MINNESOTA DEPARTMENT OF COMMERCE
DIVISION OF ENERGY RESOURCES

Commercial Roof-top Units in Minnesota

Characteristics and Energy Performance

Conservation Applied Research & Development (CARD)
INTERIM REPORT

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DISCLAIMER

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Executive Summary

Objective

Packaged roof-top units (RTUs) are ubiquitous on commercial buildings throughout the United States because of their low capital cost, reliability and well-developed service and distribution network. There is anecdotal evidence, however, that these systems tend to operate inefficiently and sub-optimally. To validate or refute this evidence, we conducted a multi-level field study to characterize the RTUs in Minnesota. The objective of this study is to characterize the existing RTUs and the new/replacement market. This characterization can be used to inform the improvement or development of utility conservation improvement programs (CIPs) whose goal is to reduce the energy consumption of new and existing RTUs.

Methodology

Our methodology for collecting and analyzing building and existing RTU characteristics followed these steps:

1. Develop sample set of Minnesota ZIP codes
2. Identify all buildings with RTUs in each sampled ZIP code
3. Find contact information on a subset of these buildings
4. Conduct phone interviews with a subset of these buildings to collect data
5. Analyze data: extrapolate characterization to Minnesota

The specific building-level data that we collected is outlined in Table 1.

Table 1: Building characteristics collected.

Building Characteristics
Building age
Total area
Area served by RTUs
Type of commercial activity
Building location
Area normalized cooling capacity
Owner type
Number of tenants
Occupancy schedule
Occupant density
Maintenance practices and schedule
Occupant complaints
Number of zones served

For each surveyed building, we collected data for each existing RTU as outlined in Table 2.

Table 2: RTU characteristics collected.

RTU Characteristics
Manufacturer
RTU age
Number of zones served
Cooling type
Cooling capacity
Cooling efficiency, full load
Cooling efficiency, part load (if applicable)
Compressor type
Number of compressors
Heating type
Heating capacity
Heating efficiency
Fan speed
Fan power
Supply airflow
Refrigerant
Homogeneity of multiple RTUs

Finally, we analyzed the new and replacement market for RTUs in Minnesota including annual shipments, annual sales, as well as their corresponding efficiency levels and refrigerant type.

Results

Following are results of our analysis of existing RTUs and the market for new and replacement RTUs.

Existing RTUs

Our analysis concludes that there are currently 20,700 statewide buildings with RTUs, with a 95 percent confidence interval of ± 3,100 buildings*. *We estimate that approximately 80% of these commercial buildings or 730 million square feet are served by RTUs. Nearly a third (30%) of these buildings are relatively new, having been built since the turn of the century. Smaller buildings (those less than 50,000 square feet) dominate the total number of buildings, comprising 78% by number of buildings. However, larger buildings (those greater than 50,000 square feet) dominate the total area of buildings, comprising 70% by area. The majority of buildings that have RTUs do not have significant secondary HVAC systems, but are served entirely by RTUs. Over half (57%) of buildings served by RTUs are in the Twin Cities or surrounding suburbs, including the seven county metro area. Of the out state buildings, the average distance from the Minnesota state capitol building was 140 miles, or approximately the distance from Saint Paul to Duluth.

The building types with the highest population are office, food service, food sales, and public order and safety. Combined these building types comprise over half (51%) of the buildings with RTUs in Minnesota. However, in terms of area served by RTUs, food service, food sales and public order and safety represent a much smaller portion due to their relatively small average area served by RTUs.

Other interesting characteristics of the Minnesota commercial buildings served by RTUs are:

- Over four-fifths (83%) are owner occupied or public.
- Over two-thirds (68%) have a single tenant. The remainder tended to be malls, strip malls or multi-tenant office buildings.
- Approximately two-thirds (67%) had occupied hours exceeding what would be considered a standard work week.
- Nearly two-thirds (64%) of buildings had relatively low occupant densities of between 0 and 5 people per 1000 square feet. These buildings were mostly office, retail and warehouse.
- Over half (53%) use contracted vendors for maintenance purposes.
- Over one-third (36%) experience comfort complaints, two-thirds of these complaints were based on RTU performance while one-third were dependent on an occupants personal preferences.
- Approximately two-fifths (40%) of buildings have RTUs serving multiple zones, increasing the frequency of occupant discomfort.

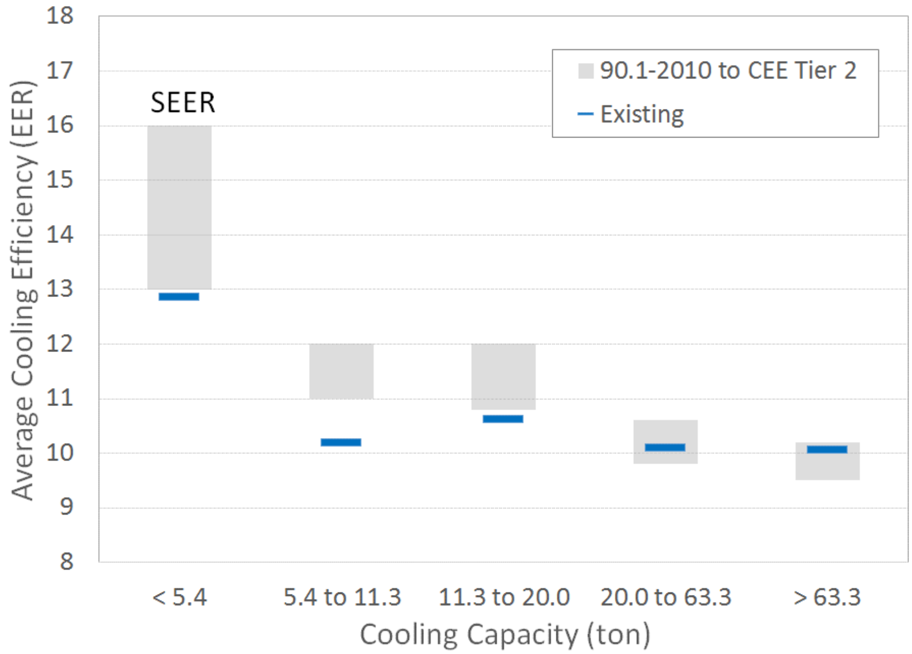
Our analysis indicated that there is a total of 136,000 ± 30,000 existing RTUs in the state. On average, there are between 6 and 7 RTUs per commercial building that is served by RTUs. Three manufacturers (Carrier, Lennox and Trane) account for approximately three-quarters (75%) of the RTUs in Minnesota and over half (52%) of the installed capacity. ***The average age of an existing RTU in Minnesota is 13.1 years.*** Newer RTUs, those that are less than 5 years old, comprise 11% of existing RTUs while only 7% of existing RTUs are older than the Minnesota Technical Reference Manual's[1] (TRM) value of 20 years for estimated useful life.

The total estimated cooling capacity of RTUs in Minnesota is approximately 1.3 million tons with an average cooling capacity of 10.7 tons per RTU. Slightly more than half (52%) of the individual RTUs have a cooling capacity of less than 5.4 ton, which is in agreement with the median cooling capacity of 5 tons. However, RTUs with cooling capacities over 20 ton comprise 45% of the cooling capacity of all RTUs.

Over half (56%) of RTUs had full load cooling efficiencies between 9 and 11 EER. ***The average full load cooling efficiency of RTUs in Minnesota is 10.6 EER***. The average cooling efficiency of existing RTUs has increased by 18% over the past 20 years. For new construction or renovation projects, the Minnesota energy code requires a minimum level of cooling efficiency for RTUs. The requirement varies by cooling capacity range. It is therefore interesting to compare the average cooling efficiency within each of these cooling capacity ranges. Figure 1 illustrates the cooling-capacity weighted average cooling efficiency by cooling capacity.

[1] State of Minnesota Technical Reference Manual for Energy Conservation Improvement Programs, Version 1.3, 2016, http://mn.gov/commerce-stat/pdfs/trm-version-1.3.pdf

Figure 1: Average cooling efficiency by cooling capacity (n=118,284).



The average existing RTU cooling efficiencies are plotted as bars, while the range of cooling efficiency between the current Minnesota energy code[2] and the Consortium for Energy Efficiency's (CEE) Tier 2[3] recommendations are also plotted to illustrate the potential programmatic savings magnitude. For RTUs with cooling capacities below 20 tons, the average existing efficiency is below the code-minimum and well-below the CEE Tier 2 recommendation suggesting that there is considerable opportunity for improved efficiency in smaller RTUs. For larger RTUs with cooling capacities between 20 and 63.3 tons, the average existing efficiency is between the code-minimum requirement and below the CEE Tier 2 recommendation. This means there is a limited opportunity for increasing efficiency for RTUs in this capacity range, as their efficiency is already relatively high. For RTUs with cooling capacities above 63.3 tons, the average existing efficiency is near the CEE Tier 2 recommendation leaving little opportunity for increased efficiency.

The current trend in increasing RTU performance is with respect to part load cooling efficiency, rather than full load cooling efficiency. We calculate that 35% of RTUs in Minnesota have some level of part load efficiency. The proportion of RTUs with part load efficiency has been growing steadily over the past 20 years. Half (50%) of RTUs with part load cooling efficiencies had an IEER between 10 and 12. ***For existing RTUs in Minnesota with part load cooling efficiencies, the average IEER is 11.2.***

The total estimated heating capacity of RTUs in Minnesota is approximately 23.8 million MBH with an average heating capacity of 205 MBH per RTU. Nearly three-fourths (72%) of

[2] ASHRAE 90.1-2010, Table 6.8.1A

[3] CEE 2016. High Efficiency Commercial Air-conditioning and Heat Pumps Initiative. Consortium for Energy Efficiency. 2016.

individual RTUs have a heating capacity less than 225 MBH. However, RTUs with heating capacities over 225 MBH comprise 58% of the heating capacity of all RTUs. We found that the heating fuel type of Minnesota RTUs is overwhelmingly (97%) natural gas fired. The remainder use electric resistance heating. The average heating efficiency of natural gas fired RTUs in Minnesota is essentially the code-minimum required value across all capacities of approximately 80%. We did not find any high efficiency condensing RTUs as they are a relatively new (but growing) technology.

Fan power is a large component of a RTU's energy consumption. ***The total estimated fan power of RTUs in Minnesota is approximately 389 thousand horsepower with an average of 3.3 horsepower per RTU.*** Fan motors of less than 3 motor horsepower are used on more than two-thirds (69%) of RTUs in Minnesota. However, larger fans with motor horsepower greater than 3 comprise nearly three-quarters (73%) of fan power used by RTUs. Single speed fans are used on four-fifths (81%) of RTUs in Minnesota, representing 56% of total RTU fan power. A large and growing proportion of RTUs use variable speed fans, comprising 42% of fan power.

Another important characteristic of RTUs is the refrigerant they use. R-22 is used in over three-fourths (79%) of RTUs, comprising 55% of RTU cooling capacity. This indicates that larger RTUs are more likely to use R-410A. Increasingly, RTUs are using R-410A with over two-thirds (69%) of RTUs less than 5 years of age utilizing it.

For those buildings that had more than one RTU per building, nearly two-thirds (62%) of the buildings had RTUs from multiple manufacturers.

New and Replacement RTUs

We estimate that a total of 6,400 RTUs are shipped to commercial buildings in Minnesota annually. Of these, 40% or 2,600 RTUs are for new construction projects, while 60% or 3,800 are for existing retrofits or replacements. ***We estimate that the total sales of RTUs in Minnesota is $88 million annually.*** Of these, 3,500 shipments are for code-compliant RTUs, while 2,900 shipments are for high performance RTUs. These levels of shipments represent $41 million and $47 million in sales for code-compliant and high performance RTUs, respectively.

Introduction

Background and Objective

Heating, Ventilation and Air-Conditioning (HVAC) energy consumption comprises just over 30% of US commercial building energy costs.[4] Within this considerable footprint, packaged RTUs serve nearly half of Minnesota's region's commercial floor area.[5] RTUs are ubiquitous on commercial buildings throughout the U.S. because of their low capital cost, reliability and well-developed service and distribution network. There is anecdotal evidence, however, that these systems tend to operate inefficiently and sub-optimally. To validate or refute this evidence, we conducted a multi-level field study to characterize the RTUs in Minnesota. The results of this study may be used to improve or develop utility CIPs whose goal is to reduce the energy consumption of new and existing RTUs.

In order to begin a characterization it is important to clearly define what is being characterized. For the purposes of this study ***we define RTUs as a forced-air HVAC system that packages the evaporator, condenser coils and heating coils into a single unit that sits on the roof of a commercial building and serves the buildings heating, cooling and ventilation loads***.

[4] Data available at US Department of Energy, "Buildings Energy Data Book: 2015 Commercial Energy End use Expenditure Splits, by Fuel Type" Accessed March 3, 2016

(http://buildingsdatabook.eren.doe.gov/TableView.aspx?table=3.3.5)

[5] Data available at 2012 CBECS Table B41, Cooling equipment, floorspace, 2012 Accessed March 3, 2016

(https://www.eia.gov/consumption/commercial/data/2012/)

Characterizing Rooftop Units

Following is a discussion of the methodology we used to characterize RTUs in Minnesota.

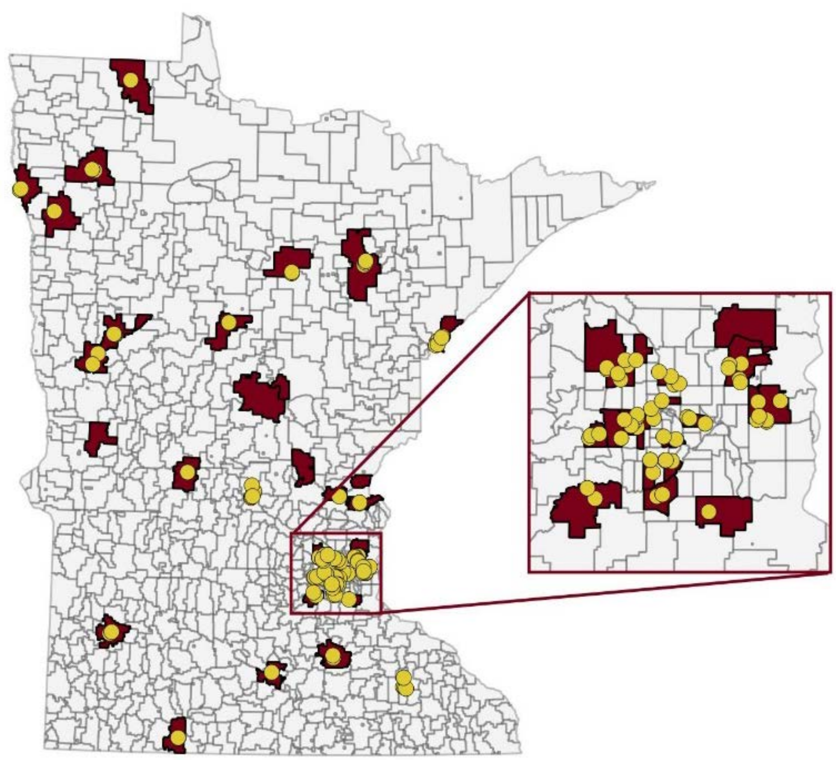
Methodology for Characterizing Existing RTUs

Our methodology for collecting and analyzing building and existing RTU characteristics is discussed in more detail in Appendix A: Sampling and Weighting. In general it followed these steps:

1. Develop sample set of Minnesota ZIP codes
2. Identify all buildings in each sampled ZIP code with RTUs
3. Find contact information on a subset of these buildings
4. Conduct phone interviews with a subset of these buildings to collect data
5. Analyze data: extrapolate characterization to Minnesota

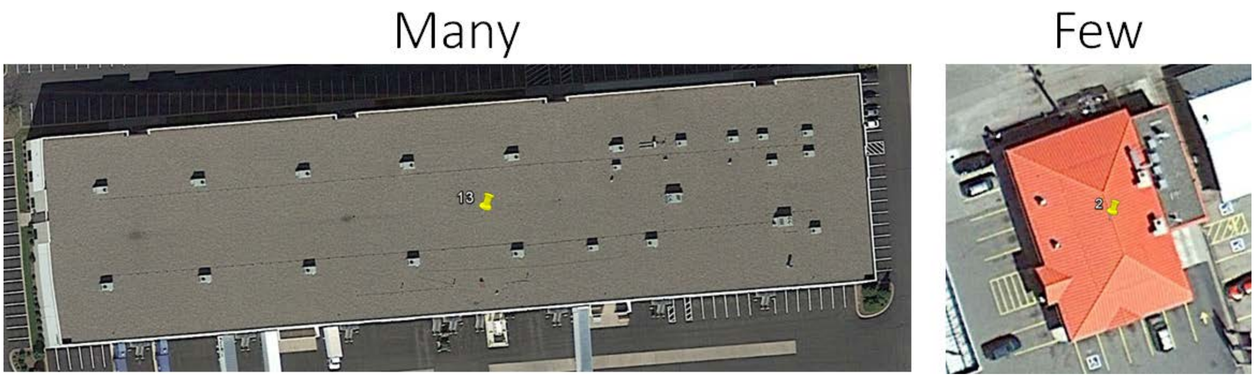
We began by using U.S. Census Bureau data to randomly sample 50 of the 936 total Minnesota ZIP codes. Our sampled ZIP codes ranged in size, density and geographic location and are highlighted in red in Figure 2.

