about the radiant system installed. The data we looked at are summarized in Table 1 and Table 2.

Category	Comment
Building name	
Building location	Geographical coordinates (latitude and longitude) and localization by Country, State and City.
Climate zone	Based on ASHRAE 90.1 – 2010 for USA and Canada and on Koppen-Geiger climate classification for the rest of the world.
Year of completion/major retrofit	
Building type and detail	By category: Office; Multi-purpose; Government; School (K-12); Higher education; Library/Learning Center; Laboratory; Exhibition/Museum; Transportation; Theater/Assembly; Residential/Hotel/Dormitory; Retail; Other.
Building area and number of floors	Square feet (ft^2) and square meters (m^2)
Owner and design team	Owner; General Contractor; Architects; MEP firm (radiant systems designer)
Certification and Awards	Not available for every project
EUI modeled and measured	Not available for every project
Building envelope	Envelope construction and materials
Web links	Publications, web-sites, articles, database and resources where the information has been found

Table 1: Building information displayed in the radiant system database (GENERAL information).

According to the international standard ISO 11855 [ISO 2012], the ASHRAE Handbook on HVAC Systems and Equipment [ASHRAE 2016], the European standard EN 15377 [CEN 2008] and the REHVA guidebook [Babiak et al. 2009] four main categories of radiant systems have been identified based on their pipes positioning within the building assembly / construction:

- Embedded surface systems (ESS): the pipes are embedded within the surface layer of the slab or wall and not in the structure [ISO 11855, type A, B, C, D, G].
- Thermally activated building systems (TABS): the pipes are thermally coupled and embedded within the concrete structural slab (floor or ceiling) [EN 15377, type E].

- Radiant ceiling panels (RCP): the pipes are fixed close to the surface of a panel hanged to the ceiling or wall [ASHRAE 2016].
- Capillary tube mats or capillary surface system: the pipes are embedded in a layer close to the surface of the ceiling or wall [ISO 11855, type F].

In addition to the four categories we displayed a fifth category based on the lack of information given from the data resources. We called it “In-slab (TABS or ESS)” meaning that we know that the pipes are located/designed in the floor but is not clear if they are embedded within the concrete structure or within a layer of screed, insulated from the rest of the building structure.

Category	Comment
Type of radiant system	By category: Embedded surface system (ESS); Thermally activated building system (TABS); Radiant panels (RP); Capillary tube mats; In-slab (TABS or ESS)
Radiant zone description	Types of spaces and/or portion of the building in which the radiant system is being installed
Radiant system description	Surface that includes the radiant system (floor, ceiling, walls) and assembly of the layers and materials involved.
Conditioning mode	Heating and/or cooling
Building energy	Energy machines and sources linked to the radiant system for heating and cooling
Building air system	Type of air system that is being designed with the radiant system (ventilation mode and distribution)
Product information	Manufacturing firm, product detail (size, orientation, quantity), installing and calculation method – not available for every project

Table 2: Radiant system information displayed in the radiant system database (SPECIFIC information).

Based on the categories displayed in Tables 1 and 2 and following the previous study started in 2014, we have focused our attention on North America, where we are developing our funded research, prioritizing our selection to this region since there are fewer examples of radiant installations, compared to Europe or Asia where radiant heating technology is well represented in publications and is well-known by the designers, although with still a lack of knowledge on radiant cooling.

For regions with a high density of radiant systems, we decide to prioritize best practices and significant projects: the building is a ground-breaking radiant system, or it has been analyzed with a post-occupancy evaluation, or it has won an architectural award [Karmann et al. 2014].

<u>Data collection</u>

To collect the data, we used the following sources:

- Peer-reviewed publications on case studies.
- Peer-reviewed publications on field measurements.
- Journals and technical magazines.
- Journals & architectural magazines and web-sites.

- Books on radiant systems.
- Design Manuals, catalogues, brochures and web-sites database from manufacturer firms and radiant systems designers.
- Case studies on databases.
- Online form for practitioners accessible under the CBE Website and within the Wikipedia page on radiant systems: http://bit.ly/RadiantFormCBE.
- Information given by building professionals.

Data organization and analysis

We used Microsoft Excel to organize the data in a spreadsheet based on the categories displayed in Tables 1 and 2. The structure of the data allows users to easily find the information needed using the built-in text search functionality. Most of the information for each building are selected from breakdown lists with key words and then further described in the specific sections.

Additionally, MS Excel allows to export the data in XML/KML/XSLS format. These formats can be imported in Google Maps Engine Lite to easily update the map.

RESULTS AND DISCUSSION

Radiant systems database

The result of this study is the largest radiant systems database in the world which displays 400 buildings with complete information, and an additional 17 buildings with incomplete information.

The following Table 3 details the breakdown of the radiant system types in the database.

Category	Number of buildings
Embedded Surface System (ESS)	148
In slab (TABS or ESS)	79
Thermally Activated Building Systems (TABS)	112
Radiant ceiling panels	50
Capillary tube mats	11

The following Table 4 details the breakdown of the building types in the database:

Category	Number of buildings
Office	77
Multi-purpose	48
Higher education	58
School (K-12)	28
Laboratory	31
Exhibition / Museum	33
Library / Learning center	17
Theater / Assembly	6
Residential / Hotel / Dormitory	27
Retail	15
Transportation	11
Government	8
Other	41

The information for each building has been classified and collected following the categories displayed in Tables 1 and 2.

Radiant systems online map

The second result of this study is the update of the map of buildings using radiant systems with a new graphic layout and more buildings added. The map currently features a total of 400 buildings. The publicly available map is accessible from any Web browser from the following link: http://bit.ly/RadiantBuildingsCBEv2 and short-cuts are included within the CBE website and within the Wikipedia page on radiant systems.

