PROJECT REPORT

HVAC EQUIPMENT DEMOGRAPHICS AND CAPACITY ANALYSIS TOOLS APPLICABLE TO MULTI-TENANT LIGHT COMMERCIAL BUILDINGS

Western Cooling Efficiency Center-UC Davis

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ABOUT THE WESTERN COOLING EFFICIENCY CENTER

The Western Cooling Efficiency Center was established along side the UC Davis Energy Efficiency Center in 2007 through a grant from the California Clean Energy Fund and in partnership with California Energy Commission Public Interest Energy Research Program. The Center partners with industry stakeholders to advance cooling-technology innovation by applying technologies and programs that reduce energy, water consumption and peak electricity demand associated with cooling in the Western United States.

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1. EXECUTIVE SUMMARY

The UC Davis Multi-Tenant Light Commercial project intends to establish a building level retrofit package that will substantially improve energy performance by collectively improving the envelope, lighting and HVAC systems. The primary goals of the UC Davis Multi-Tenant Light Commercial project are to increase the overall energy efficiency and permanently reduce the peak energy consumption of MTLC buildings. Simultaneously, the Multi-Tenant Light Commercial project aims to make these packages more economically feasible by leveraging the economy of scale through maximizing purchase potential, and by minimizing the cost through reducing the required contractor visits necessary to perform the work.

One of the key preliminary proposals of this project was to permanently reduce the connected capacity, with respect to the HVAC system, by disconnecting compressors within RTUs that contain multiple compressors. We reviewed existing literature and collected primary data by conducting field surveys in order to establish how multiple compressor RTUs are typically administered and to characterize the HVAC systems typically encountered in MTLC buildings.

Packaged cooling equipment serves nearly 70% of the light commercial building floor space in CA, making packaged HVAC systems (or RTUs) ubiquitous in Multi-Tenant Light Commercial buildings. The total cooling-related energy consumption associated with all the packaged Roof-Top Units in California is approximately 22.6 billion kWh per year[1] and growing. Therefore, even a small improvement in the efficiency of these systems will lead to significant reductions in energy use and peak energy consumption, particularly in Multi-Tenant Light Commercial buildings.

We collected primary data on 102 package units serving several MTLC buildings in northern California. The RTUs with a capacity of 5 tons or smaller account for 71% of this sample, and RTUs with a capacity of 10 tons or smaller account for 95% of the sample. Similarly, RTUs with a capacity of 5 tons or smaller account for 54% of the total surveyed capacity, and RTUs with a capacity of 10 tons or smaller account for 85% of the total surveyed capacity. This data correlates well with several other studies conducted in the western United States that were not focused specifically on MTLC, but rather a more general commercial market.

The primary field data we collected also found that the average age of the 102 RTUs surveyed was 10.2 years. Even though there are requirements for minimum HVAC equipment efficiency, these pieces of equipment were specified under less restrictive standards and have undoubtedly become less efficient with age. Furthermore, based on the estimated expected life of a typical RTU, it is unlikely that these units will be replaced in the next 5 years. Further complicating the concept that the HVAC equipment will be larger than necessary after the proposed efficiency measures are implemented is the fact that the equipment is over-sized to begin with. Aside from the obvious permanent peak reduction benefits of downsizing, reducing oversized units may also increase their efficiency as well as contribute to improved comfort. Unfortunately, a commercially available tool for assessing the extent to which the capacity of a unit may be reduced in this context has not been found. Fortunately, a methodology exists for such an assessment; however, it is limited to specific conditions that are relatively infrequent. Therefore, improving the applicability of the existing methods by expanding the scope of useful conditions is necessary.

Based on the primary data we collected, and the data available in existing literature, the majority of the RTUs serving MTLC spaces are relatively small in capacity and thus do not contain multiple compressors. In addition it does not appear that replacement is a viable option because these units have significant useful life remaining. Consequently, if the goal of permanent peak reduction is to be achieved, a new approach for assessing the extent of oversizing and subsequently downsizing existing HVAC systems must be developed. One such approach may be to reduce the size of specific components of the RTU, such as compressors and evaporator fans, but this concept must be investigated and developed further.

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[1] *Based on CEUS 2006 data, assuming an EER of 10 and a 20% cooling load factor*

2. OVERVIEW

Roof Top Units (RTUs) serve 70% of commercial floor area in CA, making them one of the most commonly encountered HVAC systems in Multi-Tenant Light Commercial (MTLC) buildings. Existing literature and field research (Section 3) reveal that these packaged systems are ubiquitous because they offer several practical advantages: low initial cost, integration of heating and cooling in a single unit, reliability, availability of trained installers and service technicians, a well established distribution network, etc. Unfortunately, however, improving the energy efficiency of RTUs has not been heavily pursued because improvements to efficiency typically oppose the advantages listed above (i.e. higher initial cost, increased complexity, increased maintenance etc.).

Constant volume RTUs comprise the vast majority of the RTUs in MTLC buildings, and commercial space in general, and are particularly inefficient when over-sized because they are subjected to part-load conditions during the vast majority of their operating time (Section 5.2). Indeed, when the cooling capacity of the RTU is much higher than the actual thermal load required to maintain an acceptable interior temperature, these constant volume RTUs satisfy the thermal load by repeatedly cycling on and off[2]. During each cycle the unit wastes energy during the start-up period when the compressor and the heat exchangers are not operating under steady state conditions. Further energy is wasted by not extracting the full extent of the energy stored in the refrigerant upon shut down.

An over sized cooling system has the added deficiency of poor humidity control that may result in undesired indoor conditions. Quick temperature and humidity swings reduce occupant comfort and can potentially contribute to health problems such as asthma and mold. An example of poor humidity control is experienced during off cycles when the ventilation air is pushed into the building and the condensation on the evaporator coil tends to re-evaporate. Conversely, unnecessary dehumidification can be experienced when the temperature difference between supply and return is relatively small and the RTU is moving a large portion of the available air within the building (i.e. more than necessary) across the evaporator coil.

There are also several economic penalties to larger than necessary HVAC equipment. One of the most often cited downfalls of over-sized RTUs, aside from the energy penalty associated with operating relatively inefficient equipment, is that the frequent cycling increases wear and tear on the RTU components, thereby reducing the lifetime of the equipment. Larger capacity equipment also has a higher initial cost and also has increased residual costs associated with corresponding increase in duct size and electrical service.

Lastly, when larger capacity RTUs are installed in a wide area, the aggregate demand can have a significant impact on utility peak. A list of disadvantages associated with over-sizing, according to ACCA, is presented in Table 1.