Figure 2: Minnesota ZIP codes including our sampled set of 50.



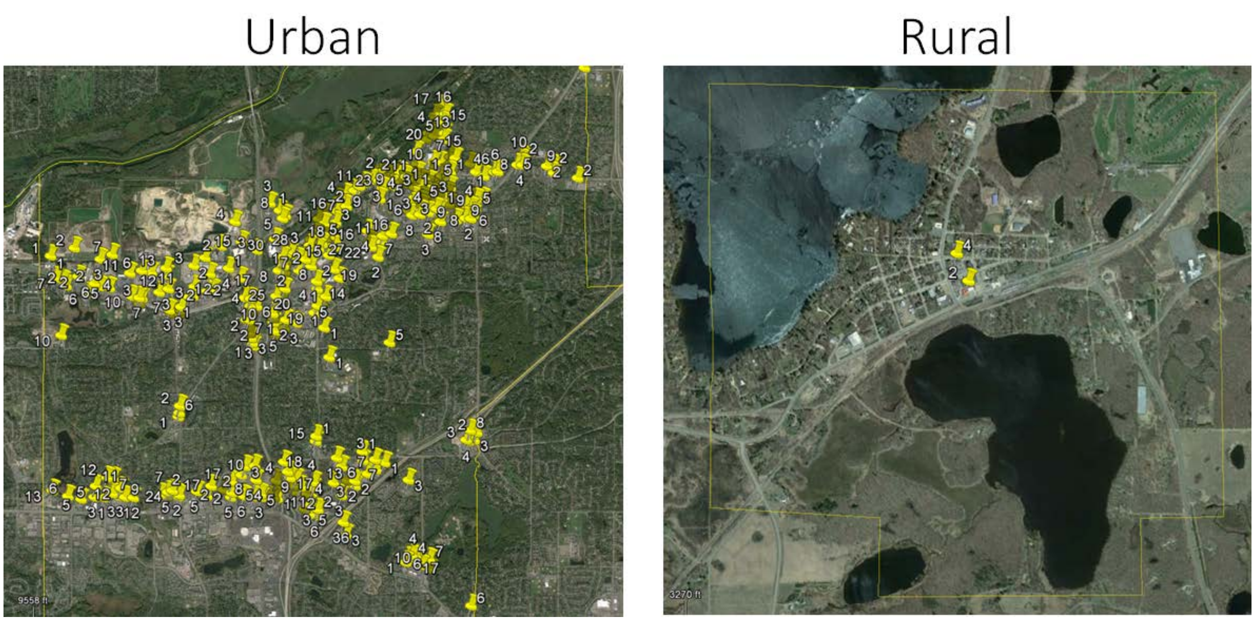
The yellow dots represent the buildings where we conducted interviews with facility staff (step 4 above), and are discussed in more detail subsequently. For each of these 50 ZIP codes, we then used public aerial imagery (such as Google Earth and Bing Maps) to systematically search for all of the commercial buildings with RTUs within a given ZIP code. For each of the buildings where we identified RTUs, we counted the number of apparent RTUs and gave the building an identification code and associated placemark. Figure 3 illustrates the aerial imagery of two example buildings with RTUs.

Figure 3: Example aerial imagery of buildings with RTUs.



We were careful not to count equipment on rooftops that looked like RTUs but were not. For air handling units, mechanical penthouses and split systems this was relatively straightforward. Other questionable units were flagged and an audit of all flags was conducted by an experienced mechanical engineer to make the final determination of whether the unit was actually an RTU. However, due to the nature of remote data collection, we occasionally mistakenly counted things that were not in fact RTUs, such as heating-only or make-up air units. We took steps to address these potential non-RTUs in our estimates as discussed in more detail in Appendix A: Sampling and Weighting. We also did not count RTUs that served non-commercial facilities such as multifamily buildings.

Figure 4: Two example ZIP codes with their corresponding placemarks showing the location of buildings with RTUs.



As mentioned previously, we endeavored to find and count every RTU by searching across the entire geographic extent of each ZIP code as defined by the U.S. Government – Postal Code

Boundaries layer within Google Earth. In order to systematically cover a ZIP code (and not miss portions of it), we used guiding gridlines to section off manageable sections of a given ZIP code. Each subsection was searched thoroughly before moving on to the next section. Two fully enumerated ZIP codes and their corresponding placemarks are illustrated in Figure 4.

The enumeration process identified a total of 4,508 buildings across the 50 ZIP codes, with an initial count of 28,946 RTUs. An average of 90 buildings with RTUs were identified per ZIP code, but this ranged from as few as 2 in rural ZIP codes to more than 300 in urban ZIP codes. For a portion of the buildings from this sample, we then identified the contact information of a subsample of 1,842 buildings from across all of our 50 sampled ZIP codes.

Using this contact information, we reached out to each building and attempted to connect with someone who would be able to provide us with pertinent building and RTU data. To increase our response rate, we first sent out a letter introducing the project with a notification that we would be following up with a call within the next few days. We offered a $50 gift certificate to interviewees who provided data. We completed 101 interviews resulting in a response rate of approximately 6%, represented as the yellow dots in Figure 2. However, respondents for five of these buildings provided information that allowed us to determine that the buildings did not in fact have any RTUs. These buildings were dropped from the analysis (except for the purpose of determining the ratio of actual RTUs to imagery-determined RTUs, which we used for estimating the total number of RTUs in the state). In addition, nine respondents did not provide sufficient information to determine if they actually had any RTUs: these buildings were dropped from the study entirely.

This left a total of 87 respondents, of which 81 provided information about the building and the RTUs associated with the building. Six respondents were able to provide information about the building only, and were not able to provide details about their RTUs. For these buildings, we included the data about the building, but not their RTUs.

The specific building-level data that we collected is outlined in Table 3.

Table 3: Building characteristics collected.

Building Characteristics
Building age
Total area
Area served by RTUs
Type of commercial activity
Building location
Area normalized cooling capacity
Owner type
Number of tenants
Occupancy schedule
Occupant density
Maintenance practices and schedule
Occupant complaints
Number of zones served

Additionally, we gathered utility bill information to support the monitoring task efforts to be outlined in the project's Final Report. For each interview, we also attained the make and model of the RTUs that served the building. This information was then used in conjunction with manufacturer specifications to collect the data for each RTU outlined in Table 4.

Table 4: RTU characteristics collected.

RTU Characteristics
Manufacturer
RTU age
Cooling type
Cooling capacity
Cooling efficiency, full load
Cooling efficiency, part load (if applicable)
Compressor type
Number of compressors
Heating type
Heating capacity
Heating efficiency
Fan speed
Fan power
Supply airflow
Refrigerant
Homogeneity of multiple RTUs

Data Accuracy

Data accuracy is important to ensure that results are admissible for utility program design, calculations, and evaluation. As mentioned previously, our first level of quality control involved developing a process to identify and count RTUs, which included the following steps:

- Staff were trained on how to identify RTUs (and rooftop equipment that were not RTUs) from aerial imagery.
- Any questionable units were flagged and subsequently reviewed by an experienced mechanical engineer.
- Guiding grids were laid out across ZIP codes to ensure that no area of the ZIP code was missed.
- Audits of preliminary, example ZIP codes identified gaps and pointed to ways of improving data gathering accuracy.

In order to minimize self-selection sampling bias when calling our building contacts, we attempted to contact a small set of sampled buildings three times before moving on to another set of buildings. However, some sampling bias may persist as buildings with more sophisticated maintenance staff may have been more likely to respond and provide accurate information.

Once data was in hand, our quality control checks for data accuracy included high level tabulations to identify and address:

- Significant gaps in data
- Number of reported RTUs that differed significantly from the number we counted from aerial imagery
- Building areas as compared to rough estimates gleaned from aerial imagery
- Cooling capacity normalized per area that were outside of reasonable engineering judgment for a given building type
- Make and model numbers that were clearly not RTUs (i.e. split systems or heating only units)
- Fan power normalized by supply flow rate that were outside of reasonable engineering judgment
- Reasonable part load efficiencies as compared to full load efficiency

We also performed a sanity check on our estimates and either corrected issues that were identified or developed reasonable explanations for them. These sanity checks included:

- Buildings with RTUs in Minnesota compared to Commercial Building Energy Consumption Survey (CBECS) estimates as proportion of total building population
- Average estimated RTUs per building
- Number of shipped RTUs as a percentage of existing RTUs as compared to percentage of new construction floor area reported by the U.S. Energy Information Administration (EIA); also percentage converted to estimated life of RTU compared to the Minnesota TRM value for RTU estimated useful life

Once a quality data set was established we applied weighting factors to scale our characterization to represent Minnesota as a whole. The weighting factor development is discussed in more detail in Appendix A: Sampling and Weighting.

Methodology for Characterizing the New and Replacement RTU Market

In order to understand the new and replacement RTU market characteristics, we interviewed representatives of major RTU manufacturers to inform our assumptions as well as gather information on market trends. The specific questions we asked are outlined below:

1. What are the energy efficient features of your RTUs?
2. What do you perceive to be the barriers to higher adoption of more energy efficient RTUs?
3. In your opinion, what factors lead to poor RTU energy performance?
4. In your opinion, what factors lead to high RTU energy performance?
5. Are utility efficiency programs effective at increasing the adoption of more energy efficient RTUs?
6. Do you have any feedback as to how to improve utility efficiency programs with respect to RTUs?
7. In your opinion, what is the approximate proportion of RTUs sales for new construction and replacement, respectively?
8. In your opinion, what is the approximate proportion of RTUs sales that are minimally code compliant versus high performance?

9. Any other thoughts?

Additionally we looked at sales and shipment data to round out our analysis. The market characteristics that we analyzed are listed in Table 5.

Table 5: Market characteristics collected.

Market Characteristics
Annual shipments
Annual sales
Efficiency level
Refrigerant type

In order to estimate the number of annual shipments of RTUs for Minnesota, we first obtained Air-Conditioning, Heating, and Refrigeration Institute data for the total number of U.S. shipments.[6] This data included not only shipments outside of Minnesota, but also information pertaining to residential and commercial split systems. Using EIA Residential Energy Consumption Survey and Commercial Building Energy Consumption Survey data, we were able to split out just the commercial RTU shipments. Finally, we used the ratio of Minnesota population to U.S. population to estimate the proportion of shipments of RTUs to Minnesota.

At this point, we had an estimate for the total number of RTU shipments to Minnesota. We were then able to differentiate between those destined for new buildings versus replacements of existing RTUs based on responses from our interviews with manufacturers. On average, manufacturers reported that 40% of their shipments were for new buildings and 60% for replacements.

Once we estimated the annual RTUs shipments, we analyzed the total sales of RTUs within Minnesota. We began this process by using RS Means[7] to determine an average equipment cost across a range of RTU types and capacities. RS Means provides this data as U.S. averages, but also includes factors for interpreting those averages for different locations to account for varying costs of labor and equipment. We therefore normalized our cost estimates to Minnesota, as well as extrapolated it to the present. From our analysis, we determined that a reasonable capital cost for a code-compliant RTU in Minnesota is approximately $1100/ton. We additionally estimate that an average high performance RTU in Minnesota costs approximately $1500/ton. Note that this does not include sales tax or installation costs, but simply represents the cost of the RTU equipment itself. Further note that there is a wide range of RTU costs based on the application, efficiency level and accessories among other factors. We then scaled this to Minnesota using the average capacity per RTU from our existing RTU characterization via:

$$MN\ Annual\ Sales = Average\ Capacity\ per\ RTU\ \times \begin{pmatrix} Code\ Compliant\ Shipments \times \$1100\ per\ ton + \\ High\ Performance\ Shipments \times \$1500\ per\ ton \end{pmatrix}$$

[6] http://www.ahrinet.org/site/496/Resources/Statistics/Historical-Data/Central-Air-Conditioners-and-Air-Source-Heat-Pumps

[7] RSMeans. 2010. Mechanical Cost Data. R.S. Means Company, Rockland, MA.

In order to better understand the varying efficiency levels of new and replacement RTUs, we used data from our interviews with manufacturers. From these interviews, we knew a reasonable approximation of the proportion of new RTUs that simply met code-required minimum performance versus those that were high performance. On average, manufacturers reported that 55% of their shipments were code-compliant compared to 45% high performance. We used these proportions to approximate the annual shipments and sales of both code-compliant and high performance RTUs.

Information regarding refrigerant types in new and replacement RTUs was compiled from data gathered on the newest existing RTUs, as well as from secondary literature.

Results

As a result of our analysis, we can characterize the buildings served by RTUs in Minnesota, existing RTUs and the market for new and replacement RTUs.

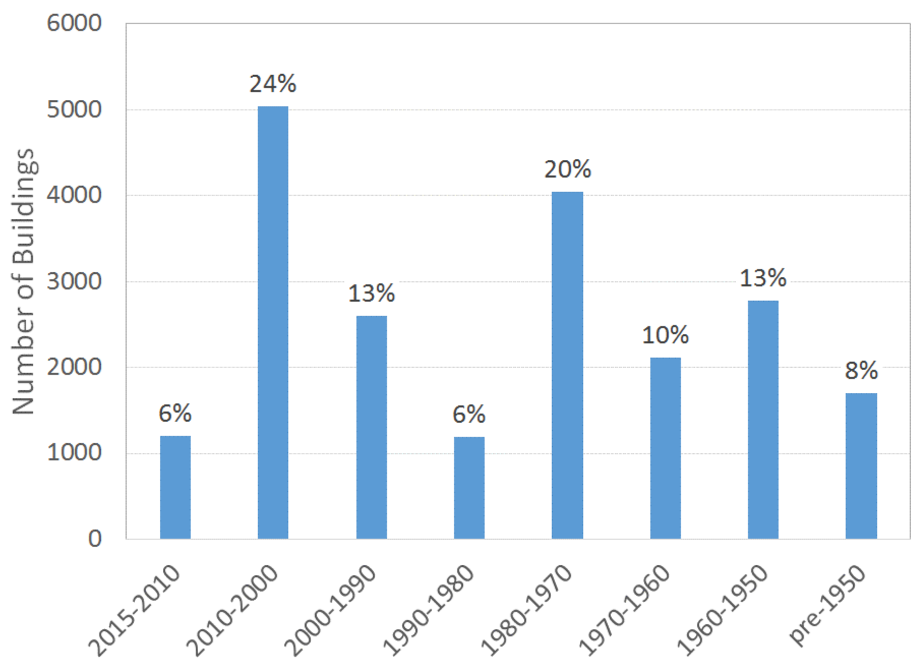
Building Characteristics

Our analysis concludes that there are currently 20,700 statewide buildings with RTUs, with a 95 percent confidence interval of ± 3,100 buildings. We characterized a number of interesting aspects of buildings served by RTUs in Minnesota. Following are some of the most relevant characteristics.

Building Age

One interesting aspect of these buildings is their age. Figure 5 shows the distribution of the age of buildings served by RTUs throughout Minnesota.

Figure 5: Age of buildings served by RTUs (n=20,700).



Nearly a third (30%) of buildings are relatively new, having been built since the turn of the century. However, buildings fall into each decade in significant numbers going back as far as the 1950s. Interestingly, the oldest building in our study was built in 1881.

Building Area and Portion Served by RTUs

Another building characteristic of interest is the building area. Figure 6 shows the distribution of the total area of buildings served by RTUs throughout Minnesota.

Figure 6: Total area of buildings served by RTUs (n=20,700).