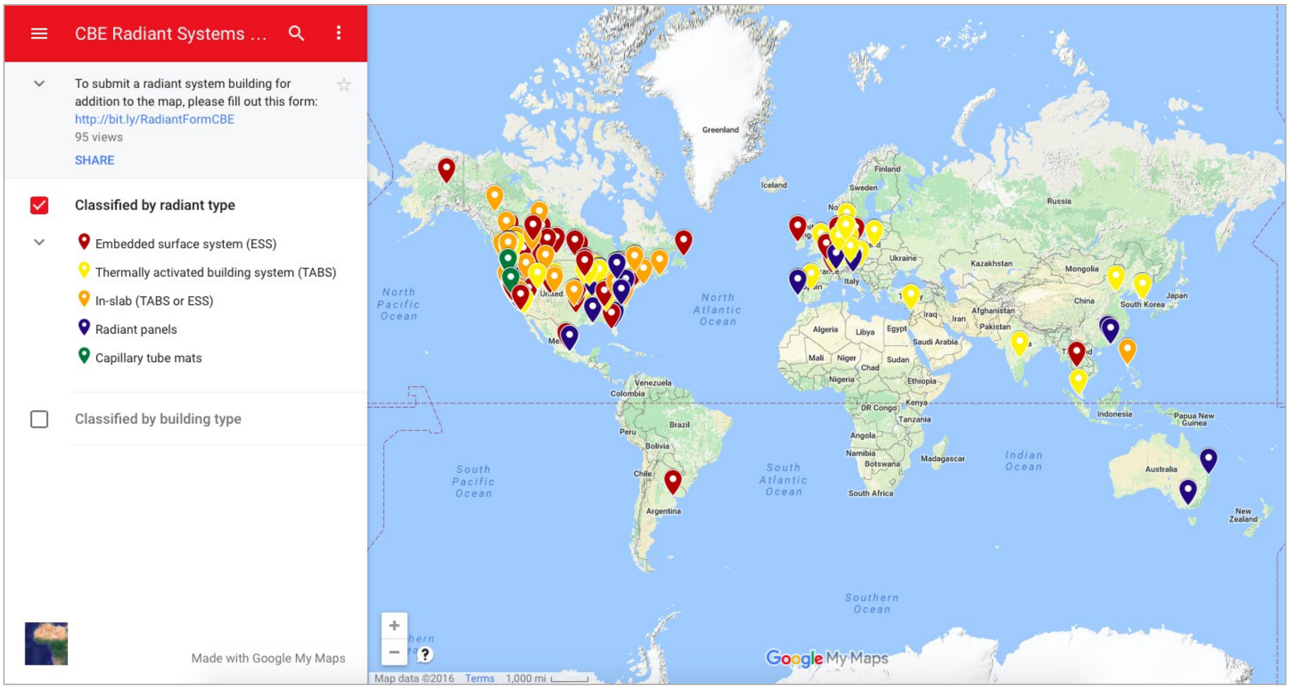
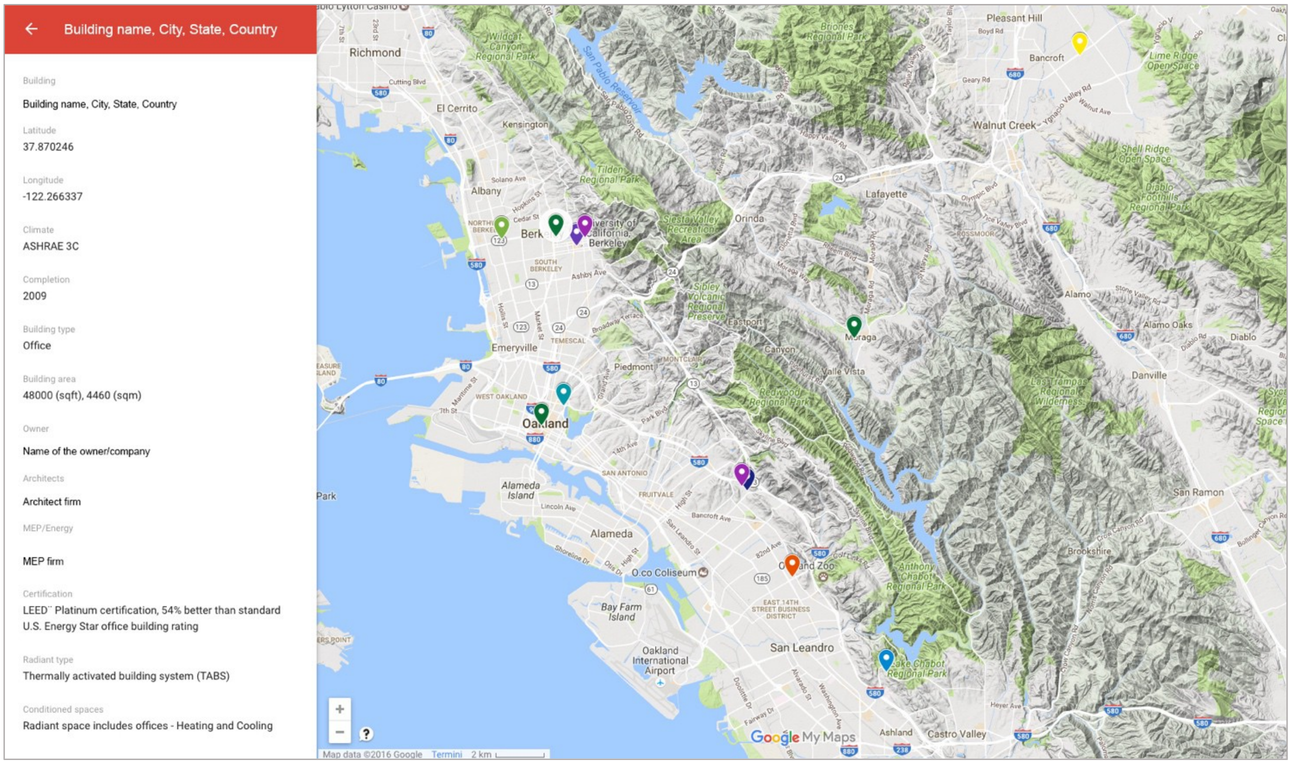


Figure 1: Screenshot of the map with buildings classified by radiant systems type and by building typology.

Figure 1 displays the main layout of the online map that features the world-wide map on the right and the main dialog legend on the left. The dialog legend allows users to display the results that they want to be shown on the map and the map is filled with colored markers representing the buildings using radiant systems. As shown in Figure 1, the first possibility is to choose the map visualization by radiant systems type or by category of buildings by clicking on one the two main layers on the dialog legend. Once the category has been chosen the markers will be colored based on these categories.

Figure 2: Screenshot of the map with an example of dialog box.



The dialog box represents a systematic format which would help map viewers to easily find the information (Karmann et al. 2014). Figure 2 shows the dialog box that opens and displays the information related to that building. We have decided to further reduce the quantity of information shown in order to allow maximum readability. We have reduced the categories from 12 to 10 to describe each building on the map based on the information that has been collected following the guidelines established in Tables 1 and 2.

The radiant systems map is not intended to be a complete world-wide census of all the buildings that have been designed with radiant systems since there is a disparity of represented cases. Therefore, our selection of buildings has been prioritized to regions showing a high potential for these systems but with limited applications. As a matter of fact, we decided to focus our attention primarily on North America with 352 cases out of 400 buildings comprised into the online map. The other 48 buildings are located in regions showing a high density of radiant installations (Europe and Asia). For these regions we decided to prioritize only best practices and significant projects: the building is a ground-breaking radiant system, or it has been analyzed with a post-occupancy evaluation, or it won an architectural award [Karmann et al. 2014]

Summary of trends in North America (USA and Canada): descriptive analysis

The following sections represent a summary of trends of radiant system technology and their features in North America (USA and Canada) through a descriptive analysis. The dataset consists of 352 buildings in North America, specifically 228 buildings in the United States and 124 buildings in Canada and is based on the information collected and organized in the radiant systems database, as specified in Tables 1 and 2. The data report is organized in sections which represent the multi-level results. The data are displayed from general (first part) to more specific information in the second part.

The same approach has been used to analyze the information into the different sections, from a general overview in large scale (North America) to a specific focus into the different analysis (e.g. the number of air distribution systems that have being designed coupled with a specific type of radiant system).

Besides, we were unable to collect every type of information for all the buildings that have been inserted in the database and consequently some of the different analysis do not show the same amount of cases. This can be considered an element of inconsistency in the results meaning that some sections should be considered on its own independent of the others. However, only the sections that analyze the air systems and energy system types are affected by inconsistency while the others are based on the same amount of cases. Therefore, every numerical result is followed by the number of buildings considered for this analysis.

Our focus was more on radiant systems involving thermal mass (TABS and ESS), and therefore there are not as many radiant panel systems in the database.

In some sections of this report where the level of uncertainty is high (especially in Canada) in-slab category can determine the predominance of TABS or ESS. For this reason, it is necessary to consider a certain level of error and approximation.

<u>Mapping locations</u>

In this section we display the distribution of buildings using radiant systems in North America.