Oversizing Impacts

Table 1: Over-sizing impacts according to ACCA (Glenn Hourahan, 2003)

Comfort	Equipment	Economic	Health
Marginal part load temperature control	Larger ducts installed	Higher installed costs	Potential to contribute to mold growth
Larger temperature differences between rooms	Increased electrical circuit sizing	Increased operating expenses	Potential to contribute to asthma and other respiratory conditions
Degraded humidity control	Excessive part-load operation, frequent cycling, shorter equipment life	Increased installed load on the public utility system	
Drafts and noise	Nuisance service calls		
Occupant discomfort/dissatisfaction			

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[2] On-off cycling is the most common control strategy to manage part-load. Other control strategies will be explored in section 5.2.1

3. MTLC RTU DEMOGRAPHICS

In order to better understand the demographics of RTUs installed on MTLC buildings in California, existing literature was reviewed and primary data was collected to characterize HVAC equipment found in MTLC buildings. HVAC literature (Felts & Bailey, 2000; Glenn Hourahan, 2003; Mowris & Jones, 2008; Proctor, Katsnelson, & Wilson, 1995; Woodcock, 1998) shows that RTUs are routinely over-sized.

Literature Review

Describing the demographics of heating and cooling systems (HVAC) used in Multi-Tenant Light Commercial (MTLC) buildings in California is a difficult task. Energy surveys such as the Commercial Building Energy Consumption Survey (CBECS) and the California Commercial End-Use Survey (CEUS) do not provide reliable detailed data on HVAC systems. On the other hand, HVAC field research often relies on very small sample size (250 or fewer RTUs) and does not necessarily focus on MTLC buildings in California. Therefore these studies might not be representative of the building segment we are interested in. Moreover, the HVAC industry does not disclose details such as the type of unit shipped, destination of unit, and does not keep track of units once they are installed (NEEA & Energy and Environmental Analysis, 2005).

AHRI lists the studies with useful information about RTUs demographics that we considered. Detailed information from these reports is included in the results section. Overall available data is sparse and hard to compare. Two reports had field data from California, but they were written more than 10 years ago (Felts & Bailey, 2000; New Buildings Institute, 2003), while four other reports described data from the Pacific North West where some Utilities have active RTU programs and research projects. However, useful information can be identified using the partial data available. This data was supplemented by primary research that WCEC conducted during summer and fall 2012, summarized in the next section.

Table 2: Studies about RTU demographics surveyed

Study/Source	Location	Year	# RTU	# Buildings	Reference
WCEC	Davis, CA	2012	112	8	Primary Research
CBECS	US	2003	N/A	N/A	(Energy Information Administration (EIA), 2003)
CEUS	CA	2006	N/A	N/A	(California Energy Commission (CEC), 2006)
CEC	CA	2001-02	215	75	(CEC, 2003)
PGE RTU/PAT	North CA	1998	250	-	(Felts & Bailey, 2000)
EWEB	OR	2001	30	19	(NEEA 2002)
NEEA	ID, MT, OR, WA	2002	140	72	(NEEA 2002)
PSE	WA	2003-04	118	15	(NEEA 2002)
UC Davis	Davis, CA	2010	84	25	(UC Davis & Cooper, 2010)
WCEC/DEG	CA	2012	115	98	(Western Cooling Efficiency Center & Davis Energy Group, 2012)

Primary data collection

During summer and fall 2012 WCEC visited several MTLC sites and gathered RTU data to supplement and confirm secondary data sources.

A total of 102 RTUs covering several buildings in Davis, California were surveyed during this period and the summary of the information gathered is presented in Table 3.

WCEC monitored some of these units for a longer period, and also downloaded and analyzed the smart meter data corresponding to the buildings they serve. A detailed analysis of this data will be included in a following report. The demographic information of HVAC systems from primary and secondary sources is compiled below. Additional information from upcoming visits to MTLC buildings throughout California are planned for 2013 and will be added to this database.

Results

HVAC SYSTEM TYPES IN MTLC BUILDINGS

The Commercial Buildings Energy Consumption Survey (CBECS) reveals that 46% of all floor area in the US is cooled with unitary packaged Air Conditioners (Energy Information Administration (EIA), 2003). Another source, the Non-Residential New Construction (NRNC) Baseline Study in California, estimates in more than 47% the floor space area cooled by DX Single Package AC/Heat Pumps (New Buildings Institute, 2003; RLW Analytics, 1999). The latest CEUS official report (California Energy Commission (CEC), 2006) does not breakdown data by type of HVAC systems. However an earlier version of CEUS for PG&E territory illustrates packaged (unitary and split systems) units as cooling approximately 2/3 of all commercial space (Hydeman, Stein, & Zhou, 2007 ; PG&E, 1999).

It is worth noting that MTLC buildings represent only a small portion of the population gathered by these surveys and MTLC buildings might differ significantly from average data. Further, inside the MTLC space there might be differences depending on the main activity, also known as "end use" of the tenant (i.e office, grocery store, restaurant, retail, etc.). For instance, it is likely for multi-tenant office parks to be cooled mostly by packaged systems, while a medium grocery store might have central/built-up systems for refrigeration and air-cooling. Regardless of these variations, it is easy to see that rooftop units (RTU) are by far the most common HVAC system in MTLC buildings.

Figure 1: Cooling Systems type distribution by floorspace in commercial buildings in California (NRNC database)

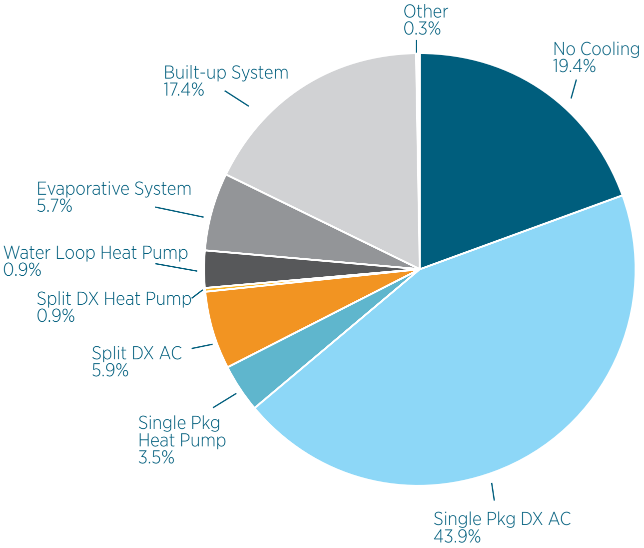

Table 3: Summary of some pertinent information gathered through primary research by WCEC

Avg. RTU Size:	Avg. Compressors per unit:	Avg. Sq ft. per ton:	Avg. age of RTU:
5.3 tons	1.1	273.4	10.2

CAPACITY OF RTUS IN MTLC SPACES

The Non-Residential New Construction database also provides the size frequency of packaged units in all commercial buildings, as shown in Figure 1. The most popular packaged DX capacity is 5-tons and units between 1- and 10-tons represent about 90% of the stock constituting 58% of the entire RTU capacity installed. (New Buildings Institute, 2003).