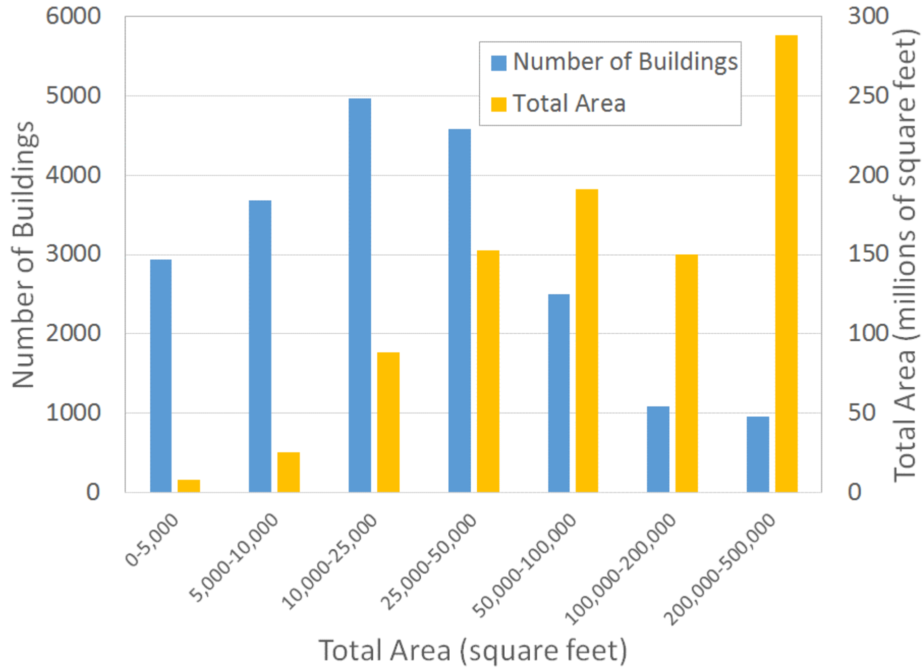
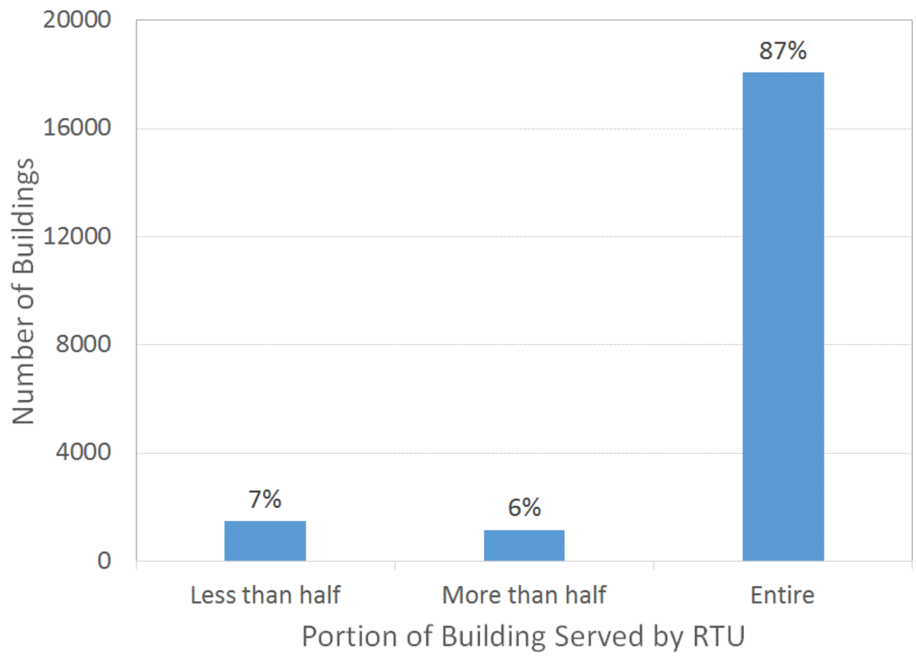


Figure 7: Portions of buildings served by RTUs (n=20,700).



Smaller buildings (those less than 50,000 square feet) dominate the **total number** of buildings, comprising 78% of all buildings. However, larger buildings (those greater than 50,000 square feet) dominate the **total area** of buildings, comprising 70% of total square feet. We were able to estimate the portion of each building that was (and conversely was not) served by RTUs from building imagery and secondary HVAC systems reported during the interviews. ***We estimate that of the 900 million square feet of total area in commercial buildings that have RTUs,***

approximately 80% or 730 million square feet are served by RTUs. The remainder of these buildings are served by another HVAC system type, or none at all. Figure 7 shows the distribution of the portion of buildings served by RTUs throughout Minnesota.

The majority (87%) of buildings that have RTUs do not have significant secondary HVAC systems, but are served entirely by RTUs. Examples of buildings that weren't entirely served by RTUs were:

- Hotels with RTUs serving the common areas, but not the hotel rooms
- Warehouses with small offices served by a residential system
- Schools with RTUs only serving the pool or an addition
- Religious worship buildings

Building Type

The type of building the RTU is serving significantly affects its energy consumption, as buildings with higher internal loads such as healthcare require different amounts of HVAC energy than more sparsely loaded buildings such as warehouses. Table 6 shows the distribution of the building types served by RTUs throughout Minnesota, in descending order of number of buildings.

Table 6: Building types served by RTUs (n=20,700).

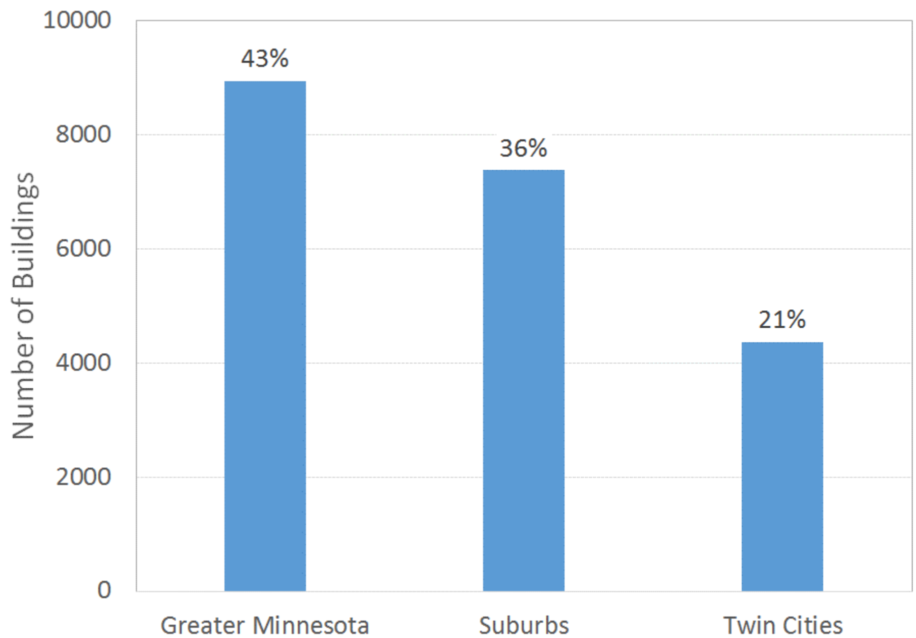
Building Type	Number of Buildings	Percentage	RTU Area (millions of sq. ft.)	Percentage
Office	3692	17.8%	170.8	23.4%
Food Service	2644	12.8%	23.0	3.2%
Food Sales	2359	11.4%	50.9	7.0%
Public Order and Safety	1869	9.0%	25.5	3.5%
Mercantile (Enclosed and Strip Malls)	1619	7.8%	67.5	9.2%
Religious Worship	1590	7.7%	28.3	3.9%
Education	1453	7.0%	100.2	13.7%
Other	1207	5.8%	23.1	3.2%
Warehouse and Storage	994	4.8%	99.3	13.6%
Public Assembly	929	4.5%	58.7	8.0%
Mercantile (Retail Other Than Mall)	848	4.1%	38.1	5.2%
Lodging	483	2.3%	18.1	2.5%
Health Care (Inpatient)	450	2.2%	10.3	1.4%
Health Care (Outpatient)	368	1.8%	15.2	2.1%
Service	195	0.9%	1.4	0.2%

The building types with the highest number of buildings are office, food service, food sales, and public order and safety. Combined these buildings types comprise over half (51%) of the buildings with RTUs in Minnesota. However, in terms of area served by RTUs, food service, food sales and public order and safety are a much smaller portion due to their relatively small average area. However, warehouse and education increase their share due to their higher average area.

Building Location

When planning programs, it is useful to know where the technology of interest is located. We therefore categorized the buildings served by RTUs by their location: the Twin Cities, the surrounding suburbs, or Greater Minnesota. Figure 8 shows the distribution of the building locations served by RTUs throughout Minnesota.

Figure 8: Building locations served by RTUs (n=20,700).

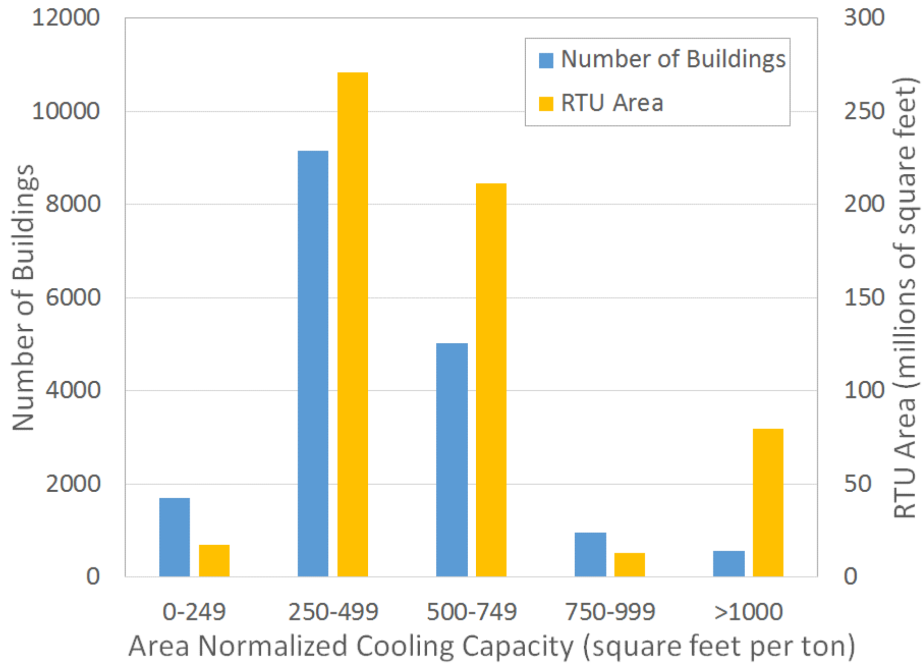


Over half (57%) of buildings served by RTUs are in the Twin Cities or surrounding suburbs, including the seven county metro area. Of the Greater Minnesota buildings, the average distance from the Minnesota state capitol building was 140 miles, or approximately the distance from Saint Paul to Duluth.

Area Normalized Cooling Capacity

RTUs serving different space types need varying amounts of cooling capacity to meet their cooling requirements. Although the needed capacity depends on area, it also depends on what is happening in the space. For example, a warehouse and an office of the same size will, not surprisingly, require differing amounts of cooling under the same outside conditions. One metric to express this is area normalized cooling capacity, or the amount of area served by the RTU divided by its cooling capacity in tons. As the area normalized cooling capacity increases, the amount of cooling per unit area decreases. Figure 9 shows the distribution of the area normalized cooling capacity for buildings served by RTUs throughout Minnesota.

Figure 9: Area normalized cooling capacity for buildings served by RTUs (n=17,397).



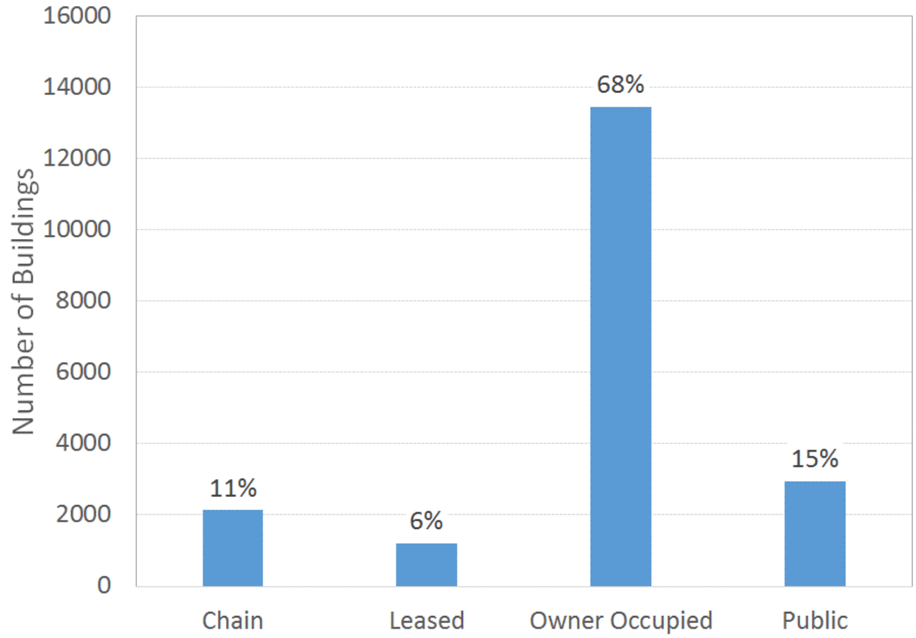
Because of data gaps, our sample size for this metric (along with several subsequent metrics) was less than our full estimate for number of buildings in Minnesota served by RTUs. The average area normalized cooling capacity for RTUs in Minnesota is 488 square feet per ton. Typically, commercial buildings fall between 250 to 750 square feet per ton, and the same is true with our Minnesota estimates as over 80% fall within this range.

Owner Type

Different owner types may make decisions that affect RTU performance based on different criteria. For instance, people that own their buildings as well as those that manage a publically-held building may have more motivation to invest in energy efficiency than those that lease their space. They may evaluate investments on a longer time horizon and may directly see the benefits of improved energy performance in terms of reduced energy costs. Decision makers in leased buildings on the other hand may be less motivated to invest in energy efficiency measures because they may not see the benefit of reduced energy costs if they are not paying their own utility bills. Figure 10 shows the distribution of owner types for buildings served by RTUs throughout Minnesota.

Over four-fifths (83%) of commercial buildings served by RTUs in Minnesota are owner occupied or public. Chain stores are an interesting owner type, in that they may have more sophisticated facility staff. However, they often have approved designs with associated bureaucratic hurdles to overcome in order for CIPs to influence efficiency decisions.

Figure 10: Owner type for buildings served by RTUs (n=19,751).

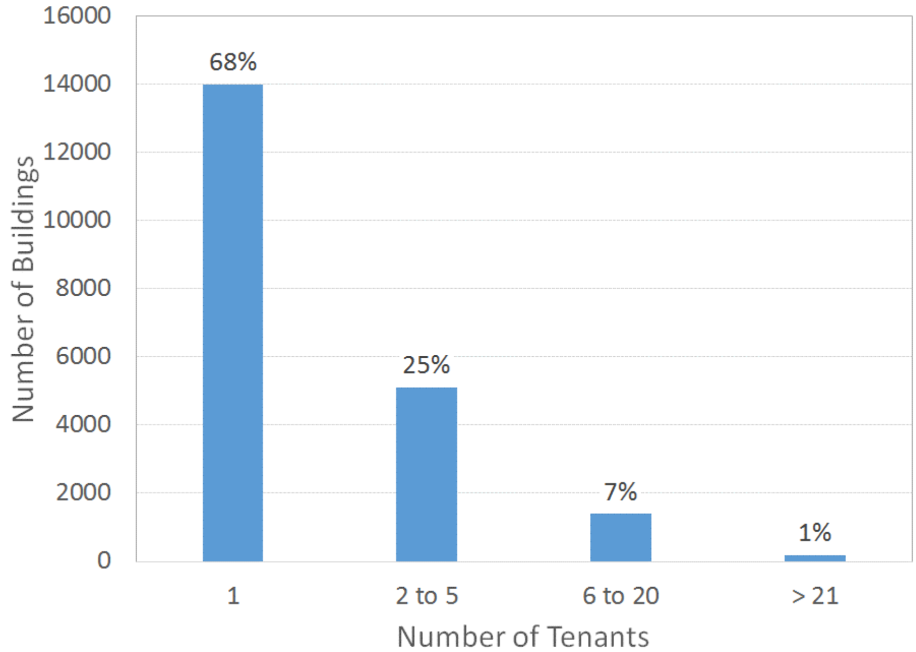


Number of Tenants

Many buildings have multiple associated businesses. As opposed to buildings with a single tenant, buildings with multiple tenants may be more difficult to approach programmatically, as they often require the additional step of connecting with the management organization. Figure 11 shows the distribution of number of tenants for buildings served by RTUs throughout Minnesota.

Over two-thirds (68%) of the buildings served by RTUs in Minnesota have a single tenant. The remainder tended to be malls, strip malls or multi-tenant office buildings.