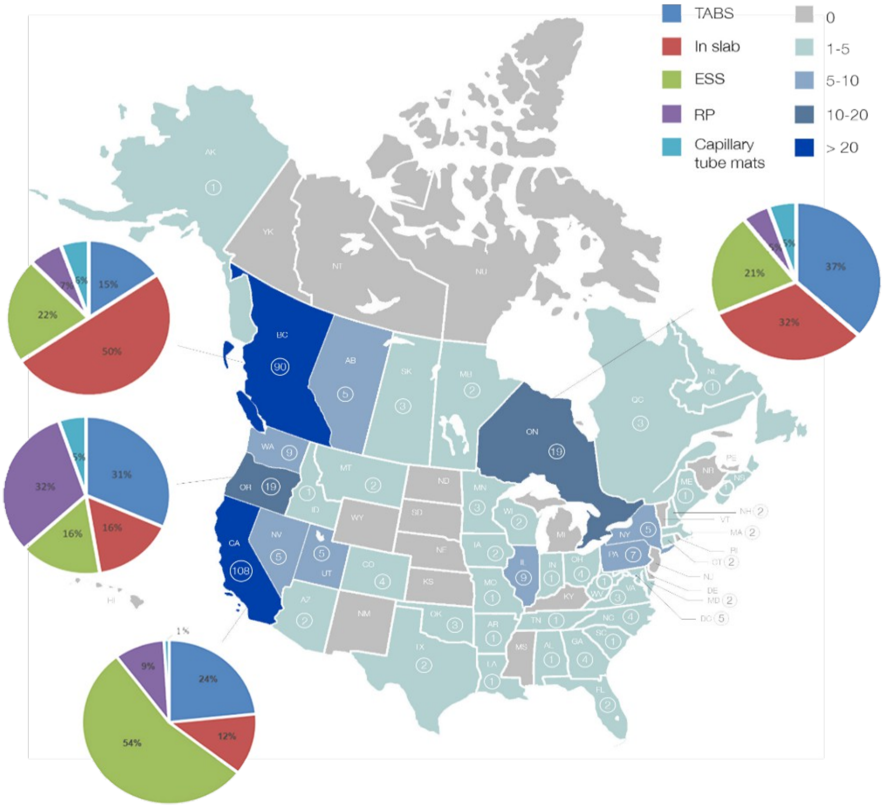


Figure 3: Mapping of the spread and distribution of radiant technology in North America

Figure 3 displays the distribution by state for the radiant buildings in North America, as well as indicating the number of buildings for each state, showing the trends across the Country. We were able to collect exemplary buildings for most of the states, however for some of them that was not possible, due to the lack of information or the scarcity of buildings using radiant systems (for 18 states no information has been found, 34 states have between 1 and 5 radiant buildings, 8 states have between 5 and 10, 2 states have between 10 and 20, 2 States have more than 20). Key points from the mapping of the locations are as follows:

- the **West Coast** has a larger number of radiant buildings compared to East Coast.
- In Northern Canada we found only one building. A possible explanation can be found considering the Subarctic temperatures (harsh climate) of these regions, but perhaps more likely is the lower population density and smaller number of buildings in this region. South Canada has several exemplary buildings.
- The central part of the United States shows a scarcity of exemplary and a reason can be found considering that these represent less populated States, with (in general) less stringent building codes regarding energy efficiency (for example, compared to California Title 24).
- **California** (108/228) and **Oregon** (19/228) are the States in the USA with the largest number of buildings in the database.
- **British Columbia** (90/124) and **Ontario** (19/124) are the provinces in Canada with the largest number of buildings in the database.

A quick analysis has been conducted for the two States in which more cases have been found. In California 54% (58/107) of the radiant buildings use ESS while in Oregon radiant panels and TABS each represent 32% (6/19). It is uncertain in British Columbia which is the most common radiant system type since the in-slab category has a percentage of 50% (45/90) while in Ontario TABS represents the largest portion at 37% (7/19).

California has the largest number of buildings with radiant systems and this trend is likely to continue when considering the State energy policies currently in place. The California Public Utilities Commission (CPUC) strategic plan requires that all new buildings and 50% of all existing buildings are zero-net-energy by 2030 [CPUC 2011].

Radiant system types

In this section we focus on the different radiant system types.

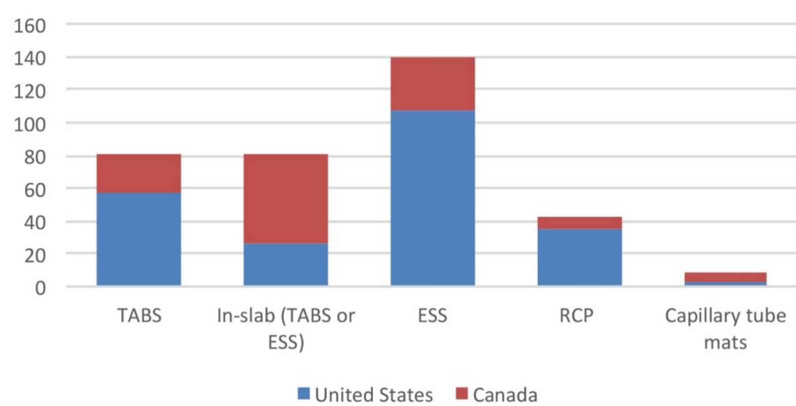


Figure 4: Radiant system types in North America.

As Figure 4 shows, radiant systems with pipes embedded in the concrete structure or in a layer of screed or timber represent the most common type with a percentage of 88% (310/352) while 12% (42/352) of buildings use radiant panels. Noticeably, between the in-floor or in-ceiling systems, **embedded surface system (ESS)** is the most common radiant system type with a percentage of 39% (139/352), followed by 23% (81/352) of thermally activated building systems (TABS) and in-slab (ESS or TABS). Radiant panels are 12% (42/352) while capillary tube mats represent just 3% (9/352) of the overall dataset.

In-slab and capillary tube mats are the only two categories with a higher percentage in Canada compared to the actual situation in the USA.

Climate distribution

In this section we analyze the distribution of buildings using radiant systems in different climate zones.

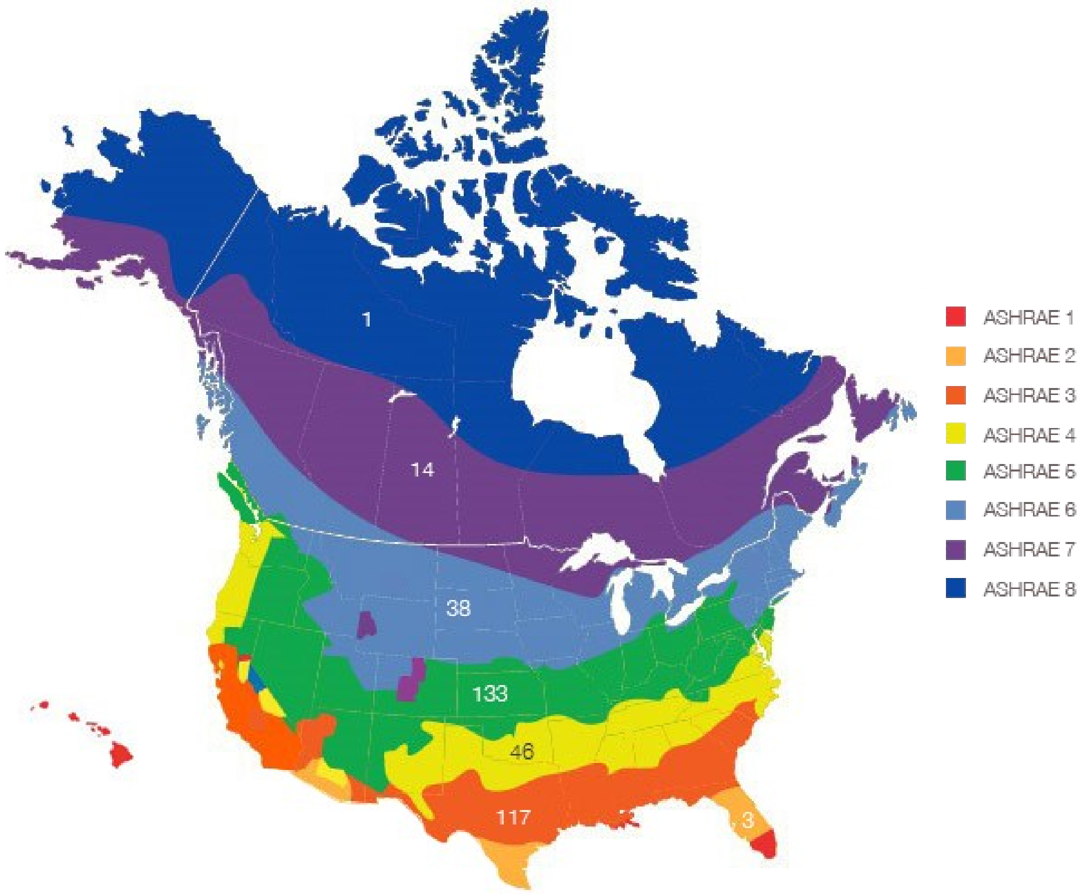


Figure 5: Mapping of the spread and distribution of radiant technology in North America.