Of the units in the PGE CEUS database, 70% are below 7.5-ton Single Zone VAV Systems (Hydeman, et al., 2007 ; PG&E, 1999). Similar results are found in the Pacific North West by Northwest Energy Efficiency Alliance (NEEA) (Reichmuth & Cherniack, 2012) as shown in Figure 4. 64 % of the buildings have RTUs with average size less than 6 ton, while 79% of the buildings have RTUs with average size less than 10-tons.

Also data from AIR CARE Plus program in 25 university buildings in Davis, California show similar tonnage distribution of package systems; Units below or equal to 5-tons represent 80% of the stock quantity and 54% of capacity installed while units below or equal to 10-tons represent 97% in number and 89% of capacity. The high frequency of 2-ton units is due to the inclusion of split systems in the statistics (UC Davis & Cooper, 2010).

Data from a field survey of RTU efficiency and operation patterns carried out by WCEC and Davis Energy Group for Southern California Edison shows units binned into "ton" bins with the most frequent bin being 5-tons and a population mean of 7.94 tons (Western Cooling Efficiency Center & Davis Energy Group, 2012)

Sites visited during WCEC's primary data collection had no central chiller, therefore 100% of the buildings floor area was serviced by RTUs or split systems. Excluding split systems, units 5-tons or smaller account for 71% of the RTU stock, which corresponds to 54% of the total surveyed capacity. Further, in the WCEC's sample, units from 1- to 10-

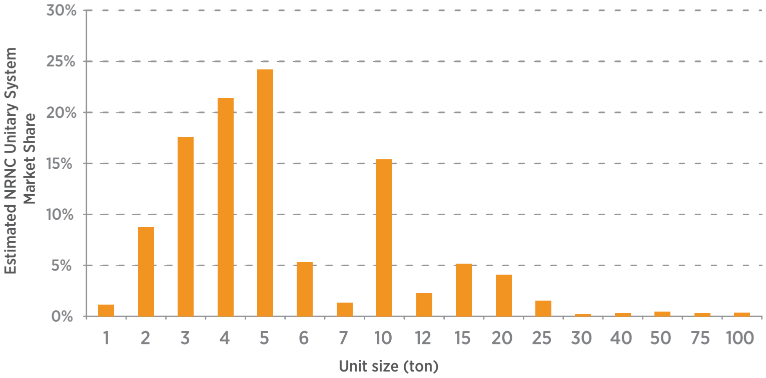

Figure 2: Package HVAC Capacity Distribution by Unit Size (New Buildings Institute, 2003)

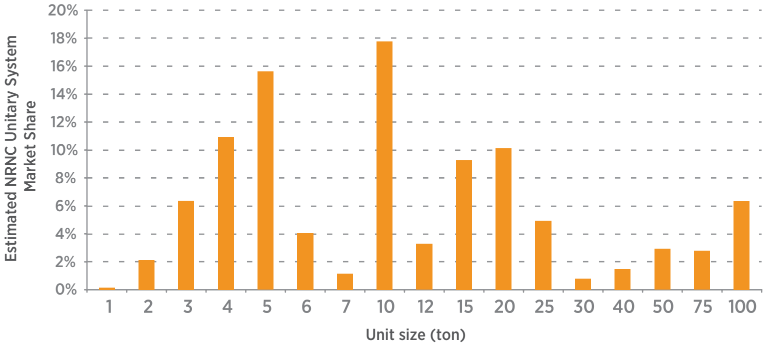

Figure 3: Package HVAC Capacity Distribution by Installed capacity (New Buildings Institute, 2003)

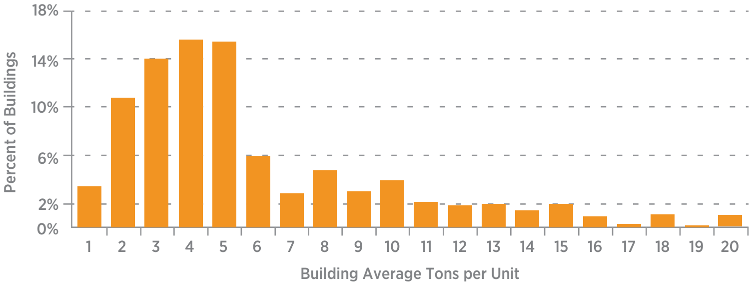

Figure 4: CBSA data: building average cooling tons per package HVAC unit (systems below 50 tons). N=1041. (Reichmuth & Cherniack, 2012)

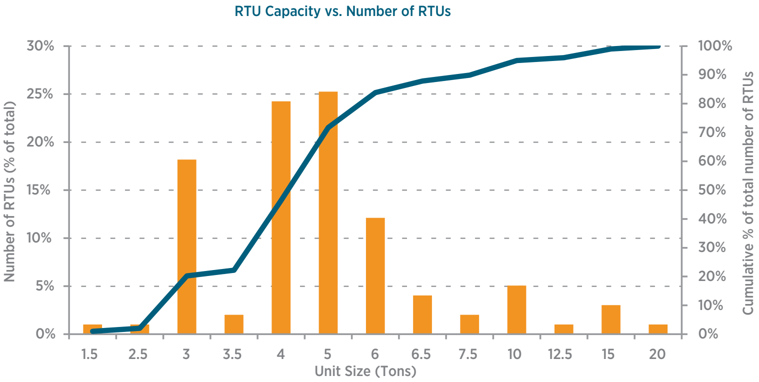

Figure 5: Rated Tonnage for RTUs in (Western Cooling Efficiency Center & Davis Energy Group, 2012)

tons account for 95% of the RTU stock, which corresponds to 85% of the total surveyed capacity (see Figure 6 and Figure 7, the blue lines represent the cumulative % of units and capacity respectively).

In addition to presenting size distribution, The NEEA report also provides a breakdown by building sizes as shown in Figure 8. The average size of the packaged units increases with the size of the buildings, up to a certain limit, after which the units are replaced with central chillers and the RTU average size starts decreasing again (Reichmuth & Cherniack, 2012).