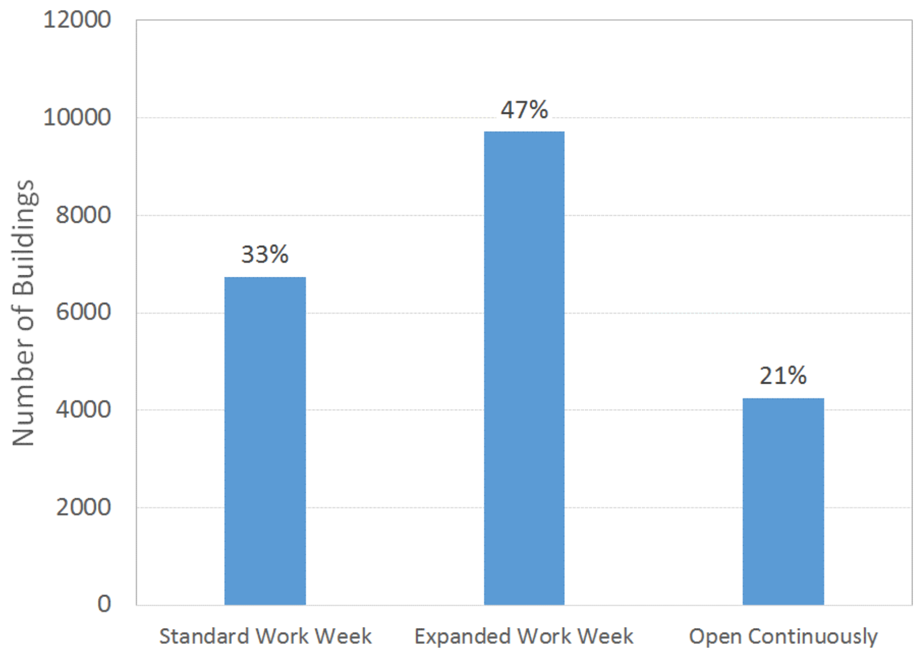
Figure 11: Number of tenants for buildings served by RTUs (n=20,700).



Occupied Hours

The hours of occupancy affect the RTU energy consumption: longer hours of operation require the RTU to work harder to maintain temperature and humidity setpoints. Figure 12 shows the distribution of weekly occupied hours for buildings served by RTUs throughout Minnesota.

Figure 12: Weekly occupied hours for buildings served by RTUs (n=20,700).

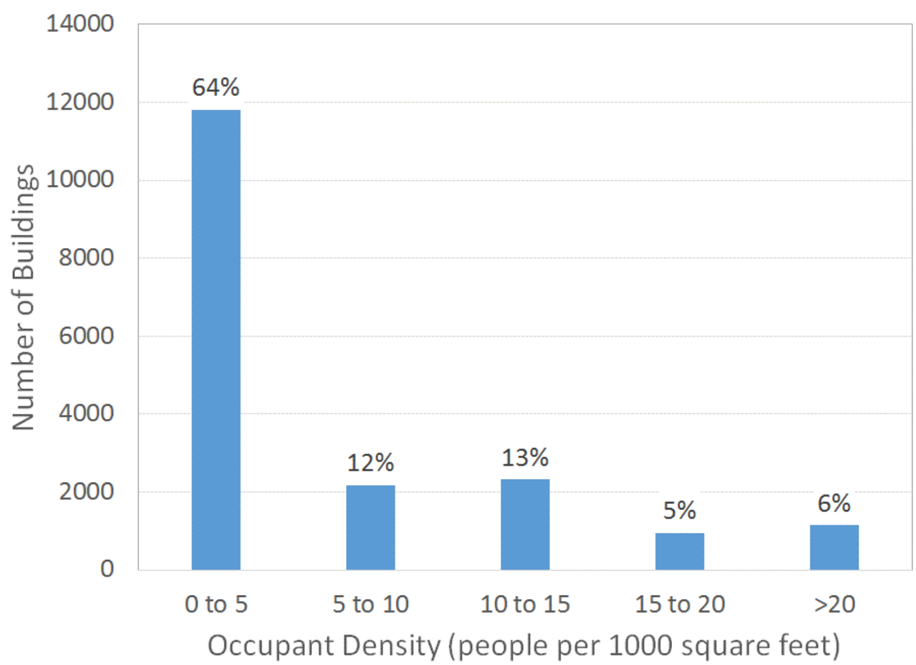


Approximately two-thirds (67%) of buildings with RTUs had occupied hours exceeding what would be considered a standard work week. The buildings with standard occupied hours (40 to 60 per week) were dominated by offices, but the other building types were also well-represented. Buildings with expanded occupied hours (61 to 167 per week) were those that were open on the weekends or had multiple shifts. This category was predominantly education, food service, retail and public assembly. Buildings that were open continuously had a significant proportion of food sales, health care and lodging.

Occupant Density

Occupant density also drives RTU energy requirements as buildings with increasing occupant density will need additional cooling to meet the increasing load. Additionally, higher ventilation requirements will increase fan energy, as well as heating and cooling energy needed to temper the unconditioned outdoor air. Figure 13 shows the distribution of occupant density for buildings served by RTUs throughout Minnesota.

Figure 13: Occupant density for buildings served by RTUs (n=18,386).



Nearly two-thirds (64%) of buildings had relatively low occupant densities of between 0 and 5 people per 1000 square feet. Put another way, the median occupancy density of this range is 2.5 people per 1000 square feet. By inverting this number it becomes 400 square feet per person or the equivalent of each person having an average of 20 feet by 20 feet of space around them. These buildings were mostly office, retail and warehouse. Buildings with occupant densities higher than 20 people per 1000 square feet (approximately 7 feet by 7 feet of space) tended to be food service.

Maintenance

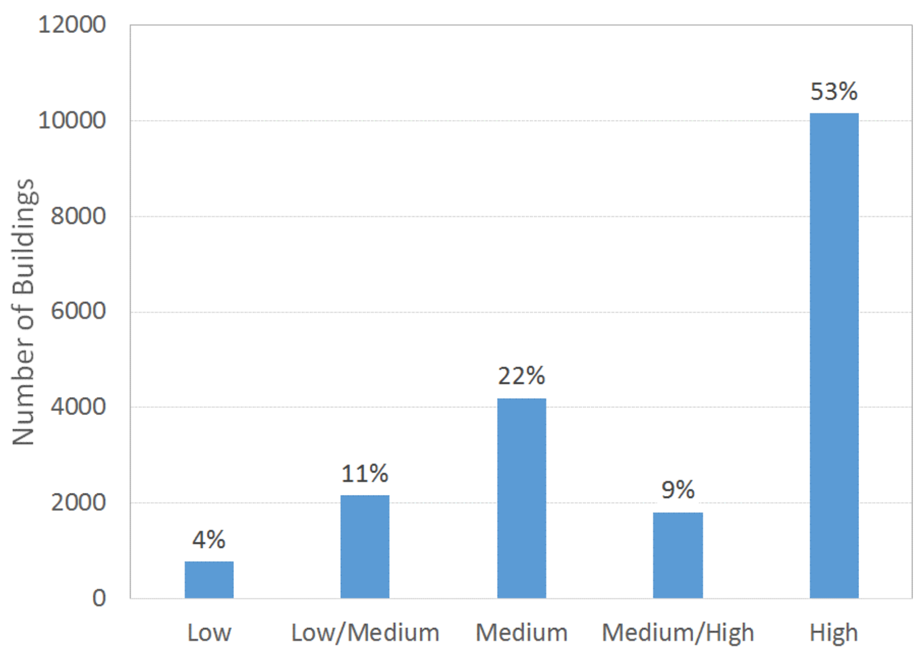
The frequency and level of RTU maintenance affects energy consumption. Table 7 outlines the various levels of maintenance that building staff reported.

Table 7: Maintenance level descriptions.

Level of Maintenance	Preventative Maintenance	Repairs
Low	Minimal to none	As needed by vendor
Low/Medium	Occasionally by owner	As needed by vendor
Medium	Varying by owner	As needed by owner
Medium/High	Frequent by vendor	As needed by owner or vendor
High	Frequent by vendor	As needed by vendor

Figure 14 shows the distribution of maintenance levels for buildings served by RTUs throughout Minnesota.

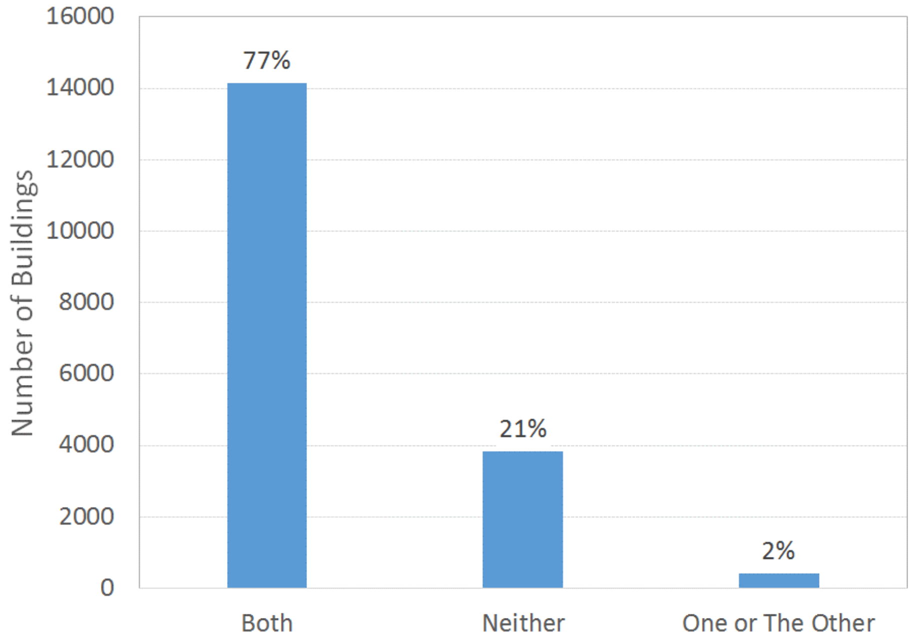
Figure 14: Maintenance approaches for buildings served by RTUs (n=19,071).



The majority of buildings served by RTUs in Minnesota use contracted vendors for their maintenance service. Although this is likely the highest level of maintenance, program opportunities for improvement exist through training of trade allies regarding proper maintenance techniques. The greatest opportunity for improved maintenance (Low and Low/Medium) comprise 15% of buildings. In these buildings, and in some buildings with a medium level of maintenance, it is likely that little to no maintenance of RTUs is being conducted.

We additionally asked whether summer or winter startup was practiced annually. Figure 15 shows the portion of buildings served by RTUs throughout Minnesota that practice summer and winter startup.

Figure 15: Summer and winter startup practiced by buildings served by RTUs (n=18,417).

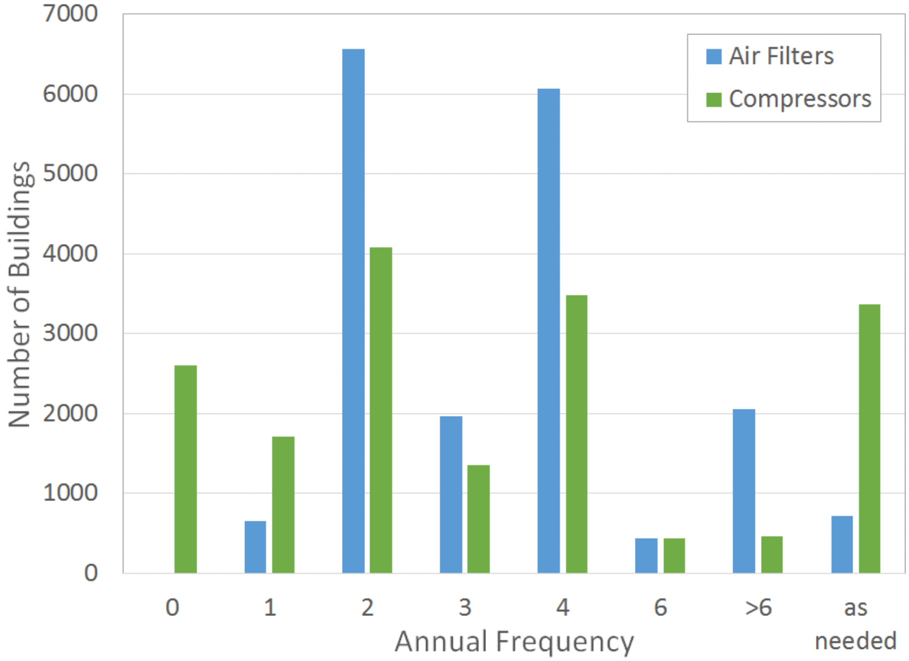


Over three-quarters (77%) of buildings had both summer and winter startup, but over one-fifth (21%) did neither.

We also asked about the frequency with which filters were changed and compressors were cleaned. Figure 16 shows the annual frequency of maintenance for buildings served by RTUs throughout Minnesota that change air filters and clean compressors.

The best practice for replacing air filters is to track the pressure drop across the filter and replace the filter when the pressure drop exceeds some threshold when it becomes too dirty. A more common recommendation is that air filters be changed on a quarterly basis or four times each year. Nearly half (46%) of buildings had their air filters changed at this level of frequency or above. In some cases higher frequency was driven by site-specific needs such as very dusty adjacent parking lots. Compressors were less likely to be cleaned on a frequent basis with over one-third (34%) never being cleaned or only being cleaned as needed.

Figure 16: Annual frequency of air filter replacement and compressor cleaning (n=18,473).



The following are other maintenance practices outside of the ones outlined previously, as well as the numbers of times they were reported during our interviews.

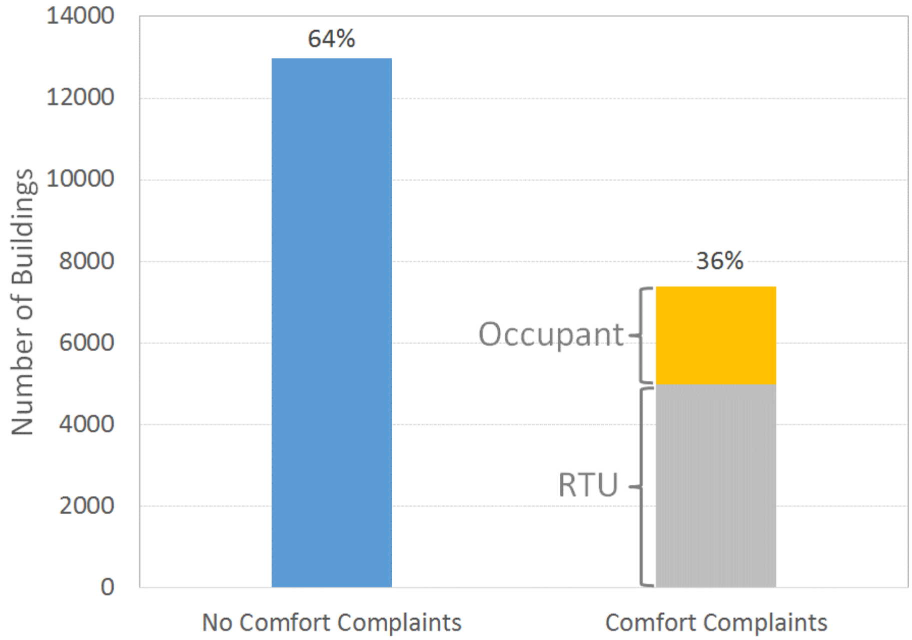
- Inspect belts and bearings; lubricate (10)
- Inspect indoor and outdoor coils; clean (7)
- Inspect drain (2)
- Inspect economizer (2)
- Check pressures and fan speeds (2)
- Check for voltage imbalances (1)
- Conduct amperage checks (1)

Occupant Complaints

During our interviews, we also asked if occupants reported any noise or thermal comfort issues. The overwhelming majority (92%) of buildings with RTUs in Minnesota do not experience noise concerns. In the few cases that noise complaints did occur, it was usually related to older units that were in need of replacement or repair.

A much more sizable portion of building occupants reported thermal comfort issues. Figure 17 illustrates the portion of buildings in which occupants reported comfort issues.

Figure 17: Comfort complaints in buildings served by RTUs (n=20,354).