Figure 5 displays the distribution of radiant systems in different climates, showing the number of buildings in each climate zone. Standardized climate zones originally developed by DOE are used for the analysis. This climate zone classification has been adopted by the International Energy Code Council as well as ASHRAE for both residential and commercial building applications. The set of Climate zones includes eight thermal zones covering the entire United States (Briggs et al. 2003). Climate zones are categorized from 1 to 8, with increasing heating degree days and decreasing cooling degree days. Most thermal climate zones are further divided into moist (A), dry (B) and marine (C) regions.

The most significant results for North America are indicated in the following list:

- The largest number of buildings (133/352) designed with hydronic radiant systems are in **ASHRAE 5** climate zone (cool climate).
- A large number of buildings is located in ASHRAE 3 (117/352), a warm climate.
- Only 3 buildings in the database are categorized into zone 2 and there are no buildings in zone 1 meaning that there are just a few exemplary projects in hot and very hot climates.
- 14 and 1 buildings are located respectively in ASHRAE 7 and 8 meaning that there are just a few exemplary projects in cold and very cold climates.

- Most of the buildings in ASHRAE 5 are in Canada (Vancouver) while most of the buildings in ASHRAE 3 are located in California.

Development of radiant systems by years

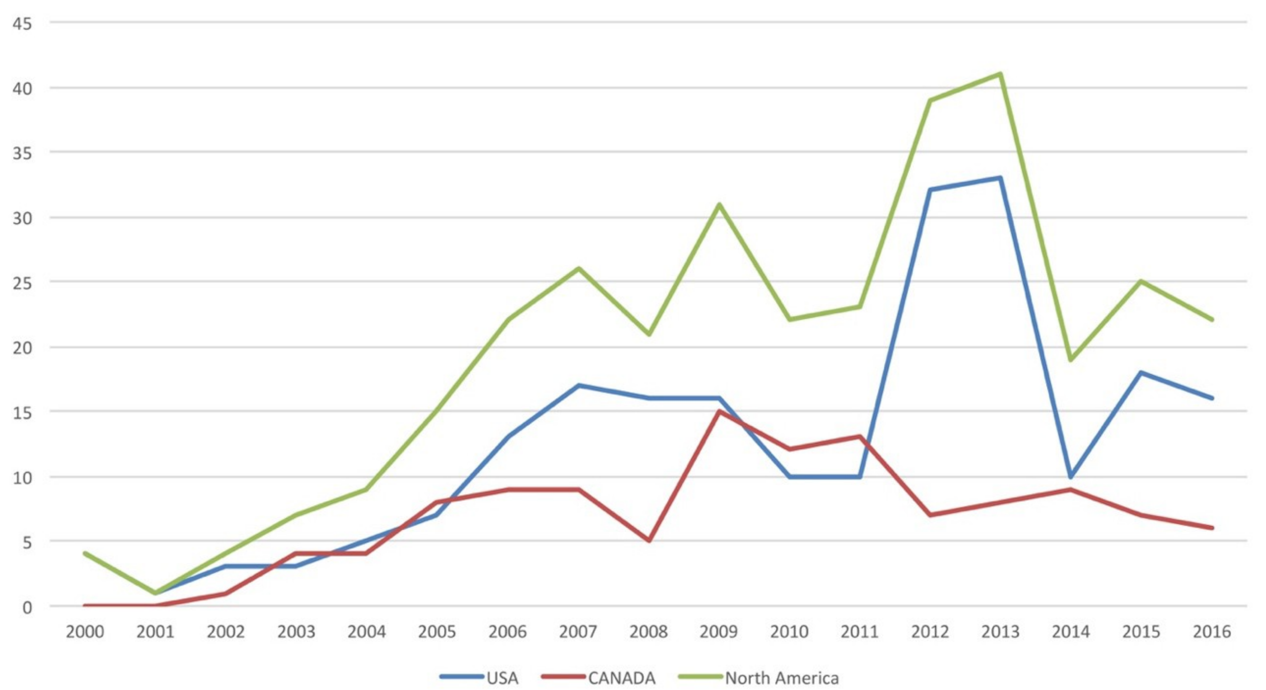


Figure 6: The development of radiant systems in North America from 2000 to 2016.

Figure 6 shows a significant growth in use and implementation of radiant systems during the period 2000-2016 for both USA and Canada. We have decided to analyze only this period, even though we had some buildings built before 2000 because we considered was more useful focusing on the most recent years and these could better represent the trend and development. Some high level findings are:

- From 2000 to 2005 the growth is similar for USA and Canada and under 5 buildings.
- Canada has a more linear growth and never goes above 15 buildings per year. The maximum peak is in **2009** (15/117).
- The USA has a more segmented growth and the maximum peak is in 2013 with an 33 buildings constructed that year.
- In North America the largest number of buildings built per year is **2013** with 41 buildings. The drop off
- The data for 2016 are incomplete since the year is not ended and more buildings are still under construction and may still be added to the database.

Application of radiant systems into different building categories

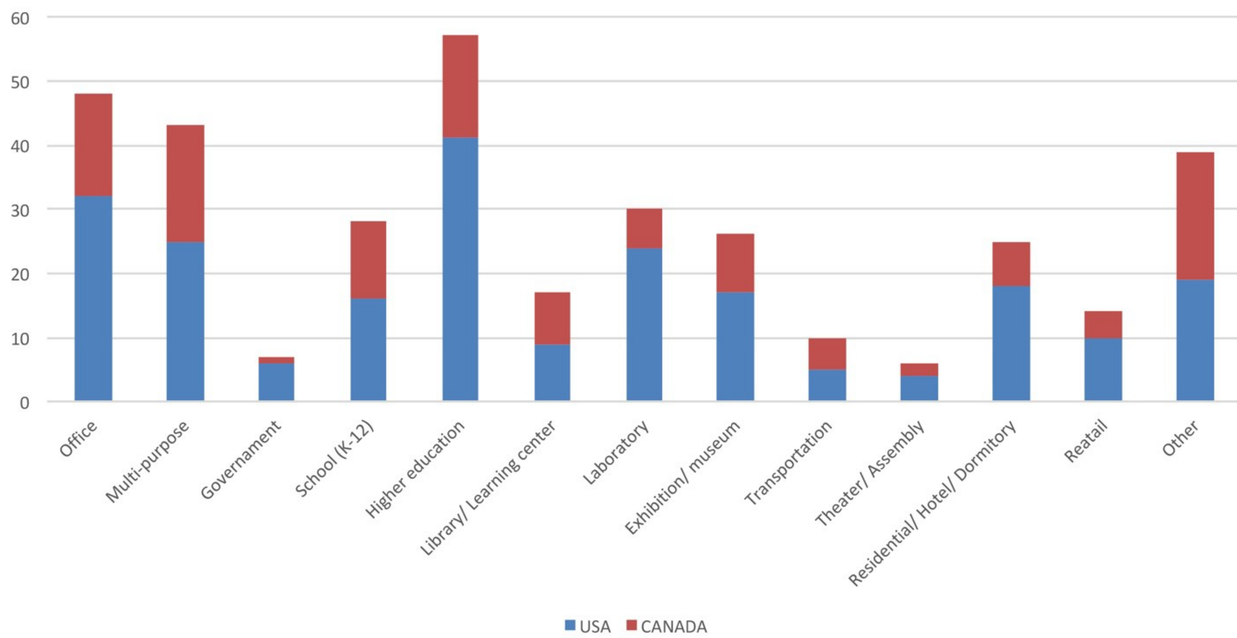


Figure 7: The application of radiant systems into different buildings categories in North America.