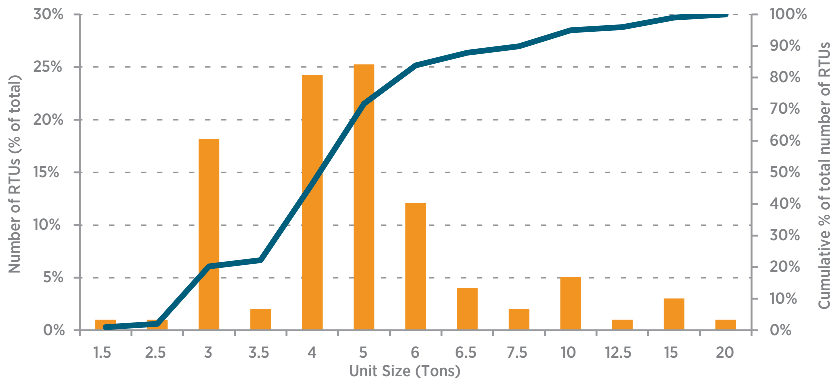

Figure 6: RTU capacity distribution by size

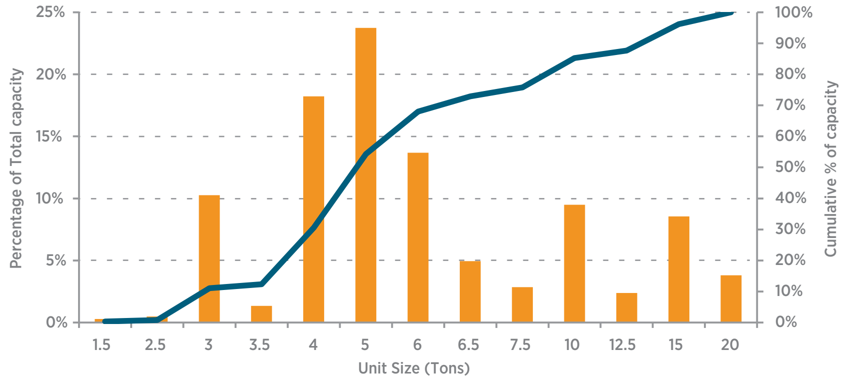

Figure 7: RTU capacity distribution by capacity

Floor Area	Average of RTU Count	Average Tons	Faction of PNW Floor Area	Building Count	Fraction with RTU	RTU Count
<5,000	1.9	4.7	10%	89877	70%	118,000
5,000-20,000	4.3	5.5	23%	57,593	61%	151,000
20,000-50,000	8.8	9.0	19%	15,616	54%	74,000
50,000-100,000	16.1	27.5	15%	5,816	35%	33,000
100,000-500,000	19.7	14.1	28%	4,946	30%	30,000
>500,000	5.5	5.2	4%	175	5%	100
TOTAL	***8.9***	***7.0***	***100%***	***174,023***		***406,100***

Figure 8: Average size of RTU by Building Floor Area (Reichmuth and Cherniack 2012)

Similar behavior is shown by the CEC small HVAC field survey and represented in Figure 9 (Jacobs, 2003).

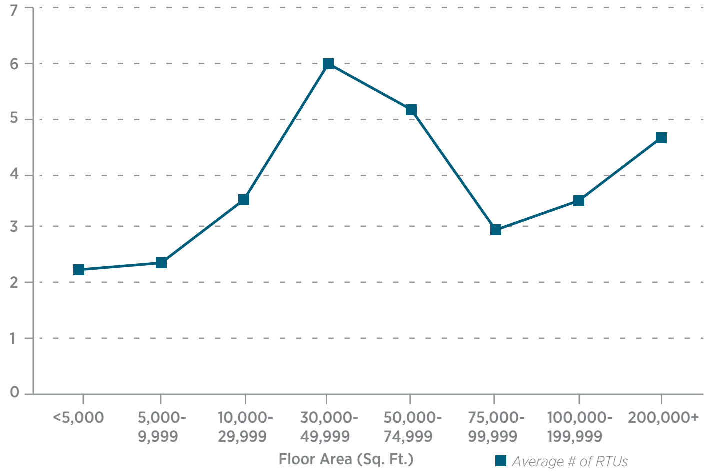

Figure 9: Average number of units vs Building Floor area (Jacobs 2003)

Based on site visits and interviews performed during primary data collection it was found that most of the tenant-spaces in MTLC buildings are cooled independently (i.e. tenants do not share equipment). It is expected that MTLC buildings split between multiple tenants to be serviced by a large number of small units, as if they were independent smaller buildings. The reasons for this widespread use of small units include flexibility, zoning requirements, economics, available space, unique load profiles and contractor suggestions (Glenn Hourahan, 2003; Woodcock, 1998). One property manager also provided experience that RTUs are installed on tenant space only when it is occupied for the first time. Therefore, because most tenants sign their respective leases at different times, it is not convenient to build a shared HVAC system for the whole MTLC complex.

HVAC SYSTEM AGE

The data presented in the CBECS and CEUS reports does not include any relevant age information related to HVAC equipment. However, a NEEA study for the Pacific North West region shows that more than 50% of the units are at least 10 years old. The age and capacity distribution of the NEAA study (NEEA & Energy and Environmental Analysis, 2005) is shown in Figure 12. In addition, the field data collected by the WCEC found that the average age of RTUs was 10.2 years (102 units surveyed). Therefore, based on the estimated expected life of a typical RTU of (15-30 years) (NEEA & Energy and Environmental Analysis, 2005) it is unlikely that these units, which are less efficient due to age and lower required standards when they were specified, will be replaced in the next 5 years.

Age (years)	% of total RTUs	Under 5 tons	5-10 tons	Over 10 tons
0-4	17%	30,000	24,000	14,000
5-10	32%	56,000	46,000	26,000
10-19	35%	62,000	50,000	28,000
20+	16%	28,000	23,000	13,000

Figure 10: RTU Age-Size breakdown (NEEA 2005)

REFRIGERANT TYPE

Our primary research, which is currently the only source available for refrigerant type data, illustrates that 96% of the RTU's surveyed contained R-22 refrigerant. The prevalence of R-22 was not unexpected as the requirements corresponding to the age of the units had not yet begun to preclude R-22. However, the fact that very few RTUs contained 410A suggests that few, if any, units have been replaced over the course of the past decade.

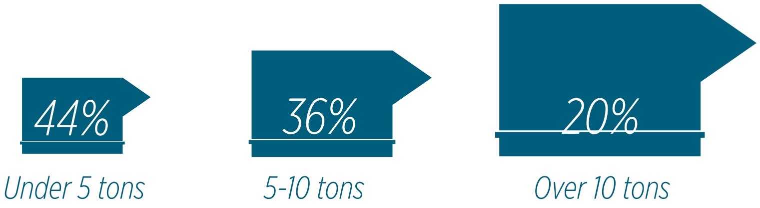

Figure 11: Total percent of RTUs based on capacity (NEEA 2005)

POTENTIAL RTU PROBLEMS

Several studies describe numerous problems that have been encountered in RTUs. A list of the most common problems is presented in Table 4 and Figure 12 and it illustrates the frequency of the problems in Jacobs, 2003. It is important to note that all of these problems were encountered in RTUs that were still functioning and were not perceived as "broken". We expect similar problems in the units installed in MTLC buildings.