Over one-third (36%) of buildings served by RTUs in Minnesota experience occupant comfort complaints. The cause of these complaints fell into two categories; the RTUs were not properly maintaining temperature and/or humidity setpoints, or the occupants personal preferences diverged from the setpoints. In the second case, the RTUs were working properly. We are not able to ascertain the cause of a given complaint without further research. However, from the information the interviewee provided, we estimate that two-thirds of complaints were based on RTU performance while one-third were dependent on an occupants personal preferences. Some of the reasons given for why the RTU was unable to maintain setpoints include:

- The system was broken and subsequently repaired
- The system was undersized
- Improper air distribution (multiple zones)
- Someone remote to the building itself (headquarters of a retail chain) controlled the setpoints and did not take occupant feedback into consideration

Number of Zones Served

RTUs are typically meant to serve only a single zone or space with a single thermostat. However, in practice, they often serve multiple zones. This is usually driven by cost or logistical considerations. In situations where an RTU serves multiple zones of which only one zone has a thermostat, the zone with the thermostat receives the appropriate amount of heating or cooling. The RTU controller does not analyze how much heating or cooling the other zones require, resulting in occupant discomfort as the temperature of these secondary spaces rise or fall relative to setpoints. Table 8 shows the portion of buildings that have RTUs serving single versus multiple zones.

Table 8: Buildings with RTUs serving single versus multiple zones (n=17,961).

Zones Served	Number of Buildings (thousands)	Percentage
Single	9900	59.8%
Multiple	8061	40.2%

Approximately two-fifths (40%) of buildings have RTUs supply conditioning to multiple zones, increasing the frequency of occupant discomfort.

RTU Characteristics

Our analysis indicated a total of 136,000 ± 30,000 RTUs in the state. On average, there are between 6 and 7 RTUs per commercial building that is served by RTUs. We characterized a number of interesting aspects of existing RTU in Minnesota. Following is a discussion of the most relevant characteristics.

Manufacturer

There are a number of RTU manufacturers, each with their own models of RTUs and differentiating performance features. Table 9 shows the distribution of the manufacturers of existing RTUs throughout Minnesota.

Table 9: Manufacturers of RTUs (n=120,860).

Manufacturer	Number of RTUs (thousands)	Percentage	Cooling Capacity (thousands of tons)	Percentage
Carrier	35.1	29.0%	243.6	18.8%
Lennox	28.8	23.8%	195.1	15.0%
Trane	26.7	22.1%	236.3	18.2%
Bryant	10.3	8.5%	64.2	4.9%
AAON	7.4	6.1%	389.3	30.0%
York	6.8	5.6%	76.9	5.9%
McQuay	1.5	1.2%	63.9	4.9%
Other	4.3	3.6%	29.2	2.3%

Three manufacturers (Carrier, Lennox and Trane) account for approximately three-quarters (75%) of the RTUs in Minnesota and over half (52%) of the installed capacity. Although AAON has a relatively small share of the number of RTUs (6%), it is the largest manufacturer in terms of installed capacity (30%). The average AAON unit is larger than the average RTU in Minnesota.

RTU Age

The age of RTUs also has an impact on energy performance because newer RTUs may have higher efficiencies and system performance tends to degrade over time. Figure 18 shows the portion of existing RTUs falling into different age ranges.

Figure 18: Age of RTUs (n=118,284).

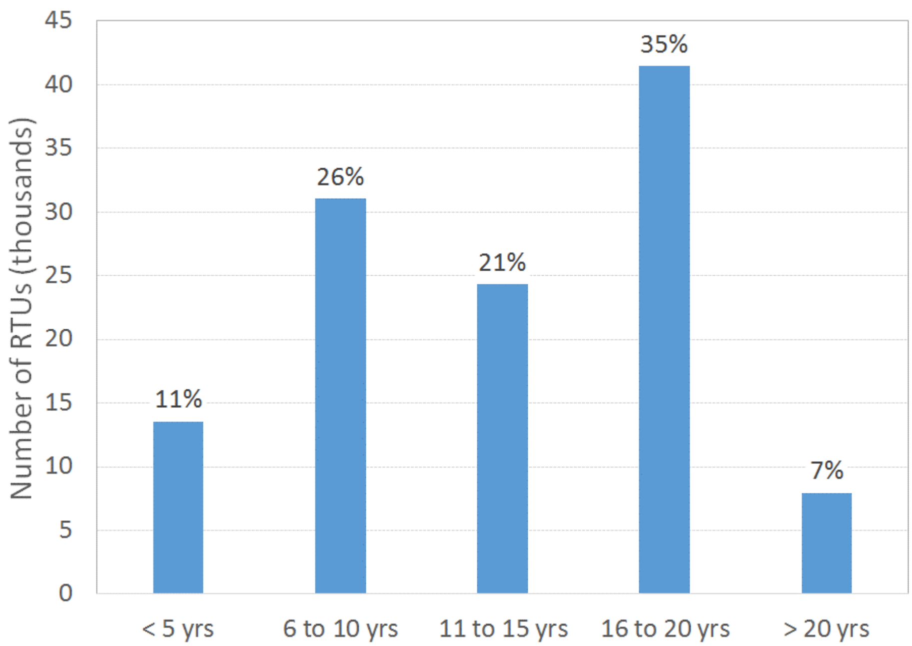
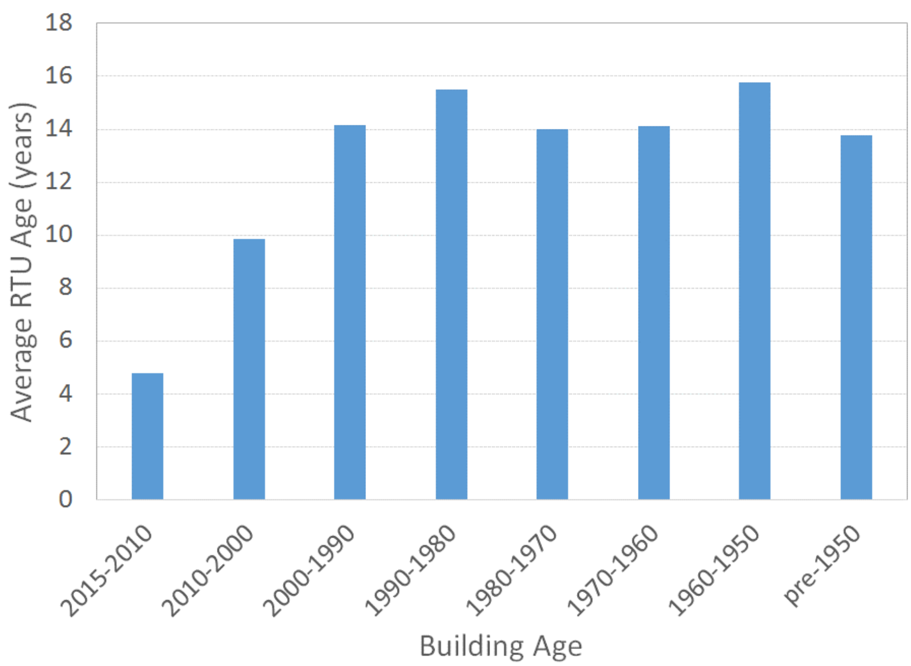


Figure 19: Dependence of RTU age on building age.



Note that it was increasingly difficult to find the age of older RTUs, meaning the accuracy of estimates becomes increasingly less precise as RTU age increases. ***The average age of an existing RTU in Minnesota is 13.1 years.*** Newer RTUs, those that are less than 5 years old, comprise 11% of existing RTUs. Also, only 7% of existing RTUs are older than the Minnesota TRM's value of 20 years for estimated useful life.

Since we collected both RTU age as well as the age of the building they serve, we can look at the relationship between them. Figure 19 shows the average age of RTUs for ranges of building age.

For buildings less than 15 years old, the average RTU age was essentially in line with the building age. For buildings greater than 15 years old, the average RTU age held pretty constant around 15 years regardless of the age of the building.

Cooling

The RTUs in this study were all cooled via a direct expansion process. None of the RTUs we characterized were water source or ground source heat pumps. The RTUs in Minnesota are overwhelmingly air cooled. Only 3 RTUs were identified as being evaporatively cooled: all of which had very large cooling capacities of 170 tons.

Another important characteristic of RTUs is their cooling capacity. Table 10 shows the distribution of cooling capacity of existing RTUs throughout Minnesota.

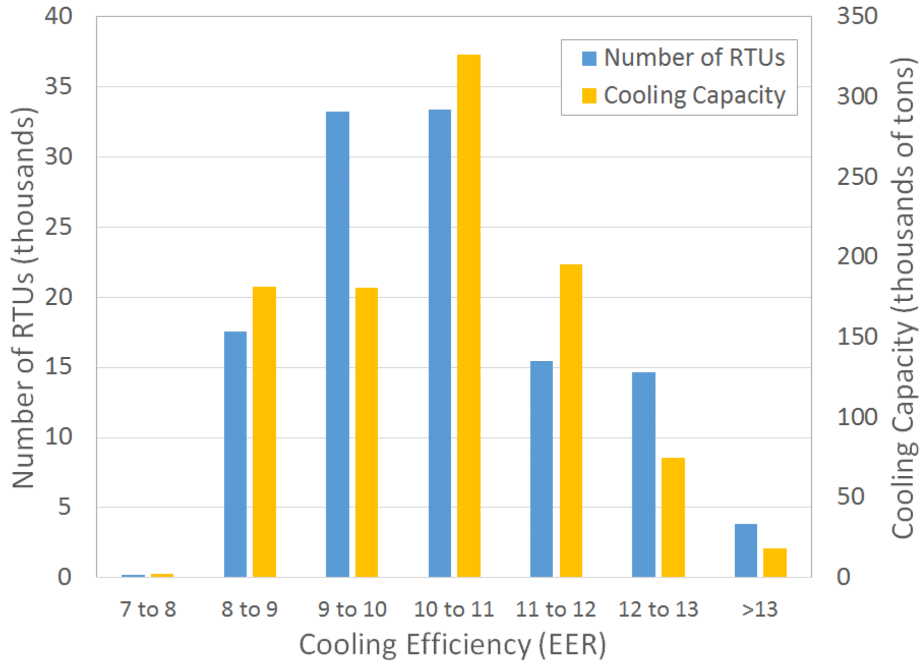
Table 10: Cooling capacity of RTUs (n=120,860).

Cooling Capacity (ton)	Number of RTUs (thousands)	Percentage	Cooling Capacity (thousands of tons)	Percentage
< 5.4	62.2	51.5%	242.8	18.7%
5.4 to 11.3	35.2	29.1%	299.5	23.1%
11.3 to 20.0	12.0	9.9%	175.5	13.5%
20.0 to 63.6	9.6	7.9%	286.6	22.1%
> 63.3	1.9	1.6%	294.0	22.6%

The total estimated cooling capacity of RTUs in Minnesota is approximately 1.3 million tons with an average cooling capacity of 10.7 tons per RTU. Slightly more than half (52%) of the individual RTUs have a cooling capacity of less than 5.4 ton. However, RTUs with cooling capacities over 20 ton comprise 45% of the cooling capacity of all RTUs.

The full load cooling efficiency is currently the major driver of how much electricity an RTU consumes. Figure 20 shows the portion of existing RTUs falling into different full load cooling efficiency ranges.

Figure 20: Full load cooling efficiency of RTUs (n=118,284).



For cooling capacities above 5.4 ton, the cooling efficiency is expressed as an Energy Efficiency Ratio (EER), while the cooling efficiency for capacities below 5.4 ton is expressed in Seasonal Energy Efficiency Ratio (SEER). RTUs with cooling efficiencies expressed in SEER were converted to EER for ease of comparison. The conversion is expressed as:[8]

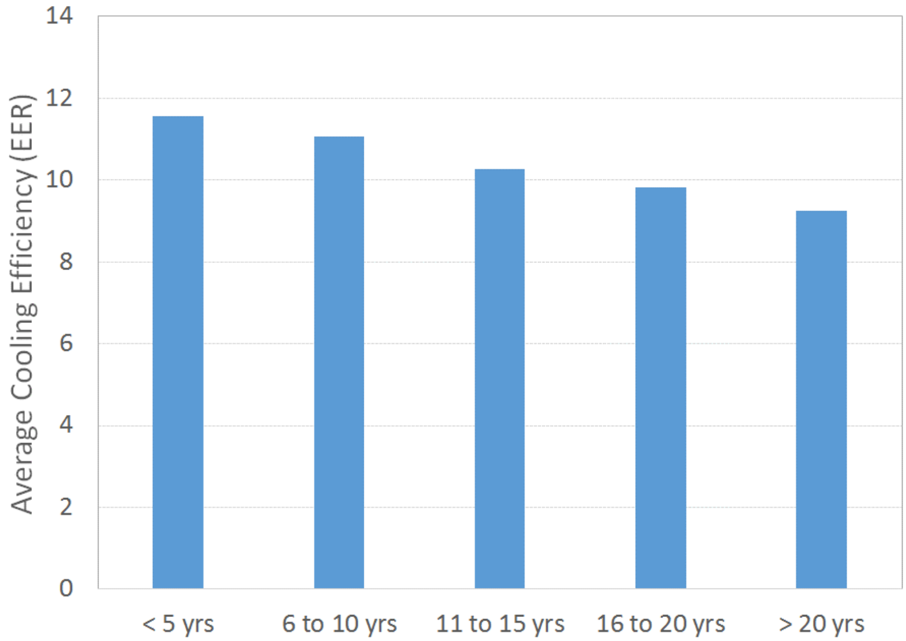
$$EER = SEER \times 0.875$$

Over half (56%) of RTUs had full load cooling efficiencies between 9 and 11 EER. ***The average full load cooling efficiency of RTUs in Minnesota is 10.6 EER***.

Since we also collected information about the age of each RTU, we are able to look at the trend of cooling efficiency with respect to RTU age. Figure 21 shows cooling-capacity weighted average cooling efficiency by RTU age.

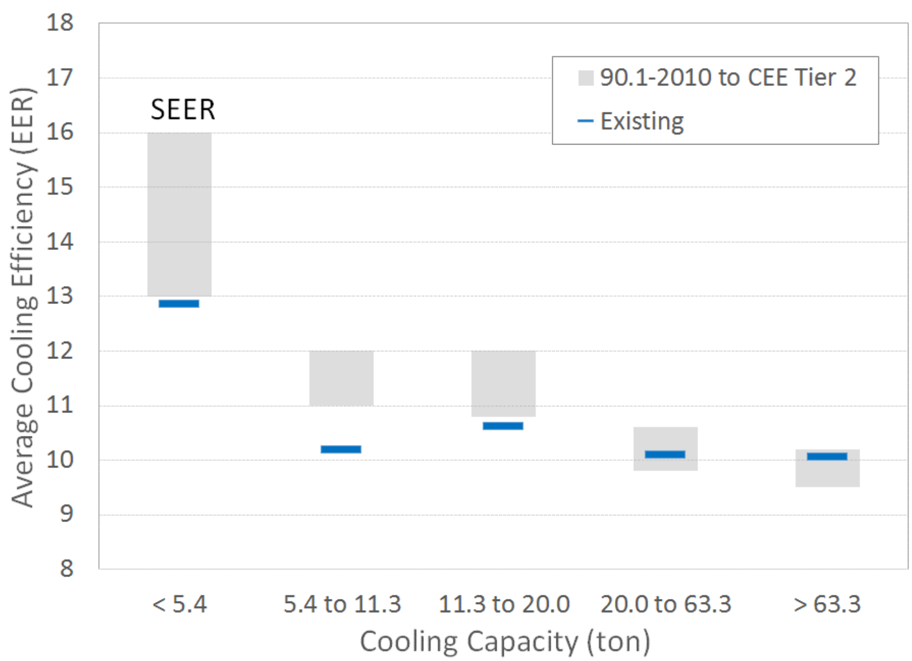
[8] Minnesota TRM, version 1.3, 2016, pg. 15

Figure 21: Average cooling efficiency by RTU age (n=118,284).



Note the clear trend of increasing cooling efficiency in newer RTUs. In fact, over the last 20 years, the average cooling efficiency of RTUs has increased by 18%.

Figure 22: Average cooling efficiency by cooling capacity (n=118,284).