In the database for both USA and Canada, **cultural** (theaters, museum, exhibition, libraries) and **educational buildings** (schools, universities and laboratories) in general represent the majority of the building types in the dataset, with respectively 111 and 47 cases. Offices are the second largest number of buildings using radiant systems (48/352). Government and Theater/Assembly are the categories with the smallest number of buildings with 7 and 6 cases respectively. "Other" is a category that includes: hospitals and care centers, wineries, fire halls, recreation and entertainment centers, correctional and justice centers, sports centers and gymnasiums. This category has basically the same percentage of buildings in Canada (20/124) and in the USA (19/228).

Figure 7 shows that higher education is the specific category with the largest number of buildings (57/352) using radiant systems in North America. Some possible explanations can be analyzed as follow:

- higher resources of funding
- directly involved in academic research and close to sustainability efforts
- more likely to be publicized, and thus more likely to be in the radiant map dataset

LEED Certification for radiant systems

We decided to report this analysis even though there are several versions of LEED certifications, developed through the years. Since it was not possible to find precise information about the version of LEED awarded to the building (depending on the year of awarding), we decided to use a simple classification based just on the four major types of certification.

LEED (Leadership in Energy and Environmental Design) is an internationally recognized green building certification system by architects, engineers and other building stakeholders. This process offers third-party verification that a building was designed and built using strategies to reduce energy and water usage, promoting better indoor air quality, and improving quality of life. The LEED rating systems, created by the U.S. Green Building Council (USGBC), are internationally accepted benchmarks for the design, construction, and operation of high performance green buildings. Since 1998, LEED comprises more than 20,000 projects in 50 USA states and 30 countries.

In order to earn LEED Certification a building project must meet some criteria, in categories such as:

- Energy and Atmosphere - improve energy performance and indoor air quality
- Materials and Resources – use locally sourced, sustainable products
- Water Efficiency – reduce potable water usage
- Location and Transportation – how close the project is to mass transit
- Sustainable Sites – utilize nearby natural resources and ecosystems that can naturally take part of the design, minimizing environmental pollution.
- Regional priority credits – addressing a particular concern based on location
- Innovation – any idea not covered in the main LEED areas.

Depending on the numbers of points received, the project can achieve 4 types of certification:

- Certified (40-49 points).
- Silver (50-59 points).
- Gold (60-79 points).
- Platinum (80+ points).

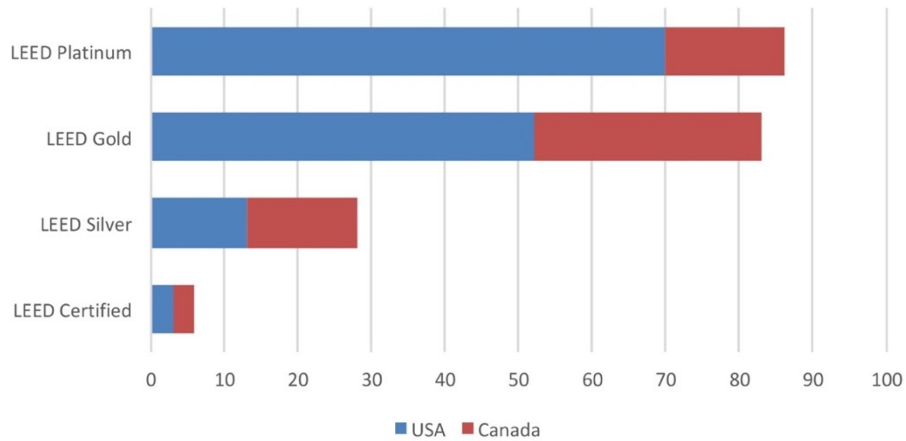


Figure 8: LEED Certification in North America.

Almost 60% of the buildings in the database (203/352) have a LEED certification and consequently approximately 40% of them (149/352) have not been certified or awarded yet or do not meet the criteria. This result shows an increasing trend and correlation between LEED certification and the use of radiant systems in buildings.

Figure 8 analyzes the different types of LEED certification in the radiant map dataset for North America:

- The largest number of buildings are certified **LEED Platinum** (86/203)
- A large amount of buildings also have a LEED Gold certification (83/203)
- There are more buildings with higher scores (Platinum and Gold certified) using radiant systems than lower scores (Silver and Certified).

<u>High performing buildings and energy use intensities with radiant systems</u>

As we described in the introduction, buildings have a significant impact on energy use and the environment. This is one of the reasons why the U.S. Department of Energy (DOE) has established the goal to create the technology and knowledge base for zero-net-energy (ZNE) commercial buildings by 2025. Similarly, the California Public Utilities Commission strategic plan which requires the goal of all new commercial buildings and 50% of the existing commercial buildings to be zero net energy by 2030 (CPUC 2011).

Torcellini et al. (2006) presented a manuscript in which they have reviewed the definition of zero-net-energy buildings ending up with the assumption that a ZNE can be defined in several ways, depending on the boundary, the metric and the project goals.

The database includes 48 buildings (14%) using radiant systems which have also been classified as ZNE buildings or that are reaching the zero energy target: the majority are located in USA (43/48) while just a small number are in Canada (5/48).

We decided then to focus our attention on the energy performance of some buildings and we have EUI (energy use intensity) reported for 56 of the buildings in the radiant map dataset. The common definition of building EUI is the building's energy use as a function of its size and it is calculated dividing the annual building energy use (measured in kBtu or GJ) by the total gross floor area of the building (measured in ft^2 or m^2). The lower the EUI is, the better the performance. However, the same building used for different uses or placed in a different climate can have a different EUI.