Problem areas	Description	Reference
Refrigerant Charge	Improper charge (decreases efficiency and capacity)	(Bob Davis, 2002; Cowan, 2004; Jacobs, 2003)
Economizers1	Economizer not present or not working.	(Cowan, 2004; Felts & Bailey, 2000; Jacobs, 2003)
Air Entering Conditions	Heat sources around inlet air	(Jacobs, 2003)
Supply Fan Power	Fan operating "auto" or continuously. Does not meet title 24.	(Jacobs, 2003)
Air Flow	Reduced air-flow (decreases efficiency, can cause icing and ineffective moisture removal)	(Cowan, 2004; Jacobs, 2003)
Thermostats/Fan Controls	Poor placement. Use of residential thermostats unable to control fan separately. Ne setback settings.	(Jacobs, 2003)
Sensors	Failed sensors, broken wires.	(Cowan, 2004)
System Sizing	Systems are generally over-sized	(Djunaedy, Van Den Wymelenberg, Acker, & Thimmana, 2010; Felts & Bailey, 2000; Jacobs, 2003)
Distribution Systems	Duct leakage or poor leak insulation.	(Jacobs, 2003)
Access to Roof	Access to equipment can be difficult/impossible during audits.	(Jacobs, 2003)

Table 4: Common problems in RTUs

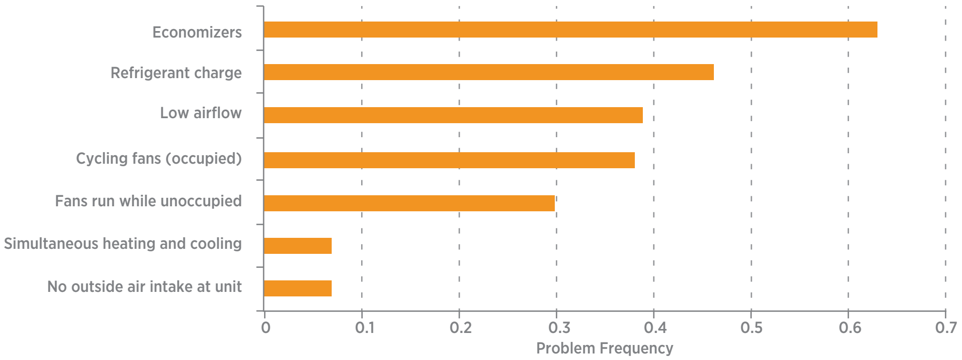

Figure 12: Frequency of RTU problems in the field

4. LIGHT COMMERCIAL HVAC DESIGN PROCESS

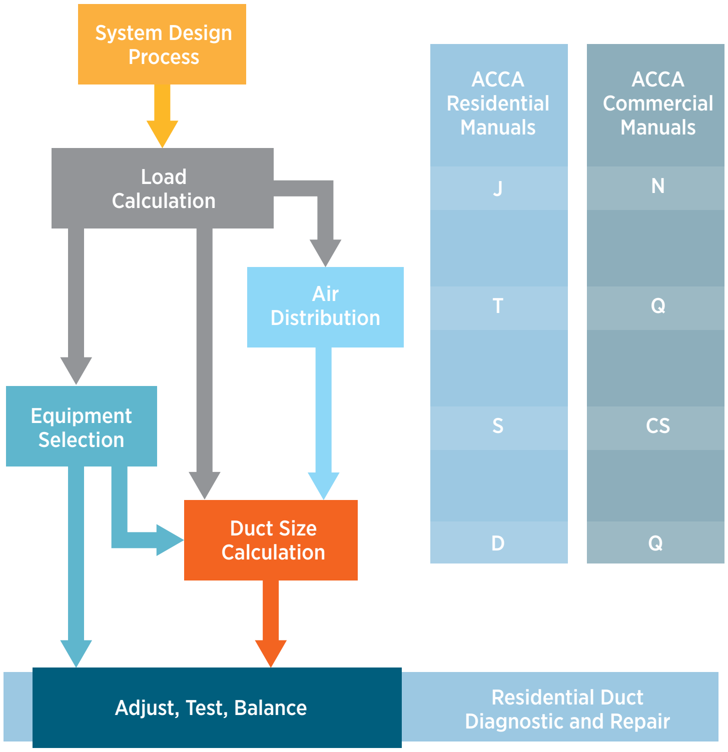

Figure 13: HVAC design process and associated ACCA manuals

When a new building is designed the HVAC engineers and/or contractors perform the following tasks (ASHRAE, 2009; Glenn Hourahan, 2003):

- Load calculations
- Unit sizing and selection
- Air distribution system layout
- Duct sizing

Figure 13 shows this process and the associated reference residential and commercial manuals developed by ACCA.

A survey by Air Conditioning and Refrigeration Technology Institute (ARTI) on design practices for small buildings (<20,000 sf) showed that the most popular sizing system for HVAC systems in new constructions is manufacturers' software, but a large fraction (17%) still use rules of thumb (Jacobs & Henderson, 2002). Results are shown in Figure 15. It is important to note that the data obtained is self-reported and was provided only by the small sample (N=198) that responded to the survey. The reality could be quite different as pointed out by several researchers for the residential sector where a higher percentage of contractors use "rules of thumb"(Glenn Hourahan, 2003; Proctor, et al., 1995; Vieira, Parker, Klongerbo, Sonne, & Cummings, 1996).

Methods commonly used by HVAC designers to calculate the building load can be classified based on the degree of complexity and accuracy of results.

- Hand calculations/previous experience
- Spreadsheets from standards
- Manufacturing or third party load calculation tools
- Building energy simulation tools

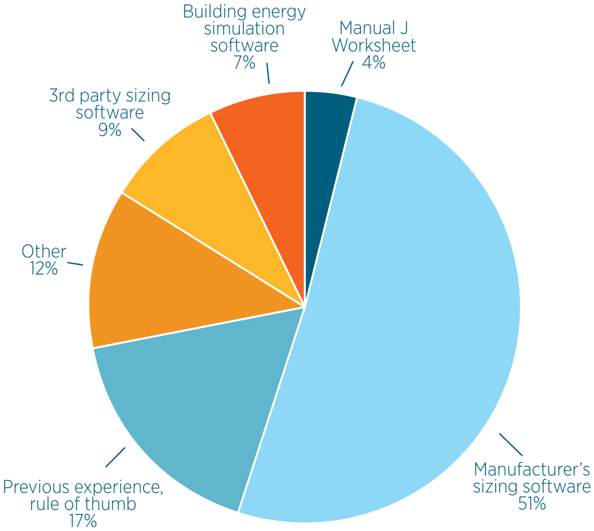

Figure 14: Design practice sizing HVAC systems for small buildings (Jacobs & Henderson, 2002)

Load Calculation Method (small commercial buildings)	Tool	Amount of inputs needed	Training needed	Time needed (order of magnitude)	Results
Manual Calculation/Rule of thumb	paper and calculator	small	1 day	a few hours	rough?
ACCA Manual N	Excel spreadsheet	medium	1 week	several hours	average?
HVAC Manufacturer Software	software	medium	months	hours-days	average?
Hourly Simulation Software	software	high	years	1 week	accurate*

Table 5: Load Calculation methods

MTLC building projects do not have a budget for extensive HVAC design, therefore quick methods are usually preferred.