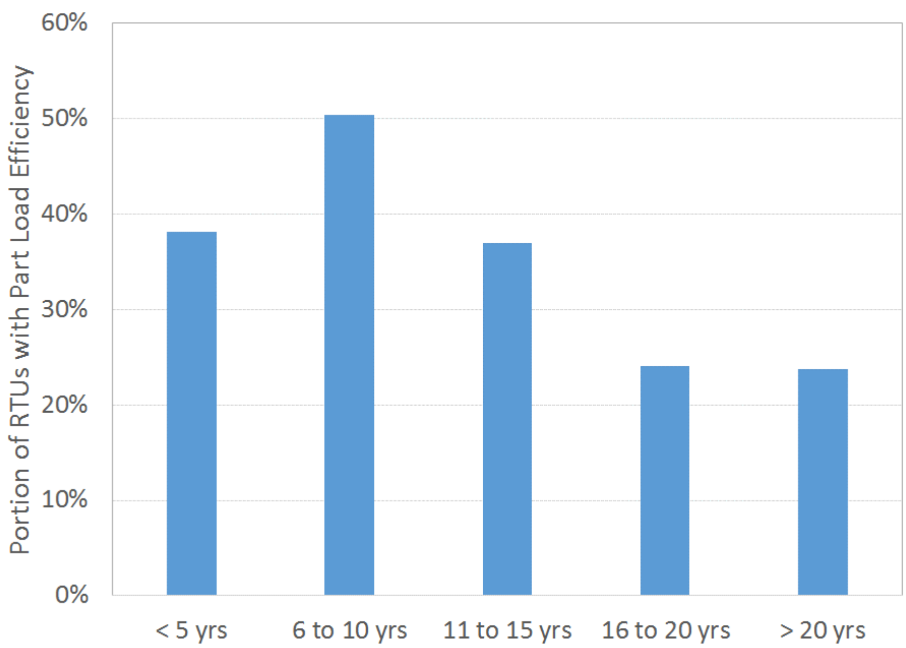


For new construction or renovation projects, the Minnesota energy code requires a minimum level of cooling efficiency for RTUs. The requirement varies by cooling capacity range. It is therefore interesting to compare the average cooling efficiency within each of these cooling capacity ranges. Figure 22 illustrates the cooling-capacity weighted average cooling efficiency by cooling capacity.

For cooling capacities above 5.4 ton, the cooling efficiency is expressed as EER, while the cooling efficiency for capacities below 5.4 ton is expressed as SEER. As opposed to previous graphs, the existing RTU data are plotted as bars. Additionally, the range of cooling efficiency between the current Minnesota energy code[9] and CEE's Tier 2[10] recommendations are also plotted to illustrate the potential programmatic savings magnitude. CEE's Tier 1 efficiency recommendations are defined at a performance level corresponding to price points with significant sales volume. CEE's Tier 2 is defined to provide significant, but achievable, savings above and beyond Tier 1.

In RTUs with cooling capacities below 20 ton, the average existing efficiency is below the code-minimum and well-below the CEE Tier 2 recommendation, suggesting considerable opportunity for improved efficiency in smaller RTUs. For larger RTUs with cooling capacities between 20 and 63.5 ton, the average existing efficiency is between the code-minimum requirement and below the CEE Tier 2 recommendation. Since their efficiency is already relatively high, there is a limited opportunity for increasing efficiency. For the largest capacity RTUs with cooling capacities above 63.3 ton, the average existing efficiency is near the CEE Tier 2 recommendation, leaving little opportunity for increased efficiency.

Figure 23: Portion with part load efficiency by RTU age (n=118,284).



The current trend in increasing RTU performance is with respect to part load cooling efficiency, rather than full load cooling efficiency. For instance, variable speed compressors (often inverter-

[9] ASHRAE 90.1-2010, Table 6.8.1A

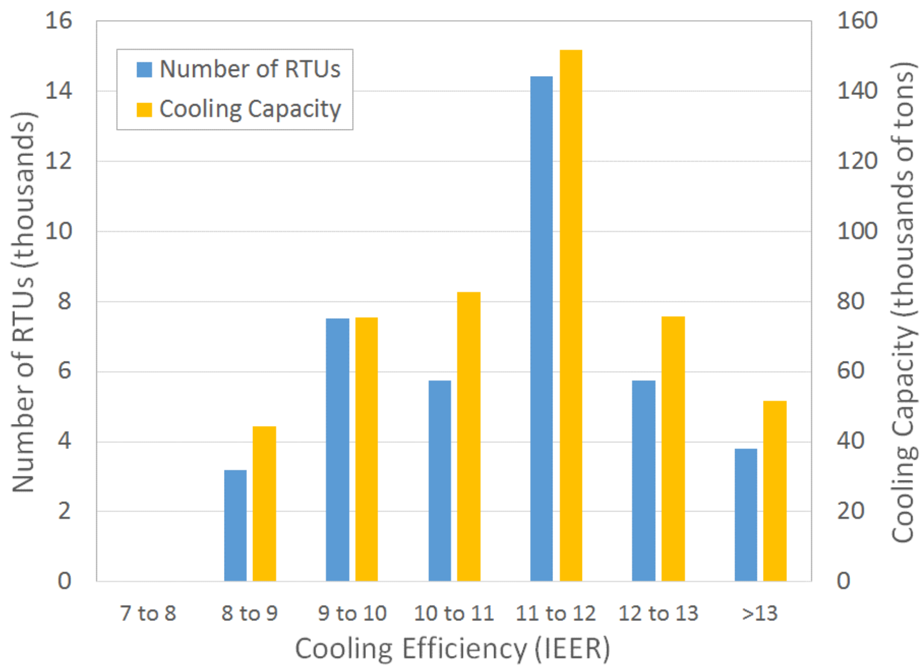
[10] CEE 2016. High Efficiency Commercial Air-conditioning and Heat Pumps Initiative. Consortium for Energy Efficiency. 2016.

driven) allow for part-load efficiencies over 18 IEER. We calculate that 35% of existing RTUs in Minnesota have some level of part load efficiency. Figure 23 shows the portion of RTUs that had some level of part load efficiency by RTU age.

Note the trend of increasing portion of RTUs with part load efficiency in RTUs from 20 years to 5 years old. The portion deceases in the RTUs less than 5 years of age, which may be attributable to the economic climate in Minnesota over that time period.

The part load cooling efficiency is increasingly important because of how much electricity an RTU consumes. Figure 24 shows the portion of existing RTUs with part load cooling efficiency falling into different ranges.

Figure 24: Part load cooling efficiency of RTUs (n=40,408).



Approximately half (50%) of RTUs with part load cooling efficiencies had an IEER between 10 and 12. ***For existing RTUs in Minnesota with part load cooling efficiencies, the average IEER is 11.2.***

Compressor

As scroll compressors have become increasingly popular over the past couple of decades, they have captured increasing shares of the RTU market. Today, nearly four-fifths (79%) of RTU compressors in Minnesota are scroll. The remaining are reciprocating, mostly legacy in the older RTUs. Table 11 shows the distribution of number of compressors of existing RTUs throughout Minnesota.

Table 11: Number of compressors of existing RTUs (n=118,517).

Number of Compressors	Number of RTUs (thousands)	Percentage	Cooling Capacity (thousands of tons)	Percentage
1	69.7	58.8%	309.6	30.4%
2	40.6	34.3%	474.9	46.6%
3	4.3	3.7%	91.0	8.9%
4	3.6	3.0%	122.9	12.1%
6	0.3	0.2%	19.7	1.9%

The majority (93.1%) of existing RTUs have 1 or 2 compressors, but the number of compressors in larger RTUs is increasing. More recently, compressors are being added for improved humidity control.

Heating

We gathered information about the heating type of Minnesota RTUs and found that, overwhelmingly (97%), they are natural gas fired. The remainder use electric resistance heating. As stated previously, we did not find any heat pump RTUs in the course of the study. The average heating efficiency of natural gas fired RTUs in Minnesota is essentially the code-minimum required value across all capacities of approximately 80%. We did not find any high efficiency condensing RTUs as they are a relatively new (but growing) technology, currently existing in such small numbers as to have a small likelihood to be randomly sampled. Since condensing RTUs can have heating efficiencies between 90% and 94%,[11] there is considerable room for natural gas savings in new and replacement RTUs from this technology.

Another important characteristic of RTUs is their heating capacity. Table 12 shows the distribution of the heating capacity of existing RTUs throughout Minnesota.

Table 12: Heating capacity of RTUs (n=116,239).

Heating Capacity (MBH)	Number of RTUs (thousands)	Percentage	Heating Capacity (millions of MBH)	Percentage
< 225	83.4	71.7%	10.1	42.2%
≥ 225	32.9	28.3%	13.8	57.8%

The total estimated heating capacity of RTUs in Minnesota is approximately 23.8 million MBH with an average heating capacity of 205 MBH per RTU. Nearly three-fourths (72%) of

[11] Nicor Gas Energy Efficiency Emerging Technology Program, 11/11/2013, pg 5

individual RTUs have a heating capacity less than 225 MBH. However, RTUs with heating capacities over 225 MBH comprise 58% of the heating capacity of all RTUs.

Fans

Fan power is a large component of RTU energy consumption. Gathering accurate information about fan power proved particularly difficult. We looked at manufacturer specifications, only some of which contained any information about fan power. When available, the specifications often contained a range of potential fan powers. In these circumstances, we recorded the median value. While a more accurate approach would be to gather the mechanical design drawings to find the fan power on the RTU schedule, getting this information from building facility staff proved too difficult to rely on to complete our dataset. Table 13 shows the distribution of the fan power of existing RTUs throughout Minnesota.

Table 13: Fan power of RTUs (n=119,206).

Fan power (motor hp)	Number of RTUs (thousands)	Percentage	Fan power (thousands of motor hp)	Percentage
fractional	39.3	33.0%	23.0	5.9%
1 to 1.5	14.5	12.2%	17.8	4.6%
1.5 to 2	4.6	3.8%	7.2	1.8%
2 to 3	24.0	20.1%	57.6	14.8%
3 to 5	20.9	17.5%	66.7	17.2%
5 to 7.5	7.1	6.0%	37.6	9.7%
7.5 to 10	3.8	3.2%	28.8	7.4%
>10	4.9	4.1%	149.9	38.6%

The total estimated fan power of RTUs in Minnesota is approximately 389 thousand horsepower with an average of 3.3 horsepower per RTU. Fan motors of less than 3 motor horsepower are used on more than two-thirds (69%) of RTUs in Minnesota. However, larger fans with motor horsepower greater than 3 comprise nearly three-quarters (73%) of fan power used by RTUs.

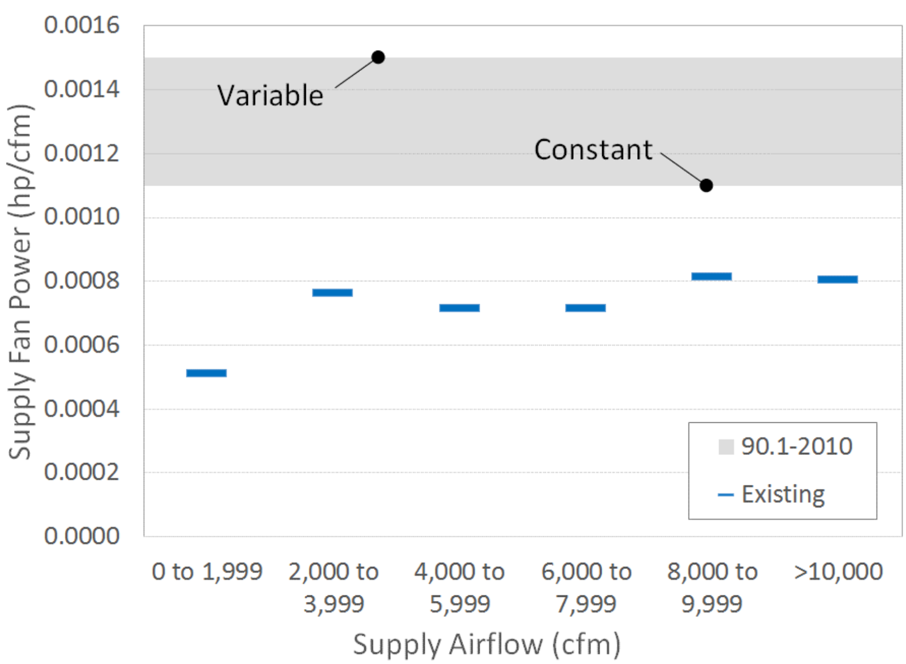
The fan speed is an important characteristic influencing how much fan energy an RTU consumes. Table 14 shows the distribution of the fan speed of existing RTUs throughout Minnesota.

Table 14: Fan speed of RTUs (n=120,526).

Fan speed	Number of RTUs (thousands)	Percentage	Fan power (thousands of motor hp)	Percentage
Single	97.5	80.9%	215.9	55.7%
Two	8.4	6.9%	8.0	2.1%
Multiple	1.3	1.1%	0.8	0.2%
Variable	13.4	11.1%	163.2	42.1%

Single speed fans are used on four-fifths (81%) of RTUs in Minnesota, representing 56% of total RTU fan power. A large and growing proportion of RTUs use variable speed fans, comprising 42% of fan power. The relatively large proportion of variable speed by fan power as opposed to number of RTUs is indicative of the higher incremental cost of variable speed being more justifiable in larger fans.

Figure 25: Supply fan power normalized by supply airflow rate.



Supply airflow is related to RTU fan energy in that the fan should be properly sized to effectively distribute the required air. Oversizing fans can result in increased energy consumption. Gathering accurate information about supply airflow proved particularly difficult. Similar to fan power, our approach looked at manufacturer specifications, only some of which contained any information about supply airflow. The supply airflow reported on manufacturer specifications does not account for the actual distribution system accompanying the RTU on a given project, and is therefore an approximation. A more accurate approach would be to gather the mechanical design drawings themselves on which the supply airflow is often called out on the RTU schedule. However, getting this information from building facility staff proved too difficult. Figure 25 shows the fan power normalized by supply airflow over a range of different airflows.

The Minnesota energy code maximum[12] requirements are also illustrated for both constant speed (the predominant type) and variable speed fans. For all supply airflows, the fan power is below code-required maximum values, indicating that there is less program potential for increasing fan power efficiency on RTUs.

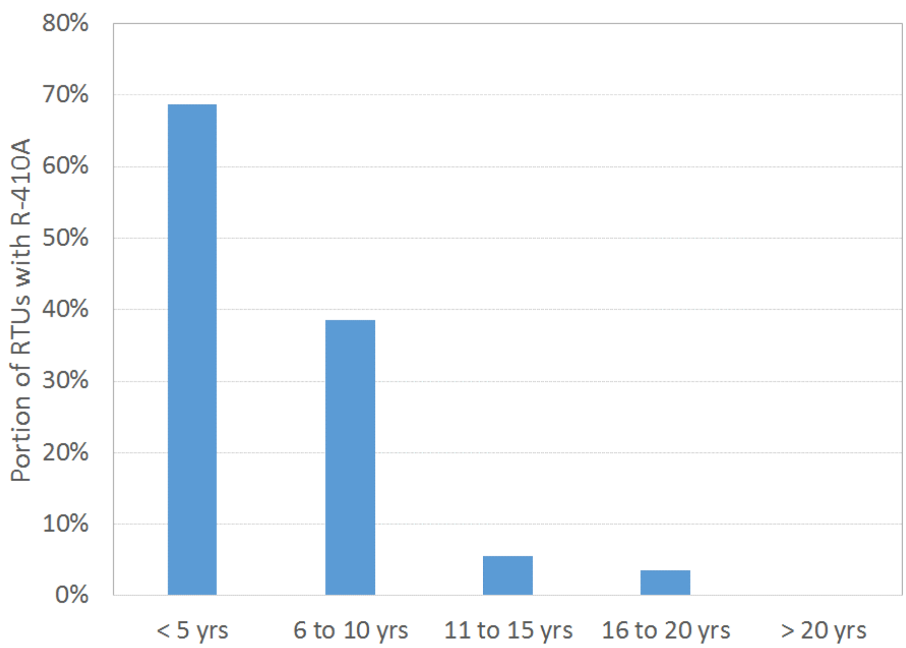
Refrigerant

Another important characteristic of RTUs is the refrigerant they use. Table 15 shows the distribution of refrigerants of existing RTUs throughout Minnesota.

Table 15: Refrigerants of RTUs (n=113,811).

Refrigerant Type	Number of RTUs (thousands)	Percentage	Cooling Capacity (thousands of tons)	Percentage
R-22	89.5	78.6%	654.3	55.3%
R-410A	24.3	21.4%	529.8	44.7%

Figure 26: Portion of RTUs with R-410A refrigerant by RTU age.



[12] ASHRAE 90.1-2010, Table 6.5.3.1.1A

Over three-fourths (79%) of existing RTUs use R-22 as their refrigerant. A smaller proportion (55%) of RTU capacity uses R-22, indicating that larger RTUs are more likely to utilize R-410A. As discussed in more detail in the New versus Replacement Market section, R-22 is being phased out as part of the 1989 Montreal Protocol. In fact, this treaty currently places restrictions on imports and production of R-22 at 10% of the 1989 baseline amount. The reason that R-22 still comprises such a large component of the RTU market is the long lifetime of RTUs relative to the restrictions themselves. However, over time R-410A will increase in proportion to R-22 as the restrictions cause newer RTUs to be predominantly R-410A. Figure 26 illustrates this, showing the percentage of RTUs using R-401A by RTU age.

Note the increasing proportion of RTUs with R-410A. In RTUs less than 5 years of age, over two-thirds (69%) utilize R-410A.