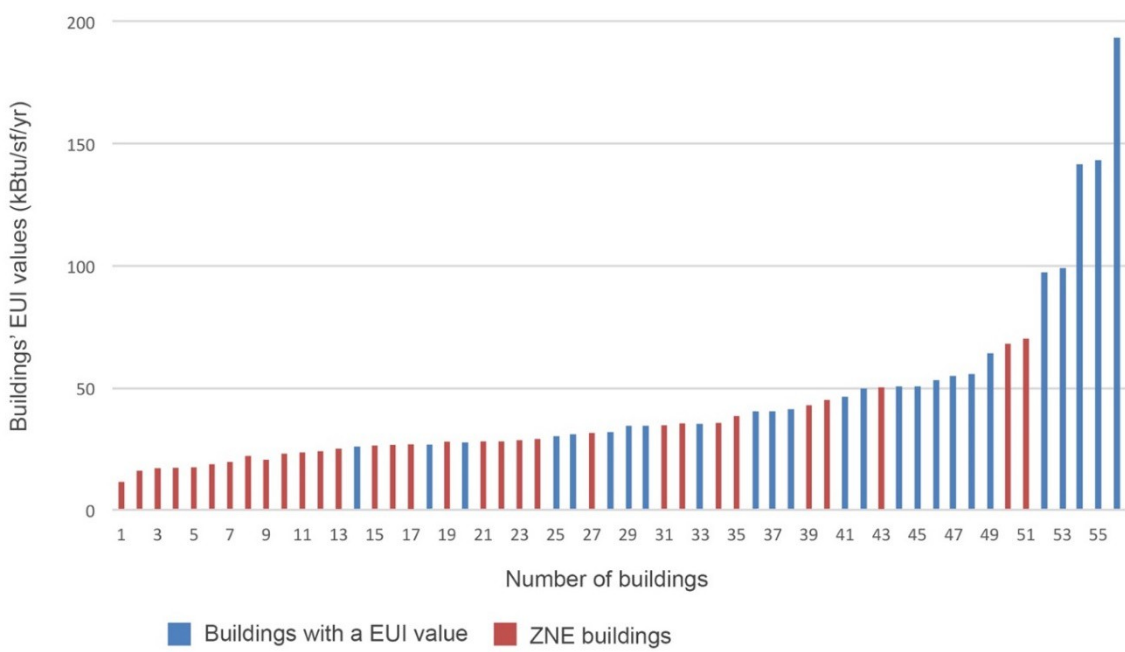


Figure 9: EUI of buildings using radiant systems

Figure 9 presents the EUIs of the buildings from the lowest to the highest value that we have found, distinguishing the ZNE buildings marked as red. Each bar represents one building. Some key points are:

- 57% of buildings (32/56) are ZNE.

- 42 buildings out of 56 findings have an EUI under 50 kBtu/sf/yr (158 kWh/m^2/yr); 11 buildings have an EUI comprised between 50 and 100 kBtu/sf/yr (316 kWh/m^2/yr); just 3 buildings have an EUI over 100 kBtu/sf/y.

- From 0 to 29 kBtu/sf/yr (92 kWh/m^2/yr) (24 buildings); only 3 buildings are not ZNE.

- There are no ZNE buildings with an EUI over 100 kBtu/sf/yr.

- The higher the energy use intensity for a building the lower the possibility of finding a zero-net-energy building.

- The energy use of these buildings collectively has a mean EUI of 43 kBtu/sf/yr (136 kWh/m^2/yr). This is 46% lower than the US national average of 93 kBtu/sf/yr (294 kWh/m^2/yr) (CBECS,2003).

Continuing our focus on these 56 buildings we analyzed the certification type achieved for each building.

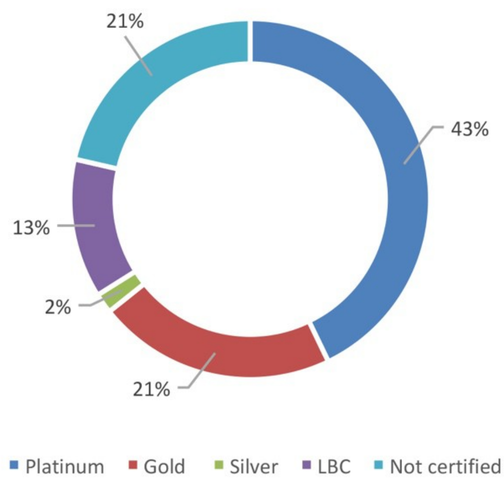


Figure 10: Certification types of high-performance buildings in the radiant system database.

- 79% (44/56) of the buildings have a certification.

- 66% (37/56) of the buildings have a LEED certification.

- The highest percentage of LEED Certification types is LEED Platinum with 24 buildings.

- 7 buildings have a Living Building Challenge (LBC) classification with a percentage of 13% of the total.

- 5 buildings with a LBC certification out of 7 found are in the first six positions of the EUI scale and under 20 kBtu/sf/yr (63 kWh/m^2/yr).

- All the buildings with a EUI under 23 kBtu/sf/yr (73 kWh/m^2/yr) (first 10 positions) have a LEED platinum or LBC certification.

The Living Building Challenge is an international sustainable building certification program more rigorous than LEED and BREAM. The challenge is comprised of seven performance categories called Petals: Place, Water, Energy, Health & Happiness; Materials, Equity and Beauty. Petals are subdivided into a total of twenty imperatives, each of which focuses on a specific sphere of influence [International Living Future Institute 2014].

Based on the radiant map dataset, there is a clear correlation between ZNE buildings and the use of radiant systems. According to NBI (2012), more than 50% of zero-net-energy buildings use hydronic radiant systems, which further supports this correlation. The most famous and higher performance buildings, those used as zero net energy case studies or that have achieved the Living Building Challenge certification, all use radiant systems for heating and/or cooling the spaces. Miller et al. (2016) conducted a survey of 23 ZNE buildings and by assessing the HVAC distribution system, they found another unique aspect of ZNE buildings. Within the dataset, 64% of the buildings use radiant systems (specifically 52% use radiant heating; 35% use radiant cooling) to meet thermal comfort needs coupled with a Dedicated Outdoor Air System (DOAS) to address ventilation needs.

Radiant conditioning modes

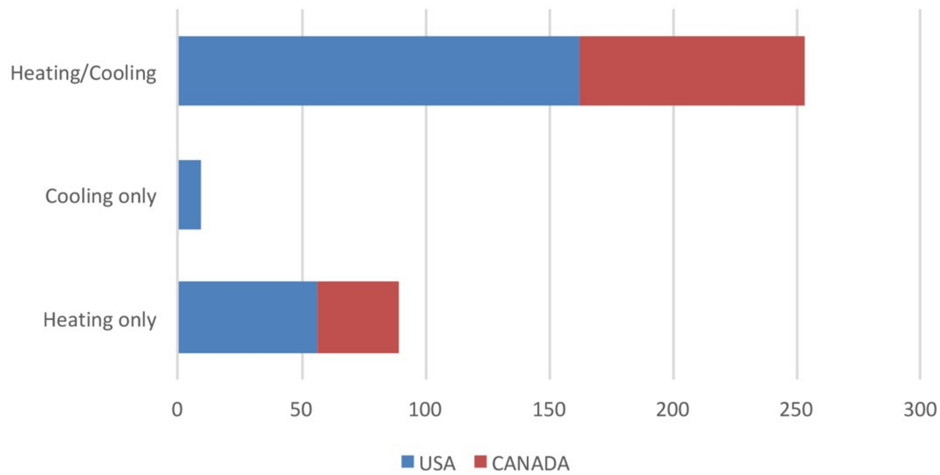


Figure 11: Radiant conditioning modes in North America.

Looking at Figure 11 and analyzing the data it is clear that a larger number of buildings have **radiant heating** (342/352) for both US and Canada. This result has been obtained by summing the buildings radiantly coupled heated/cooled with the buildings just radiantly heated and after with the buildings just radiantly cooled. Looking specifically at the numerical data we saw that almost all the buildings in the database (218/228) have radiant heating (that can be only heating or coupled with cooling) and all the buildings in Canada use radiant heating (124/124). Furthermore, analyzing the data for cooling and working with the same principles, we can determine that in USA 172 out of 228 buildings and in Canada 91 out of 124 have radiant cooling.

For many buildings and climates in North America, radiant cooling represents a critical conditioning mode, depending for design and operation. This can be a possible explanation for the larger number of radiant heated buildings that have been found and a confirmation of the study conducted by Moore et al. (2006) with the more complexity on sizing [Bauman et al. 2013, Feng et al. 2013] and the limited experience and lack of familiarity [Tian and Love 2009] by U.S engineers and architects.