HVAC Equipment Over-Sizing

Several studies to survey existing RTUs and develop tools for analyzing performance have been conducted, including the work performed for PG&E in 1998 by Felts and Bailey (Felts & Bailey, 2000),. Based on the information Felts and Bailey collected on the 250 units they surveyed, they found that only 40% of the units were correctly sized (not exceeding the peak condition), 20% were over-sized by 25% or less (limit in the ASHRAE manual). The remaining 40% of the units they surveyed were more than 25% over-sized with 10% of them being more than 50% over-sized.

A variety of situations lead designers and contractors to over-size HVAC equipment. Some of these situations include poor application of accepted load calculation methodologies, poor inputs and assumptions, unknown future status (i.e. building expansions), legal considerations, equipment availability and, of course, cost. Many of these problems are well understood and several studies have demonstrated their correlation to incorrect equipment specification. Unfortunately, there does not appear to be significant motivation to change the current status quo and there are limited strategies available to cost effectively down-size RTUs.

ERRONEOUS LOAD CALCULATIONS

One of the foremost challenges facing designers and contractors is poor application of load calculation methodologies. Improper use of these tools and methodologies can stem from several potential deficiencies ranging from inadequate training to over simplification. For example, both ACCA and ASHRAE specify detailed procedures to calculate the cooling load for a commercial building (ASHRAE, 2009; G. Hourahan, Rutkowski, & America, 2008) and several software packages and spreadsheets have been developed to help and guide contractors and engineers, however, these procedures require a significant amount time and accurate information to produce valuable results. Indeed, the HVAC industry is aware of the fact that these procedures are frequently not performed at all and, instead, rules of thumb, or previous experience, are used to determine equipment capacity (Glenn Hourahan, 2003; Proctor, et al., 1995; Vieira, et al., 1996).

Incorrect interpretation and usage of guidelines and procedures for determining the maximum thermal load the HVAC equipment must satisfy often leads to flawed results. A common practice in the HVAC field or "fix" used to deal with the uncertainty of these results is to apply "safety factors", often of 25% or more, that increase the specified capacity. This practice seems to be so widespread that an article in the ASHRAE journal dedicated to equipment sizing included explicitly "Do Not Add Safety Factors" as one step in the sizing procedure (Glenn Hourahan, 2004).

Indirect evaporative retrofit for RTUs

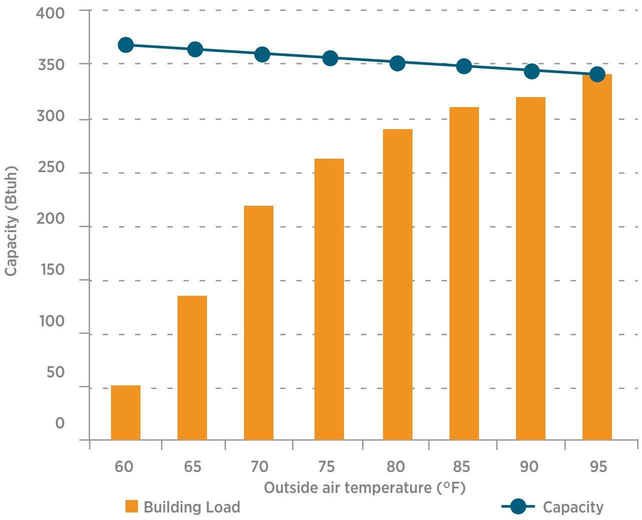

Figure 15: building load and RTU capacity dependence on temperature (example from (Woodcock, 1998)

Other sources report the use of "fudging" factors in the calculation process (Proctor, et al., 1995). For example, contractors were found to increase the size of windows, change the internal or external design temperature, and/or increase the internal loads in order to obtain a higher load allowing them to recommend a larger unit. In addition, the rounding-up to the next available capacity (RTUs are typically available only in 0.5-ton increments) exacerbates the over-sizing problem.

Yet, even when the commonly accepted processes for calculating loads are applied, there are several potential shortfalls. According to ASHRAE/ACCA Manual N procedures (ASHRAE, 2009; G. Hourahan, et al., 2008) RTUs should be selected based on local design conditions[3] that occur only for a few hours during the year[4]. In most of the conditions experienced throughout the year the building is subject to an external temperature that is much lower than the design day temperature. Simultaneously, the system capacity is higher during non-peak days because cooling equipment capacity is inversely proportional to external temperature (capacity increases with decreasing external temperatures) (Figure 15) (Woodcock, 1998). The combined effect of lower loads and higher equipment efficiency is exactly opposite to what would be preferred.

OVERSIMPLIFICATION

Examples of frequently used rules of thumb include: floor area per ton of cooling (e.g. Table 6), airflow-to-ton relationship (such as 350 to 450 cfm/ton), and latent load to full load relationship (such as latent load = 30% of total capacity). These rules frequently produce over-sized equipment because they are an over simplification and do not take into account new materials, orientation, local weather while assuming the worst-case scenario. Furthermore, when old RTUs are replaced, they are swapped with units of the same capacity, without re-computing the load, thereby failing to capture any change in the building envelope/efficiency or tenant activity (Glenn Hourahan, 2003). It is also possible that the replacement units are larger than their predecessors if any complaints are raised by occupants(Glenn Hourahan, 2003).

INTENTIONAL OVER-SIZING

Contractors and engineers often intentionally specify over-sized equipment for several reasons. One of the most frequently cited reasons for intentionally specifying large equipment is to avoid customer complaints (i.e. callbacks) or, potentially, lawsuits (Proctor, et al., 1995). Another common reason for intentionally specifying larger than necessary equipment is to compensate for installation flaws such as excessive pressure drop (Mowris & Jones, 2008) and/or because the customer requests "more cooling" or lower temperatures.

Future considerations, such as building additions and/or expansions, have also been cited as a driver for requiring larger systems (Vieira, et al., 1996). Proctor and alt. also mention other sizing methods called "sizing by cost" such as "buy the distributor overstock", "install the rejected unit from the previous job" and "install the unit sitting in the truck or at the shop" (1995).

Building Type	ft^2/ton
Offices, Commercial: General	300-400
Offices, Commercial: Large perimeter	225-275
Offices, Commercial: Large interior	300-350
Offices, Commercial: Small	325-375
Banks, Court Houses, Municipal Buildings, Town Halls	200-250
Police Stations, Fire Stations, Post Offices	250-350
Precision Manufacturing	50-300
Computer Rooms	50-150
Restaurants	100-250
Medical/Dental centers, Clinics, Offices	250-300

Table 6: Example of rules of thumb for sizing equipment (Bell, 2008)

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[3] *Usually expressed in terms of dry bulb temperature*
[4] *Less than 5% of the year*

In summary, it can be shown that several stakeholders have benefits in choosing an over-sized system, whereas the parties that experience the negative consequences (mostly users, and utilities) are not involved in the decision-making process. This concept is analogous to the principal agent problem but whereby tenants are loathe to, or are not empowered to, improve an asset they do not own and the owners have no incentives, financial or otherwise, to improve efficiency. Unfortunately, it is exceptionally unusual for either the owner or the tenant to be consulted during the design phase of these systems (see Table 7 for the details of the stakeholder analysis).