Homogeneity

For those buildings that had more than one RTU per building, nearly two-thirds (62%) of the buildings had RTUs from multiple manufacturers. A significant number of buildings (38%) had RTUs that were all from a single manufacturer. However, none of these buildings had RTUs that were all the same model, typically with varying capacities and corresponding efficiencies.

New versus Replacement Market

We estimate that a total of 6,400 RTUs are shipped to commercial buildings in Minnesota annually. Of these, 40% or 2,600 RTUs are for new construction projects, while 60% or 3,800 are for existing retrofits or replacements. This estimate represents approximately 4.7% of our estimated existing RTUs. Another way to think of this percentage is that if 4.7% of the existing RTUs are replaced each year, then the average life of an RTU is approximately 21 years. This compares very well with the Minnesota TRM's value for RTU estimated useful life of 20 years,[13] providing a higher level of confidence in both estimates. This sanity check gives an estimated average life of RTUs that is longer than our existing RTU estimate of 13.1 years. This is likely due to recent economic conditions resulting in fewer RTUs being replaced over the past few years. Another useful sanity check is to compare the percentage of the existing RTUs that are for new construction with typical rates of new construction square footage increases. Our estimate that 1.9% of shipments were for new construction buildings compares well with the estimates of new construction activity from the EIA.[14]

We estimate that the total sales of RTUs in Minnesota was $88 million annually, which is approximately 0.03% of Minnesota's gross domestic product.

Using the proportions from our manufacturer interviews, we estimate that 3,500 shipments are for code-compliant RTUs, while 2,900 shipments are for high performance RTUs. These levels of shipments represent $41 million and $47 million in sales for code-compliant and high performance RTUs, respectively.

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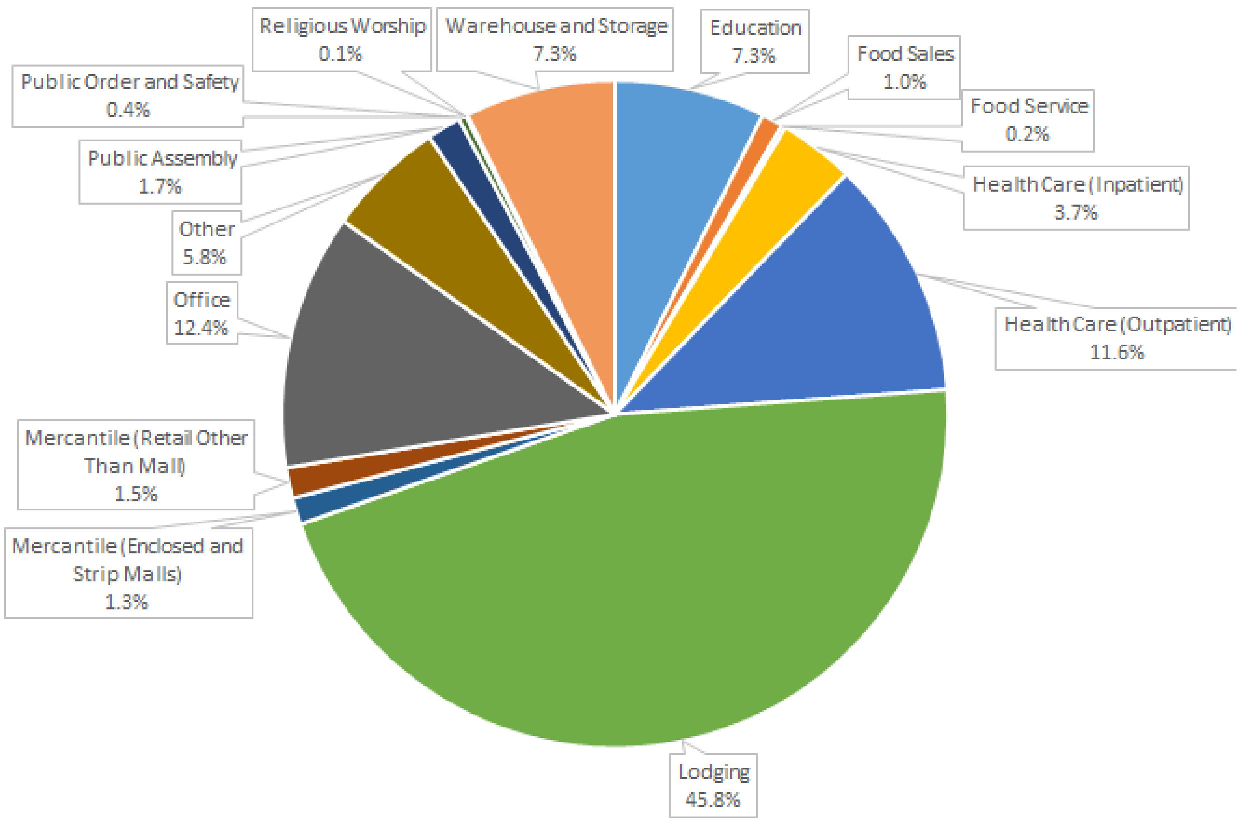
[13] State of Minnesota Technical Reference Manual for Energy Conservation Improvement Programs, Version 1.3, 2016, http://mn.gov/commerce-stat/pdfs/trm-version-1.3.pdf

[14] http://buildingsdatabook.eren.doe.gov/ChapterIntro3.aspx

We also analyzed new construction data to ascertain what types of commercial buildings are being built in Minnesota that are likely to include RTUs. The analyzed dataset was obtained from ConstructionWire,[15] and represented over 90% of the new construction and renovation activity in Minnesota over the past 5 years. We determined the following mix of commercial buildings by square footage that were built or planned to be built in Minnesota from 2013 to 2016 (Figure 27).

Figure 27: Mix of new construction and renovation activity in Minnesota by building type square footage.



There is a clear trend of rapid growth in the lodging sector over the past several years, driven by multifamily, assisted living and hotels/motels. Although RTUs are not typically applied to multifamily buildings, opportunities are certainly available for efficiency programs to increase RTU efficiency on the other lodging building types. Two sectors with strong growth were health care and education, again both not traditionally known for using RTUs. However, RTUs do serve portions of each sector, and such institutions' longer-term mindset suggest they may be more open to improved energy performance even if it means increased capital costs. Office spaces remain a large sector for growth, and with their high use of RTUs, remains a significant opportunity for programs. Warehouses round out the sectors with the most growth. Although a portion of warehouses are not typically conditioned, those warehouse spaces that are conditioned have high use of RTUs.

[15] http://www.constructionwire.com/

From our existing RTU data, we know the mix of refrigerants of the newest RTUs. In RTUs less than 5 years old, the market is 69% R-410A and 31% R-22. Going forward the R-22 portion will only decease as HCFCs like R-22 will be phased out based on the provisions of the 1989 Montreal Protocol.[16] By 2020 restrictions on imports and production of HCFCs will be limited to 0.5% of a 1989 baseline. Currently, these restrictions are at 10% of the 1989 baseline, meaning that limitations will increase another 20 folder over the next 4 years. Although the refrigerant may still be used in existing RTUs, it will become increasingly difficult and expensive to recharge these systems.

Currently, the alternative for HCFCs are HFCs such as R-410A. However, these refrigerants are also being phased out, albeit on a less aggressive schedule according to the 2015 amendment to the Montreal Protocol.[17] Under this amendment, the phase out will occur in incremental steps, culminating in a goal of 10% of baseline by 2036.

The alternatives to HFCs are currently Hydro-fluoroolefins (HFOs), which are similar to HFCs but have significantly shorter atmospheric lifetimes (HFOs only take days to degrade when exposed to atmospheric conditions as opposed to decades for HFCs). This significantly decreases HFOs Global Warming Potential as compared to HFCs.

One drawback of HFOs is their mild flammability. They are now classified under a new ASHRAE flammability designation 2L or mildly flammable with low burning velocity. Although their risk of flammability is relatively low, there still exists additional safety requirements for working with them as opposed to existing refrigerants.

An additional drawback is that replacement refrigerants currently result in system efficiencies that in most cases are worse (in some cases equivalent, but rarely better) than if the system had used current refrigerants. Ongoing research is underway to improve alternatives in terms of their resulting system efficiency.[18,19]

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[16] Data available at United Nations Environment Programme website.
(*http://www.unep.org/ozonaction/ecanetwork/Portals/138/SER%20Montreal%20Protocol%20&%20HCFC%20phase-out.pdf*)

[17] Data available at EPA's website. (*https://www.epa.gov/sites/production/files/2016-01/documents/hfc_amendment_2015_summary.pdf*)

[18] Data available at AHRI's website. (http://www.ahrinet.org/site/514/Resources/Research/AHRI-Low-GWP-Alternative-Refrigerants-Evaluation)

[19] Skye, H., NIST Technical Note 1895, "Heat Pump Test Apparatus for the Evaluation of Low Global Warming Potential Refrigerants", November 2015.

CIP Recommendations

Opportunities

Manufacturers are offering new products and features that continually increase the available efficiency options for new RTUs. The main trend for increasing RTU energy performance is in increasing its part load efficiency through the use of variable speed and variable capacity components and associated controls. These systems have the added benefit of increased humidity control, thereby increasing occupant comfort as well as energy performance. Also, variable air volume capabilities, as opposed to the current standard constant volume systems, are becoming available on increasingly smaller capacities.

Other efficiency options now available include:

- Demand control ventilation: reducing ventilation during unoccupied periods by using carbon dioxide or occupancy sensors thereby saving fan energy, as well as the energy needed to heat or cool the outside air.
- Improved economizers: ensuring that the outdoor air dampers do not let in unconditioned air when closed. Also ensuring that the economizer is working properly through advanced fault detection.
- Casing insulation: properly insulating the RTU casing reduces heating and cooling loads to the building in a manner similar to roof insulation.
- Efficient supply fan: increased supply fan efficiency through improved blade design. Also direct drive motors reduce frictional losses as compared to belt driven fans, increasing overall fan system efficiency.
- Condensing gas-fired heat exchanger: capturing the latent heat in the combustion exhaust increases the heating efficiency of gas-fired RTUs to 90-95%.
- Energy recovery ventilation: utilizing a sensible or latent heat exchanger to recover energy from the exhaust air stream to preheat incoming ventilation air.
- Evaporative cooling retrofit packages: adding evaporative cooling kits to existing RTUs to increase cooling efficiency by allowing condensing temperatures to approach outside air wetbulb temperature as opposed to drybulb temperature.

Increasingly, sophisticated, intelligent controls are also being applied to RTUs. These controls are capable of precisely controlling RTU operation to optimize energy performance, as well as detect faults and alert maintenance staff to address degraded performance quickly.

Barriers

The most significant barrier to increased penetration of high performance RTUs is incremental cost. Building owners pursuing an RTU HVAC system are generally less interested in life cycle cost and more interested in capital cost. They therefore are less likely to view the investment in more efficient equipment as worthwhile.

For existing RTUs, there are two kinds of replacements; emergency and planned. Emergency replacements occur when an RTU fails unexpectedly, causing an immediate need for replacement to satisfy building occupant comfort requirements. For emergency replacements, tight timelines and restrictive budgets typically necessitate the standard efficiency option. Planned replacements are scheduled based on RTU life and facility budgeting cycles. Although there is more opportunity for improved efficiency under this scenario, tight budgets and restrictive specifications still limit its potential.

An additional barrier to increased penetration of higher efficiency RTUs is physical size. Higher efficiencies are often achieved through increased heat exchanger size. This often increases the overall size of the unit as well. For replacement RTUs, this can be a barrier as replacement RTUs may need to fit on the same curb or meet building code-imposed height constraints.

Finally, stakeholder's lack of knowledge regarding RTU's dynamic, evolving capabilities is a major barrier to increased penetration of high efficiency RTUs.

Recommendations

Due to the large HVAC market penetration of RTUs, increasing their efficiency has been a target of energy efficiency programs for many years. As RTU manufacturers develop increasingly complex efficiency capabilities, developing programs to reflect them is important.

Currently, the 2016 Minnesota TRM contains two RTU-related measures; cooling efficiency and economizer measures. Both of these measures focus on electric consumption savings. A review of Minnesota programs found prescriptive rebates available for RTU cooling efficiency, demand control ventilation, and energy recovery ventilation. Expanding the TRM to include a wider scope of RTU-related measures will aid in the development of more comprehensive RTU programs. A few examples of RTU programs outside of Minnesota, including several that address RTU controls, are shown in Table 16.

Table 16: Examples of RTU programs outside of Minnesota

Program	Unit Type	Incentive	Project requirements
Focus on Energy Rooftop Unit Optimization (Wisconsin)	Economizer DCV Programmable thermostat Advanced programmable thermostat	$200 $350 $30 $80	Incentives for optimizing RTUs. DCV incentive available for single zone RTUs only.
ComEd Rooftop Unit Optimization (Illinois)		$100/ton	Advanced control systems installed on existing packaged rooftop units from 7.5 to 25 tons serving constant volume HVAC systems.

Program	Unit Type	Incentive	Project requirements
Puget Sound Energy Rooftop Unit Premium Service (Washington)		$360 to $1,925 per unit serviced	Customer must use an approved contractor and the incentive is determined by facility type, size/tonnage of the unit and the types of diagnostic and/or system improvements and sensors that the service enables.
PGE Advanced Rooftop HVAC Controls (California)		$20 - $194/ton	Retrofit an existing RTU with one of several advanced control options.
Save On Energy (Ontario)		Varies based on size	Replace RTU with high efficiency unit

The capital cost barrier is addressed programmatically through rebates to defer a portion of the incremental cost of higher efficiency units. Historically, these rebates have been based on exceeding a minimum full load efficiency. Since the trend in efficiency for RTUs is increasing part load efficiency, developing rebates based on IEER would be beneficial. For instance, a more expensive, higher performing RTU would receive similar rebates as a standard RTU if its full load efficiency is similar, even if its part load efficiency is substantially better. Since cooling loads are frequently well below the peak, an RTU capable of variable capacity would spend considerable time operating at part load. The actual energy performance of the variable speed unit would be much better than the standard unit. For utility programs whose priority is annual energy savings, providing incentives for part load efficiency is a better approach. For utility programs whose priority is peak demand reduction, providing incentives for full load efficiency makes more sense.

Building owners and design teams have limited time and resources to spend on understanding and interfacing with utility efficiency programs. Therefore, clear and simple program requirements will increase program participation. Additional insights we gathered from our interviews with stakeholders include:

- Recast rebates in units that are more understandable. Prescriptive rebates have traditionally been based on RTU cooling capacity (i.e. $75 per ton). This aligns well with the energy savings, which scale with cooling capacity. However, it is not a metric that most building owners understand. Potentially recasting rebates based on square foot would make the rebates more understandable from a program participant perspective. It can also be more readily incorporated into project budgeting as it sends a consistent, upfront signal. Note that the rebates may need to be specific to various building types and there relative cooling needs. However, the Minnesota TRM already has this type of information in its Equivalent Full Load cooling hours tables.
- Reduce transactional costs of participating in programs, less time via less paperwork and more online, simple interactions.
- Stabilize incentives as it is confusing to program participants and trade allies when incentives run out or change.

- Educate trade allies such as manufacturers and distributors about the programs so that they can more easily embed program information into their process. They can be further supported with simple tools and calculators for calculating available rebates, as well as energy and utility cost savings.
- Require some level of commissioning since expected RTU performance is often not achieved without proper commissioning. Requiring some level of commissioning, such as its inclusion in contractor report, will help ensure energy savings.
- Ensure proper RTU installation to achieve expected levels of performance. The Air Conditioning Contractors of America have developed guidance for proper installation.[20] This standard also includes recommendations for owner training, which is important for ensuring persistence in high levels of energy performance and savings.

[20] ACCA Standard 5, 2010, Air Conditioning Contractors of America

Next Steps

As the characterization component of this project was finalizing, the monitoring component of the project has been progressing. Monitoring equipment has been installed at 9 sites capable of monitoring electricity (fan and compressor) and natural gas energy consumption of 52 RTUs. The monitoring period will include winter 2015-2016 through the fall of 2016 to encompass heating, cooling and shoulder seasons as well as changes in operating conditions for each building. The data itself will be analyzed to draw conclusions regarding characteristics that lead to high and low RTU performance as well as typical consumption patterns for different building types. From this work, we will develop insights into how RTUs are used in a small sample of building types and into best approaches to improve RTU efficiency.

Once the monitoring and analysis are complete, we will develop a final report that summarizes the results of the entire project including both the characterization (summarized in this interim report) and monitoring components. This final report will be completed by February of 2017. A live, free video webinar that clearly describes the project findings to stakeholders will coincide with the release of the final report.