Furthermore, Figure 11 shows the different radiant conditioning modes for buildings claiming that the most common conditioning mode for radiant systems in North America is **heating coupled with cooling** (253/352). There are just 10 buildings in which the radiant system only provides cooling. In Canada we did not find any building in which the radiant system only provides cooling.

Air system types designed with radiant systems

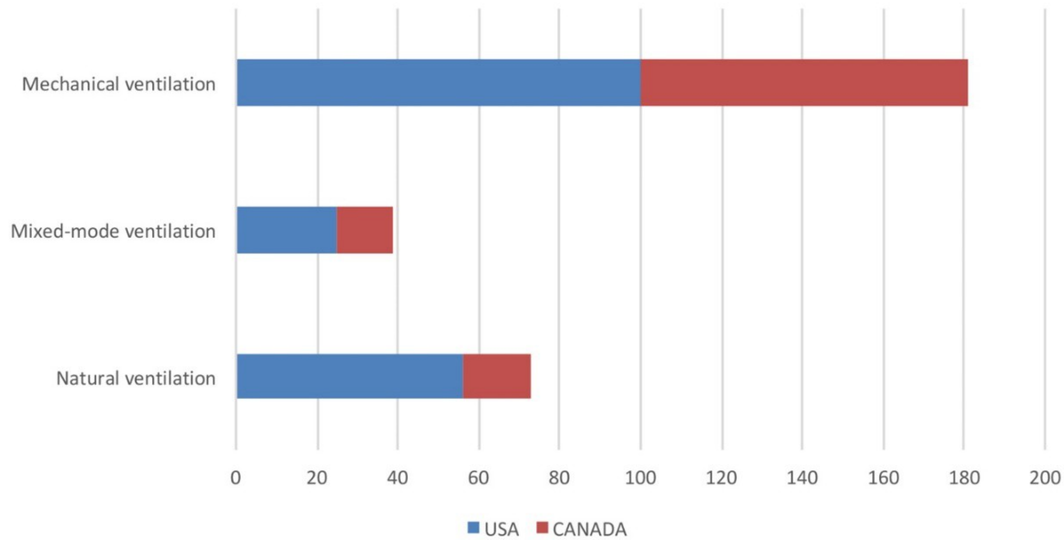


Figure 12: Air system types in North America.

In North America, as Figure 12 shows, the most common air system type that has been designed with radiant systems is **mechanical ventilation** (181/293).

We have found that in the database there is a higher number of dedicated outdoor air systems (DOAS) for the air ventilation needs. A DOAS offers a dedicated system for delivering outdoor (ventilation) air into the building spaces, without using recirculated air. It is also commonly used to handle latent loads, and a small portion of sensible loads in the building. This type of system is interesting coupled with radiant systems since they offer energy and space savings (smaller ductwork) and decouple the latent loads from the sensible loads which are primarily handled by the radiant system.

“Mixed-mode” refers to a hybrid approach to space conditioning that uses a combination of natural ventilation from operable windows (either manually or automatically controlled), and mechanical

systems that provide air distribution and some form of cooling (air-conditioning, radiant cooling, etc.) [Brager and Baker 2008. Brager et al. 2007]. Mixed-mode buildings can reduce HVAC energy consumption and increase occupant satisfaction. Only 39 buildings out to 293 analyzed have been found using mixed-mode ventilation.

Natural ventilation for buildings represents an interesting combination with low energy systems, such as radiant technology and the database shows 79 of these cases. Design of traditional natural ventilation strategies relies on the wind and buoyancy-driven stack effects to drive air flow through the openings in the building façade, between the exterior and interior, without the use of fans, mixing the air within the space. As a matter of fact, Baker and Steemers (2000) have found that the energy consumption of a naturally ventilated building can be less than half of a fully air-conditioned, mechanically ventilated one.

Furthermore, out of 293 cases collected, for mechanical ventilation 100 buildings are in USA and 81 in Canada representing a percentage of 55%-45%. However, analyzing buildings in which have been designed a mixed-mode ventilation or natural ventilation, the situation is less equal, even though USA has more cases for each air system type. 64% of buildings in USA have a mixed-mode ventilation system (25/39) and 36% in Canada (14/39) while the disparity is even more spread for natural ventilation with 77% of buildings in USA (56/73) and 23% in Canada (17/73).

Air distribution system types designed with radiant systems

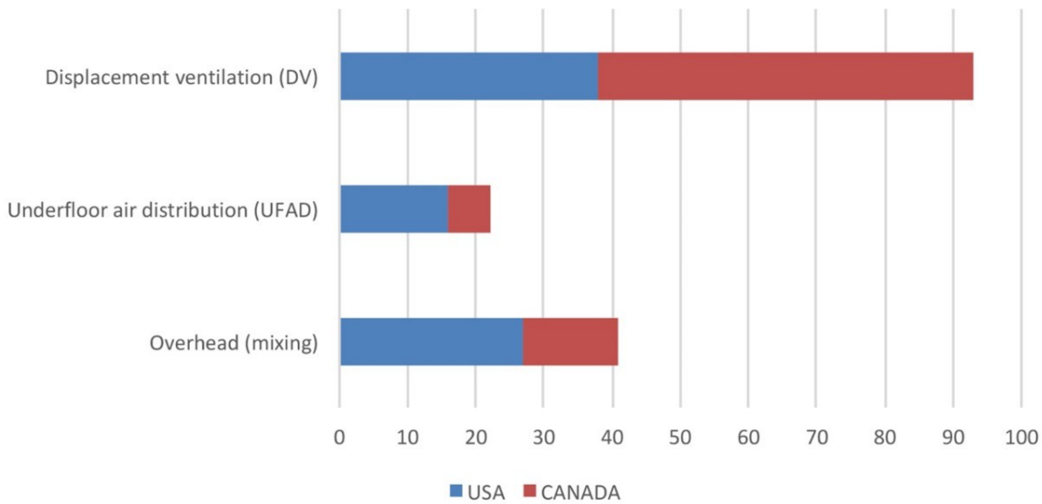


Figure 13: Air distribution system types in North America.

Figure 13 shows that the most common air distribution system type that has being designed with radiant systems is **displacement ventilation (DV)** with 93 cases out of 156. Out of the 93 cases that have being found the majority of them are located in Canada (55) and 38 in USA. Displacement ventilation supplies air to the occupied zone at a very low velocity (100% outdoor air). DV diffusers are often mounted near the floor level (floor or wall), causing vertical temperature stratification in the space. This feature allows a high ventilation effectiveness compared to mixing systems since the supply air must pass through the breathing zone before being exhausted carrying contaminants away from the occupants [Cho et al. 2005].

Underfloor air distribution (UFAD) system is the less represented in the database (22/156). UFAD introduces air supply to the occupied zone from a raised access floor plenum through floor diffusers providing conditioned air that is partly mixed. However, DV and UFAD are sometimes considered synonymous although it is important to understand the differences between these two systems [McDonnell 2003].

Overhead or mixing air distribution system delivers supply air, usually at the ceiling level, in a manner such that the entire volume is fully mixed (outside the occupied zone). The cool supply air exits from the diffusers at a high velocity and contaminants are diluted with supply air and are distributed evenly throughout the space. Mixing ventilation system is generally the most common compared to other applications since the first cost is lower than DV and UFAD and this technology is well-known among many U.S. building designers and considered an established practice [Hamilton et al. 2004]. However, this air distribution system was not the most frequently coupled one with radiant systems since only 41 buildings out of 156 use an overhead air distribution. For UFAD and Overhead systems, the highest percentage of buildings in the radiant map dataset are found in USA:

- Overhead: 66% in USA (27/41) and just 34% in Canada (14/41)
- UFAD: 73% in USA (16/22) and just 27% in Canada (6/22)

However, the largest number of buildings using DV can be found in Canada with a percentage of 59% (55/93) compared to 41% in USA (38/93).