Impacts of HVAC Equipment Over-Sizing

There are several negative consequences that result from over-sizing HVAC equipment. These consequences include undesirable increases in peak power consumption, increased energy use (typically as a result of decreased part load performance), and decreased comfort. Several strategies have been developed to manage and improve part-load conditions; however, these solutions are constrained by the degree of over-sizing and the type of units that must be addressed. For example, a large unit with multiple compressors could be configured to reduce peak power consumption by physically disconnecting a compressor, whereas a small unit with single compressor cannot be effectively addressed using the same approach.

PART-LOAD CONTROL STRATEGIES

Different RTUs respond differently to part-load conditions, depending on their physical characteristics and control strategies adopted. The simplest and most common RTU system configuration is a single speed, constant-volume system. When these constant volume units are on the supply volume of the RTU does not change, which is to say that they are either operating at 100% or are turned off.

Constant volume RTUs are generally controlled by a single thermostat (Woodcock, 1998) in the most simplistic way possible. The thermostat calls for cooling and switches the RTU on when the room temperature is 1-2 F (deadband) above the desired temperature and switches it off when the temperature is below 1-2 F of the same desired temperature. Unfortunately, this strategy often collides with controls within the RTU that are designed to protect some of the components of the RTU. Specifically, RTUs often have minimum run times (typically >5minutes) in order to prevent frequent compressor cycling (AKA short cycling) that often leads to premature compressor failure. The combination of these two simple control features results in large temperature swings due to significantly more cooling being supplied than necessary and is further exacerbated by over-sized units.

For RTUs that contain two or more compressors, the unit can have at least two stages of cooling, which helps mitigate excessive on-off cycling[5]. Staging can be accomplished by having two independent refrigerant circuits within the rooftop unit or by using other capacity controls such as suction pressure unloaders (Woodcock, 1998). Suction pressure unloaders, or simply unloaders for short, prevent the flow of refrigerant from entering some of the compressors, reducing the overall capacity of the RTUs. Figure 17 shows a simplified behavior of a 4-stage RTU (Timmons & Tozzi, 2000).

Stakeholder	Benefits	Drawbacks
Designer	Reduced risk of callbacks Higher project cost (higher profit) Allows less detailed calculations (reduce time needed, therefore cost) and mask design flaws	Higher cost in case of bids
Contractor	Reduced risk of callbacks Higher project cost (higher profit) Allows for less detailed calculations (reduce time needed, therefore cost) and mask installation flaws	Higher cost in case of bids
Owner	Allows new tenants with higher internal loads without replacing the equipment	Higher maintenance, shorter equipment life (short cycling)
User/Tenant	Equipment meets the load even in extreme conditions (peak temperature and peak internal load)	Higher maintenance, shorter equipment life (short cycling) Poor temperature and humidity control
Bill Payer (Tenant/Owner)		Higher operation cost
Utility		Higher peak demand Higher energy use

Table 7: Stakeholder analysis of the impacts of over-sizing

Another option to modulate the load delivered by an RTU is termed hot-gas-bypass whereby some of the hot refrigerant is short-circuited and sent directly to the evaporator coil increasing suction temperatures and reducing the capacity. Unfortunately, the thermal energy of the refrigerant is wasted during this process making this method very energy inefficient. Therefore, hot-gas-bypass is only used in extreme cases when the unit must remain running for long periods of time at low load levels (Woodcock, 1998).

Modern techniques to regulate the RTU capacity include multiple-speed and variable-speed motors mounted on compressors and fans. These methods are very effective, but they require dedicated controllers, advanced control strategies and variable frequency motor drives. Even thought the energy savings can be substantial, the associated increase in complexity, in addition to the necessary hardware, increases the overall cost of these measures.

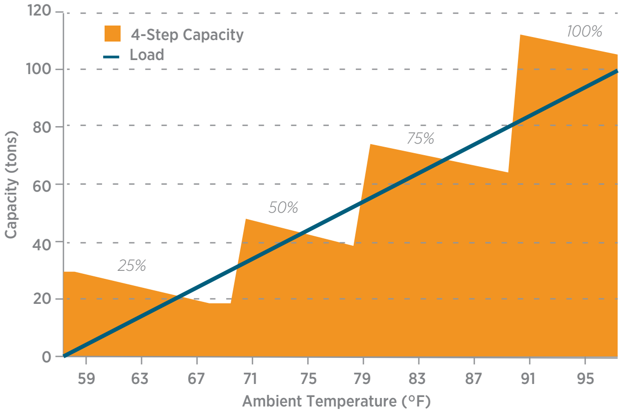
Many components of the cooling system, some of which are outside the realm of the RTU, can, and often do, affect the cooling capacity of an RTU. Problems such as improper refrigerant charge, duct leaks and improper flow across the coils all reduce the delivered capacity (Proctor, et al., 1995) and represent opportunities for improving energy efficiency. Unfortunately, addressing these problems in a retrofit situation will result in delivering more cooling capacity to the space and have the unintended consequence of exaggerating the problems of over-sizing.

Assessing Over-sizing in Existing Systems

Literature and industry practice did not reveal any known commercial tool that could be used to identify the presence or severity of existing over-sized systems even though the problem of over-sizing is a frequent problem that has yet to be effectively addressed. This lack of any available tool likely stems from a lack of incentives for contractors and designers to right-size the equipment and, because the HVAC industry has no known commercial tool to assess over-sizing, there are few options for down-sizing.

Fortunately, some researchers have studied these problems and developed methods that may be used to quantify the extent of over-sizing. Two studies in particular (Djunaedy, et al., 2010; Handerson, Raustad, & Rengrarajan, 1991) developed a relatively straightforward methodology to calculate the degree of over-sizing as well as the performance degradation and penalties associated with over-sizing. This method requires only the measurement of run-time data (tON and tOFF) during the peak hour of the day in a day with dry-bulb outdoor temperature close to design conditions. The idea is that if the unit does not run continuously during the most extreme days of the year it means it is over-sized. To identify over-sizing the methods calculate two parameters: maximum cycle rate (NMAX) and run-time fraction (RTF). The combination of high NMAX and low RTF is a signature of over-sizing. Using these two parameters allows two other parameters to be calculated: the part-load ratio (PLR) and the part-load fraction (PLF). Energy and Peak-load penalties can be calculated using the following formulas (Djunaedy, et al., 2010):

Figure 16: Building Load and Capacity in a 4-stage RTU (Timmons & Tozzi, 2000)



$$PLR = \frac{t_{ON}}{t_{cycle}} - \frac{\tau}{t_{cycle}}\left(1 - e^{\frac{-t_{ON}}{\tau}}\right)$$

$$PLF = 1 - \frac{\tau}{t_{ON}}\left(1 - e^{\frac{-t_{ON}}{\tau}}\right)$$

$$PeakDemand\ Penalty\ = Energy_{IN}(1 - PLR)$$

$$Energy\ Penalty\ = \left[\frac{t_{ON}}{t_{ON} - \tau\left(1 - e^{\frac{-t_{ON}}{\tau}}\right)}\right] - 1$$

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[5] *Multiple-stage units generally require specific thermostats to operate correctly*

IDENTIFYING AND ASSESSING OVER-SIZING

If one can correctly evaluate the degree of over-sizing of an installed cooling system, one can then re-calculate the load of the building. Using a simplified method such as ACCA manual N the total load can be divided by the internal load, external load and system load. To calculate the internal load it is necessary to know all the thermal properties of the walls, windows and other boundary surfaces and the air infiltration rate. The location-specific design conditions must also be used. External loads are usually dominant in small commercial buildings in California, but to accurately evaluate the degree of over-sizing the internal loads concurrent with the maximum external loads must also be evaluated, together with the system loads (e.g. duck leaks).