Appendix A: Sampling and Weighting

The sample of buildings for the characterization study is based on a two-stage sample design that involved first selecting a random sample of ZIP codes in the state of Minnesota, then identifying and sampling commercial buildings with RTUs within each sampled ZIP code. Sampling at each stage was done with probability proportional to size (PPS), so that, in theory, any given RTU in the state has an equal probability of inclusion in the study. In practice, survey non-response and other factors created deviations from this goal. The details of sample selection and weighting are described in more detail in this appendix.

ZIP code sampling

The first step in the process was to draw a sample of ZIP Codes within the state to create an initial sample frame for which commercial buildings with RTUs could be enumerated for further subsampling. The basis for the ZIP Code sampling was the Census Bureau's 2012 ZIP Code Business Patterns (ZBP) database, which provides a count of commercial establishments by ZIP code.[21] The sample frame was limited to the 337 (of 936 total) ZIP codes with at least 75 establishments, which comprise 91 percent of total 145,420 commercial establishments in the database. We also removed four ZIP codes in downtown Minneapolis that largely comprise high-rise office towers with a large number of businesses but for which an initial imagery review suggested very few RTUs. The final sample frame for ZIP Code selection thus included 333 ZIP Codes across the state comprising 88 percent of the state's population of commercial establishments, per the ZBP database.

We then drew a PPS random sample of 50 ZIP codes (with replacement), with selection probability equal to ZBP number of commercial establishments in the ZIP code. This sample of ZIP codes formed the basis for further subsampling for the study. As described below, only 40 of the 50 originally-sampled ZIP codes were ultimately needed to complete the characterization survey, though the original sample of 50 is used to estimate the statewide total number of buildings with RTUs and total RTUs.

Initial Enumeration and Sampling of Buildings with RTUs

The next step in the process was to enumerate all buildings with RTUs in each of the 50 sampled ZIP codes. This was done visually using public aerial imagery (Google Earth and Bing) to find what appeared to be commercial rooftops with RTUs present. The land area for each ZIP code was systematically searched, and each commercial rooftop with one or more RTUs was place-marked, given an identification code, and the apparent number of RTUs on the rooftop was recorded. As described later, subsequent adjustments account for the fact that not every rooftop object identified at this stage was in fact an RTU.

[21] Data available at United States' Census Bureau website. (http://www.census.gov/econ/cbp/)

The enumeration process identified a total of 4,508 buildings across the 50 ZIP codes, with an initial count of 28,946 RTUs. An average of 90 buildings with RTUs were identified per ZIP code, but this ranged from as few as 2 in rural ZIP codes to more than 300 in urban ZIP codes. The number of preliminarily-identified RTUs per building at this stage averaged 6.4, with a range from 1 to 189.

From this enumeration list, a PPS sample (without replacement) of buildings was selected within each ZIP code. The measure of size for the PPS sampling was the number of RTUs recorded for the building from the imagery review.[22] The sampled number of buildings within a given ZIP code was the lesser of: (a) the total number of RTU buildings identified from the imagery review (i.e. a census of all RTU buildings in the ZIP code); or (b) 30 times the number of times the ZIP code was sampled in the first stage of sampling. In this manner, a total of 1,842 buildings with RTUs were sampled for the study. Of these, about a third came from ZIP codes where all buildings with RTUs were selected for the study, and 70 percent came from ZIP codes were a sample of RTU buildings was drawn. This collection of buildings comprised the starting sample for the telephone characterization survey of buildings.

Execution of the Telephone Survey

To execute the telephone survey, the list of sampled buildings was randomized, first by ZIP code, and then by building within ZIP code. Telephone interviewers worked through the list sequentially, attempting to complete two interviews per sampled ZIP code. An interviewer would attempt 3 calls to a building. If they were unable to connect with the building staff in this number of calls, that building was considered unreachable and the interviewer would move on to the next set of buildings. If two completions could not be obtained in a given ZIP code, the remainder of the sample quota was pushed to the next ZIP code.

A total of 101 survey completions were ultimately obtained in this manner, resulting in a response rate of approximately 6%. However, respondents for five interviewed buildings provided information that allowed us to determine that these buildings did not in fact have any RTUs. These buildings were dropped from the analysis (except for the purpose of determining the ratio of actual RTUs to imagery-determined RTUs, which we used for estimating the total number of RTUs in the state). In addition, nine respondents did not provide sufficient information to determine if they actually had any RTUs: these buildings were dropped from the study entirely.

This left a total of 87 respondents, of which 81 provided information about the building and at least some of the RTUs on the building, and six were able to provide information only about the building, and were not able to provide details about their RTUs.

[22]For technical reasons, the PPS sampling at this stage, which we implemented using the gsample add-in for Stata, Version 13.1, would not work if the range of RTU counts per building in a ZIP code was large. In these cases we compressed the range of weights to the point where sampling could proceed.

Case Weights

For analysis, case weights were developed and applied to account for the sample design, and to reflect the best estimate of the population from which the sample was drawn. Two sets of case weights are used in this report: one at the building level, to represent the total number of buildings in the statewide population of buildings with RTUs; and the other to represent the total number of RTUs statewide represented by a given RTU for which information was gathered in the telephone survey.

The building weights are a combination of the inverse of the probability of selection of the ZIP code at the first stage of sampling and of selecting an individual building within a ZIP code at the second stage. For survey respondent *j* in ZIP code *i*, the case weight is calculated as:

$$Building\ weight_i = \left[\left(\frac{\sum_{i=1}^{N_{zip}} E_i}{E_i}\right) * \left(\frac{1}{40}\right)\right] * \left[\left(\frac{\sum_{j=1}^{N_{bldgs_i}} RTUs_j}{RTUs_j}\right) * \left(\frac{1}{87}\right)\right]$$

where:

E_i is the Census number of commercial establishments in ZIP code *i*

N_{zip} is the total number of ZIP codes in the Census database

40 is the number of ZIP codes represented in the final survey dataset

$RTUs_j$ is the number of RTUs initially identified for the *j*th survey respondent

N_{bldgsi} is the total number of commercial buildings with RTUs identified in ZIP code *i*

87 is the total number of survey respondents with RTUs in the study

PPS sampling in complex survey designs sometimes leads to large differentials in weights, which can be problematic in later analysis. To avoid these problems, we applied a weight trimming procedure to limit the range of weights in the survey sample. The procedure substituted the weight of the next lowest case for cases where the initial weight exceeded five times the median weight, which affected 3 cases. A similar trim for weights that were less than one-fifth of the median weight affected one case.

We then scaled all of the building weights to reflect our best estimate of the total number of commercial buildings with RTUs in the state. This estimate is derived from a weighted estimate of the ratio of imagery-determined buildings with RTUs to Census commercial establishments at the first-stage sample of 50 ZIP codes (adjusted to account for the fact that five of 87 buildings that were surveyed were determined not to have any RTUs). When applied to the ZBP-database count of 145,420 commercial establishments, the estimate works out to 20,700 statewide buildings with RTUs, with a 95 percent confidence interval of ± 3,100 buildings. Final building-level weights were scaled to this value: the weights had a mean of about 238 and a range from 42 to 797.

Information about individual RTUs was sometimes provided by survey respondents for all units associated with the building, but was sometimes provided for only some units—and, as noted above, six respondents provided no information about their RTUs. For analyzing and reporting characteristics about RTUs, an RTU-level weight was developed. For all RTUs with reported information in Building i, the RTU weight is calculated as:

$$RTU\ weight = Building\ weight_i \left(\frac{Total\ RTUs_i}{Reported\ RTUs_i}\right)$$

These weights were scaled to account for the six survey respondents that did not report any RTU information, and were trimmed to be within a factor of five of the median weight. , We also scaled the weights to our best estimate of the total number of RTUs in the state. For the this, we used the weighted survey dataset to get a ratio estimate of actual RTUs to imagery-based counts of RTUs from the final survey sample, and then applied this ratio to an extrapolated statewide estimate of total imagery-based RTU counts from the n=50 ZIP code sample.[23] The analysis indicated a total of 136,000 ± 30,000 RTUs in the state. RTU-level weights were scaled to match this total.

[23] For the survey-based ratio estimate, we omitted 11 cases where the survey respondent did not speak for the entire building: these were mostly strip malls, for which the interview was conducted with the proprietor for only one of multiple businesses.

Appendix B: Building Staff Interview

Building Information

1. What is your building's age? (approximate OK) _____ years

2. What is your building's total area? (approximate OK) _____ square feet

3. What is your building's owner type?

- ☐ Owner Occupied
- ☐ Leased
- ☐ Public
- ☐ Other: ____________________

4. If your building has multiple tenants/businesses, how many? ____ tenants

5. What kind of commercial activity is conducted in your building? (to clarify: the most applicable for the largest square footage) (open-ended)

5a: Category ** (to be filled out by interviewer following the interview):

- ☐ Education
- ☐ Food Sales
- ☐ Food Service
- ☐ Health Care (Inpatient)
- ☐ Health Care (Outpatient)
- ☐ Lodging
- ☐ Mercantile (Retail Other Than Mall)
- ☐ Mercantile (Enclosed and Strip Malls)
- ☐ Office
- ☐ Public Assembly
- ☐ Public Order and Safety
- ☐ Religious Worship
- ☐ Service
- ☐ Warehouse and Storage
- ☐ Other
- ☐ Vacant

6. What hours of the day is the building open? Or what hours are there people in your building (i.e., during what times do HVAC systems need to keep the building comfortable?)?

Weekday:	Begin Time _____	End Time _____
Saturday:	Begin Time _____	End Time _____
Sunday:	Begin Time _____	End Time _____

7. On a typical day, approximately how many people are in your building when it is most full?

8. Are you aware of any noise complaints specific to your building's RTUs?

- ☐ Yes, Description:____
- ☐ No

9. Are you aware of any comfort complaints from occupants of this building?

- ☐ Yes, Description:____
- ☐ No

10. Are there other HVAC systems serving large portions of this building?

- ☐ Yes
- ☐ Description:____

Rooftop Unit Information

13. How many RTUs are on your building?

13a. About how old are they? Are they all about the same age?

13b. Do any of the RTUs serve multiple zones? (i.e., are there any spaces served by a rooftop unit that do not have a thermostat controlling that unit?)

14. Who maintains the Rooftop Units?

- ☐ Owner
- ☐ Contracted vendor
- ☐ We call vendor when there is an issue
- ☐ Other: _______________

15. Which of the following maintenance procedures do you do (or have someone else do) on the RTUs?

- ☐ Winter Startup
- ☐ Summer Startup
- ☐ Additional filter replacement Frequency:____________ months
- ☐ Clean Compressors Frequency:____________ months
- ☐ Other: ____________ Frequency:____________ months

16. We are done with the high level questions and my next questions focus on details specific to the building's RTUs. This information is summarized in a few different places, like the Rooftop Unit Schedule in the building's mechanical drawings or on the units themselves. Were you able to get any of these documents to have on hand for this interview? [*if contact doesn't know about the RTU schedule, then suggest:]* The make and model number would be useful too. If it would be easier for you, you could fax the RTU schedule or make/model to us.

Appendix C: Literature Review

The following annotated bibliography represents a sample of the literature we reviewed in the course of this project and provides additional information related to RTUs.

AE 2012. Commercial Rooftop Unit Optimization Product Literature Review: Retrofit Devices for Single-Zone Rooftop Units. Advanced Energy. 2012.

A review of manufacturing marketing literature for three RTU retrofit devices.

ACHR 2015. *Predicting the Future of RTUs*. The Air Conditioning Heating Refrigeration News, June 15, 2015.

RTU manufacturers discuss changes and improvements to increase system efficiency. These improvements include enhanced IAQ (dehumidification and ventilation control), enhanced controls, improved energy efficiency and recovery, as well as increased connectivity. They're also making systems easier to install and maintain. Finally, there is an increasing focus on part load efficiency, i.e. compressor staging, variable-speed compressors.

ACHR 2016. *DOE Sets 'Groundbreaking' Rooftop Unit Standards*. The Air Conditioning Heating Refrigeration News, January 18, 2016.

DOE released a new set of standards requiring approximately a 10 percent increase in RTU minimum efficiency by January 2018 and between 25-30 percent increases by January 2023. These upgrades will save an owner of a typical commercial building between $4,200 and $10,100 over the lifetime of the RTU.

CARD 2014. Advanced Rooftop Unit HVAC Controls Pilot. Center for Energy and Environment and PECI. 2014.

Results of a study evaluating three advance control optimizers and their potential to save energy in a non-cooling dominated climate.

CEE 2016. High Efficiency Commercial Air-conditioning and Heat Pumps Initiative. Consortium for Energy Efficiency. 2016.

A summary of CEE's initiative to increase the availability of high efficiency commercial unitary air conditioners and heat pumps, and to encourage efficient upgrades to these systems across the North American market.

Cherniack 2013. Rooftop Units Fault Detection and Diagnostics. California Energy Commission.

A summary of the results of a project conducted for the California Energy Commission's evidence-based design and operation research program. The project goals were to develop software for evaluating diagnostic protocols that identify and measure operating faults in RTUs, assess the market availability, usability and cost of Fault Detection and Diagnosis (FDD) products and propose a minimum standard for FDD functionality.

DOE 2016. 2016-01-15 Energy Conservation Program for Certain Industrial Equipment: Energy Conservation Standards for Small, Large, and Very Large Air-Cooled Commercial Package Air

Conditioning and Heating Equipment and Commercial Warm Air Furnaces; Direct final rule. Federal Register, 81:10, January 15, 2016.

Published amended minimum efficiency standards for RTUs.

Faramarzi 2004. Performance Evaluation of Rooftop Air Conditioning Units at High Ambient Temperatures. 2004 ACEEE Summer Study on Energy Efficiency in Buildings, 3-52.

Laboratory testing was used to quantify the impact of high ambient temperatures on the electric demand and cooling efficiency of five-ton RTUs.

Heinemeier 2014. Free Cooling: At What Cost? 2014 ACEEE Summer Study on Energy Efficiency in Buildings, 3-121.

Survey of California contractors found that 30-40 percent of the time, the economizer is disabled and the outside air dampers are closed, thereby eliminating associated cooling energy savings.

NICOR 2013. 1001: High Efficiency Heating Rooftop Units (RTUs) Public Project Report. Nicor Gas Energy Efficiency Emerging Technology Program.

Results of a pilot test of a higher efficiency, condensing RTU in a big box retail store in the Chicago area.

PECI 2011. Unitary HVAC Premium Ventilation Upgrade. ASHRAE Winter Conference Technical Program. Las Vegas, NV. 2011.

Field surveys of RTUs have found that, while the units are maintaining building comfort, most of them have performance issues that result in poor ventilation and inefficient energy use. These performance problems include outside air economizers that don't work effectively, incorrect refrigerant charge, and fans either running when not needed or not running when needed.

PECI 2012. Advanced Unitary HVAC Control Sequence. ASHRAE Transactions, Vol. 118, Issue 1. 2012.

Details on a field-tested advanced sequence of operation using three different BACnet controllers to improve ventilation and energy savings for RTUs.

PNNL 2011. Energy Savings and Economics of Advanced Control Strategies for Packaged Air-Conditioning Units with Gas Heat (PNNL-20955). Pacific Northwest National Laboratory. 2011.

An evaluation of strategies that can be implemented in a controller to retrofit an existing RTU and improve its operational efficiency.

PNNL 2013a. Part-load Performance Characterization and Energy Savings Potential of the RTU Challenge Unit: Daikin Rebel (PNNL-22720). Pacific Northwest National Laboratory. 2013.

Documents the development of part-load performance curves to use with EnergyPlus to estimate the potential savings from Daikin Rebel units (the first RTU to meet DOE's RTU Challenge specification) compared to standard RTUs.

PNNL 2013b. Advanced Rooftop Control (ARC) Retrofit: Field-Test Results (PNNL-22656). Pacific Northwest National Laboratory. 2013.

A multi-year research project to determine the magnitude of energy savings from retrofitting RTUs with advanced control strategies not ordinarily applied to RTUs.

PNNL 2014. RTU Comparison Calculator Enhancement Plan (PNNL-23239). Pacific Northwest National Laboratory. 2014.

Documents the enhancements needed to the RTU comparison calculator to support estimating savings from products meeting the RTU Challenge (an IEER of 18) or using advanced controls on existing RTUs.

Purdue 2014. Workshop on FDD for RTUs – Moving from R&D to Commercialization. Purdue University. 2014.

Workshop on the status of FDD products for RTUs and strategies for accelerating commercialization of these tools.

SDGE 2013. Multi-vendor RTU Retrofit Controller Field Study Final Report. San Diego Gas and Electric Company Emerging Technologies Program. 2013.

Results of testing four different retrofit RTU controllers on 7.5 ton heat pumps on a building in San Diego.