Energy system types for heating designed with radiant systems

In this section we analyze the different mechanical plant/system for heating and cooling that have been designed with radiant systems. Since heating and cooling are provided to buildings sometimes coupling different types of systems (e.g., boiler + thermal solar panels) the numbers do not represent the amount of buildings, but the total number of systems installed.

All heating and cooling systems have three basic components: source, distribution and control system. We were unable to provide a descriptive statistic on the source for heating and cooling, although the Department of U.S. Energy claims that the most common heating fuel is natural gas. However, in the database we have collected a certain number of buildings using geothermal energy source and a lot of buildings using photovoltaic panels to provide energy for the installed systems.

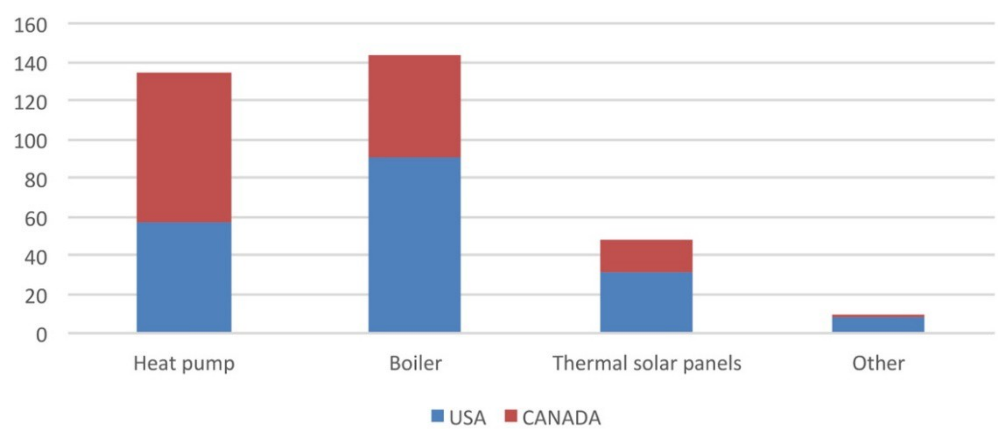


Figure 14: Energy system types for heating in North America.

Figure 14 shows that in North America the most common energy system for heating is a boiler (143/334) and 64% of cases are being installed in USA. Specifically, the great majority are **condensing boilers** that are more efficient than non-condensing models.as they capture some of the heat from the flue in the form of hot gases and use it to heat water returning from the central heating system.

Heat pumps represent a large portion of systems installed in the radiant map dataset (134/334). Out of 134 cases that have being found, the majority of them are located in Canada (77) with a percentage of 57% and 57 in USA (43%). The majority of these are ground-source heat pumps. However, in the database we have collected also buildings using air source heat pumps, usually easier to install, and buildings using water source heat pumps if in proximity to lakes, rivers or the ocean.

Thermal solar panels are an innovative, efficient and clean energy source that is gaining popularity, with 48 systems installed in the radiant map dataset. 16 systems are in Canada and 32 in USA.

Energy system types for cooling designed with radiant systems

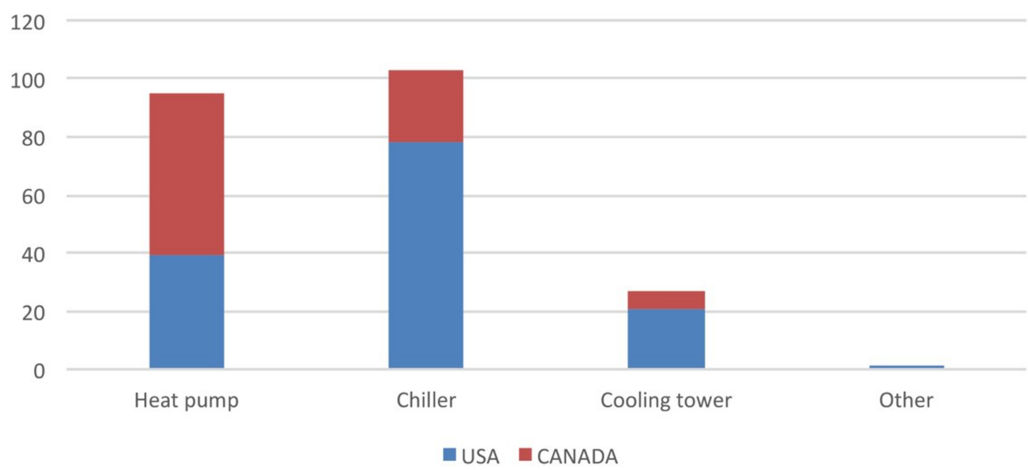


Figure 15: Energy system types for cooling in North America.

Figure 15 details that in North America the most common energy system for cooling is a chiller (103/226). The great majority are **high efficiency air-cooled or water-cooled chillers** that cut energy costs. Air-cooled systems eliminate the need for a cooling tower but are significantly less efficient than water-cooled chillers

Heat pumps are present in great quantity in the radiant map dataset (95/226). The majority are located in Canada (56) with a percentage of 59% and 39 in USA (41%)

In the database we have found 27 cooling tower applications installed with radiant systems. A cooling tower is a specialized heat exchanger in which air and water are brought into direct contact with each other in order to reduce the temperature of the water. As this happens, a small volume of water is evaporated, reducing the temperature of the water being circulated through the tower. Only 6 systems installed are in Canada and 21 in the USA. It is not clear for the information in the radiant map dataset whether the cooling tower is the primary (or only) source of mechanical cooling for the radiant system, or if other supplemental cooling systems are present.

Further considerations

Most of the buildings collected in the database have a high-performance envelope. This feature reduced heating and cooling loads when compared to poorer envelope systems, and allows better performance for radiant cooling and heating applications.

SUMMARY AND CONCLUSIONS

There are a number of noteworthy findings from the descriptive analysis that has been conducted. The results do provide some valuable insight into market conditions and trends of radiant cooling and heating systems in North America. Even though these results may not be representative of the total population of radiant system projects because of the impossibility to gather all the buildings in the country that have been designed with radiant system, they provide additional information about the subset in the radiant map dataset.

To our knowledge, this review of trends in radiant cooling and heating technology is based on the largest radiant systems database of its kind. We are not aware of other studies using the same approach with a high number of buildings analyzed: most papers and reports are based on individual buildings. However, as the population of radiant systems installed in buildings will grow through the years and will be implemented, further research would be needed to confirm the results or provide updated information.

Following we provided a summary of the main findings regarding the radiant map dataset:

- The West Coast has a larger number of radiant buildings compared to East Coast.
- California is the state with the largest number of radiantly conditioned buildings.
- Embedded surface system (ESS) is the most common radiant system type.
- The largest number of radiant buildings are classified into ASHRAE 5 climate zone (cool).
- 2013 is the year in which the largest number of buildings with radiant systems have been built.
- Higher education category is the most common building type.
- Among the buildings that have received a LEED classification LEED Platinum is the most common.
- More buildings have radiant heating but the most common operating mode for radiant systems is to provide both heating and cooling.
- Mechanical ventilation is the most common air system type that has been designed with radiant system.
- Displacement ventilation (DV) is the most common air distribution system type that has been designed with radiant system.
- The largest number of buildings use condensing boilers to provide heating to the radiant system.
- The largest number of buildings use high-efficiency water cooled chillers to provide cooling to the radiant system.

These results are representative of the descriptive statistics in North America, including the USA and Canada, during the period 2000-2016, as identified in the radiant map dataset. This dataset is publicly available here: http://bit.ly/RadiantBuildingsCBEv2.

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