Depending on the principal activity of the building, the peak internal load might not coincide with the maximum external load (e.g. retails during holidays or restaurants during the evening meals). The relevant load calculation must check whether these internal load peaks are higher than total peak during the hottest day of the year. Finally, the latent load must be taken into account explicitly and not as a percentage of the sensible load.

Using a more simplified method a first-cut analysis could be done comparing square feet served by Square feet/ton method

After the load is calculated it must be compared with the real capacity delivered by the current RTU. Calculating the real capacity delivered is tricky because the flow rate from the air-side or from the refrigerant-side must be measured. Unfortunately, there is no easy way of measuring these air flows for a variety of reasons including the internal velocity distribution within the duct, unknown thermal zoning configurations, and difficulty of accessing a representative position within the system. In its entirety, this process is expensive, time consuming and needs a large amount of information (an energy audit and building drawings are most likely needed).

Alternatively a measurement of the real performance of the units can be done. The unit must be tested in a time period close to the peak external load condition (high dry-bulb external temperature, high insolation, high humidity) and internal load (# people, lights and electrical equipment on). If in these extreme conditions the units still cycles on and off it means it is oversized. The relationship between time on and off determines the degree of over-sizing. The problem with this method is that measurements must be taken in peak-hour or close-to-peak hour conditions. Details of this method will be explained in the following section.

Air Care Plus data (office buildings in Davis) shows on average 385 square feet area serviced by one ton of nominal equipment capacity. This value is close to the rule of thumb of 350-400 sf/ton used in the field (Figure 18). However, data collected in our primary research in an office park in Davis is significantly lower (273 sf/ton), most likely denoting over-sized systems.

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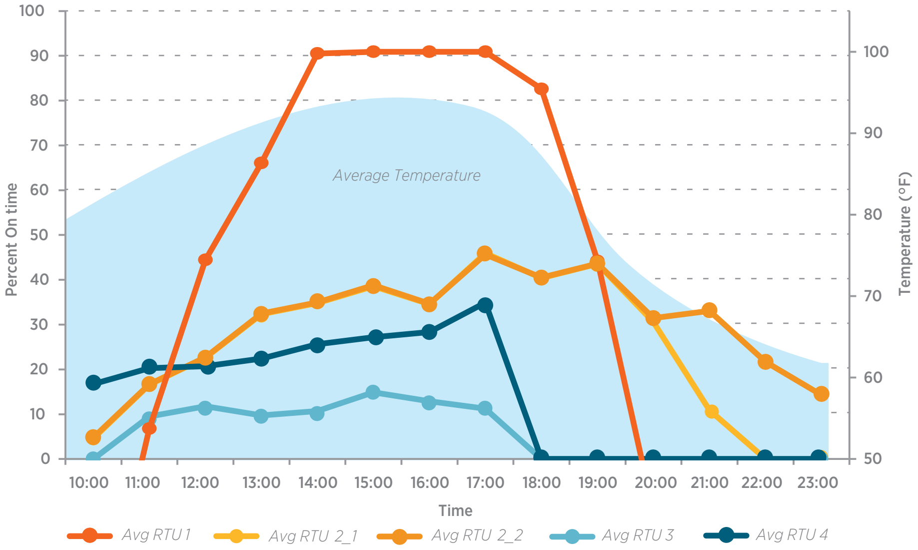
Building Information	
Average (mean) building sf.	6051
Median building sf.	3200
RTU Information	
#RTU per building	3.54
Avg. ton per RTU	4.375
Avg sf. per ton	385.1
avg. sf. per RTU	1,665
% units w/ second stage	8%
%ton in second stage	11%

Figure 18: Summary of Air Care Plus data for UC Davis

RUNTIME METHOD

A deeper analysis was performed in Davis with 4 RTUs during 4 hot days of August 2012. The maximum external temperature was slightly higher than the design day temperature making this data a good example of peak conditions. Figure 18 shows the percent on time of the four units in one selected day in August and the external temperature. During the hottest hour of the day 3 out of 4 units were running only a small fraction of time. From 1 pm to 5 pm units 2,3,4 where running 10-30% of the time. By definition, if the runtime of the unit during peak day conditions is less than 100% the unit is over-sized. According to the methodology in Djunaedy et.al these units are anywhere from 120% to 300% over-sized. (Djunaedy, et al., 2010)

Figure 18: Runtime and outdoor dry bulb temperature for four RTUs in our data collection



5. CONCLUSION

One of the key concepts of the MTLC project lies in reassessing the size of the HVAC systems. Common design practices frequently lead to the problem of light commercial HVAC systems being oversized. This problem will be accentuated after all of the proposed MTLC project retrofits have been implemented. The initial idea for reducing the size of the HVAC system was based on the assumptions that most of the units had multiple compressors (possibly 3-4). For example, disconnecting one compressor out of four available stages would only in a 25% capacity reduction. However, based on the primary data collected, and the data available in existing literature, the majority of the RTUs serving MTLC spaces are relatively small in capacity and, therefore, do not contain multiple compressors.

Several control retrofit solutions are commercially available that actively modulate the delivered cooling capacity of the RTU through the use of variable frequency drives. These retrofit control kits effectively "right-size" the unit continuously to deliver only the cooling necessary to satisfy the thermal load at any given time. While these control kits can save a substantial amount of energy they do not permanently reduce the capacity and are, at present, prohibitively expensive for most units smaller than 10-tons. Similarly, because these units have significant useful life remaining, it does not appear that replacement with a new, smaller, more efficient RTU would be an economically viable option.

Developing an assessment protocol that has wider applicability than the "catch a design day" method described in literature will be directly tied to the potential adoption of the MTLC project's whole building approach. Future efforts will focus on adapting existing assessment approaches and expanding the applicable conditions that will produce meaningful results. Another subject of future focus will be to determine the savings potential, risks, and costs associated with replacing specific components of the RTU, such as evaporator fans and compressors. Improving both the assessment of existing systems and the retrofit approach will contribute notably to the success of the MTLC project.

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