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Evaluation of Air Conditioning Performance Degradation: Opportunities from Diagnostic Methods

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ABSTRACT

This paper reports the first ever long-term empirical measurement of the degradation of residential air conditioner/heat pump (AC/HP) performance. We describe opportunities from development of automated heuristic algorithms to identify poorly performing systems. From 2012 - 2016, FSEC monitored 56 homes in Florida as part of a retrofit project which gathered detailed HVAC end-use energy data. Many research sites had two consecutive years of heating and cooling data and some had more than three years along with interior temperature data available. Within the analysis, cooling system performance at many sites was found to worsen over the baseline period, typically degrading 5%, and ranging from -8% to 40%, per year. Some systems experienced sudden, severe declines in performance often associated with need for system replacement. Using these data, an algorithm was developed to automatically evaluate AC/HP performance against weather. These findings were empirical in a large sub-metered sample of air conditioners and heat pumps evaluated over 2-5 years.

Introduction

Monitored Savings from HVAC Replacements

In recent decades, Florida utilities have been enthusiastic about air conditioner replacement as a reliable method of obtaining peak cooling energy reductions in residential systems. Indeed, a Florida utility monitoring project found air conditioning system change outs to have large impacts on energy savings and peak demand (Masiello et al. 2004)—even when the replacement systems were basic, lowest SEER (Seasonal Energy Efficiency Ratio) equipment. Within this study, older single-speed AC systems were replaced with the same type, but of newer vintage. Here the cooling savings were 29% and 34%, with an average savings of 20.2 kWh/day. The reduction in peak demand averaged 0.30 kW. A key conclusion in the study was that even standard equipment replacing existing air conditioning systems could produce savings of 30% or more—higher than would be estimated by comparing SEER alone. This suggested that the replaced equipment likely had degraded performance.

Air Conditioner and Heat Pump Performance Degradation

The rate of performance degradation and factors affecting its progression (filter and evaporator coil fouling and improper refrigerant charge) are not well understood, but age-related influences are likely causes. The steep response of system efficiency to changing weather conditions and set points over time may suggest opportunities for buildings needing either efficiency improvements or replacement of the heating and cooling system. Learning thermostats which compare air conditioner runtime against indoor temperature, setpoint differential, and broadband (internet) weather might be able to predict performance. Tracking of cooling and heating capacity and efficiency over time with smart phone apps could allow early intervention for failing heating and cooling systems as well as the ability to easily evaluate the impact of installed household efficiency improvements.

The only previously available estimates on AC degradation came from an LBNL study by Matson et al. (2002) done for California which applied a simulation to estimate the degradation rate of air conditioning and heat pump systems. It estimated a degradation rate of 2-3% per year without rigorous and regular maintenance of that equipment. Equation [1] was adopted by the Building America benchmark methods for analyzing existing buildings (Hendron, 2006):

$$\mathrm{SEER}_{\mathrm{degrade}} = \mathrm{SEER}_{\mathrm{nominal}} * (1- \mathrm{M})^{\mathrm{Age}}. \quad [1]$$

Where M is the Maintenance factor, 0.01 for expertly maintained equipment and 0.03 for unmaintained; and Age is equipment age in years.

The two most common problems with residential air conditioning systems are improper refrigerant charge and/or evaporator coil air flow. Other problems include non-condensibles in the system refrigerant and suction line flow restriction. On the condenser side, fouled outdoor condenser coils are also common. It is known that rectifying these two problems in field installations can result in improved system performance as revealed, for example, in CheckMe! studies in California (EDU 2001). We briefly summarize these influences below.

Refrigerant charge. Improper refrigerant charge is a very common problem with residential air conditioning systems. Deficiencies lead to low cooling and heating capacity for heat pump systems. Heat pump efficiency can be adversely affected since reduced capacity often translates into greater use of low efficiency electric resistance auxiliary heat. Field studies in in California and the Southwest by Proctor (1997) found incorrect charge in greater than 50% of examined field installations. Blasnik et al. (1996) found that 78% of evaluated systems in the Phoenix area were undercharged – often due to long refrigerant lines that were not properly augmented at the time of installation. Based on laboratory tests, a 20% undercharge condition for a 3-ton machine typically leads to a 24% decrease in sensible capacity at a 95°F outdoor condition (Neal and O'Neal 1992). These impacts are greater on lower efficiency machines without thermal expansion valve (TXV) refrigerant modulation.

Low coil air flow and coil fouling. Low evaporator coil air flow is another common problem with residential air conditioning systems. A study in Florida of twenty-seven air conditioners had one-time tests performed in the field to establish *in situ* performance and coil air flow (Parker et al. 1998). Coil air flow was consistently deficient (average = 317 cfm/ton against the 400 cfm/ton typically recommended). Other investigations have found similar problems in California (Proctor 1990) where the median measured coil air flow was 333 cfm/ton. A field study of 4,168 air conditioners (Mowris et al. 2004) found the 77% of audited systems were over- or under-charged with refrigerant and 44% had improper airflow. The main reason for poor flow was undersized duct systems and return grilles leading to a system external static pressure averaging 0.55 inches water column (IWC) against the 0.10 IWC used to rate air conditioning system in the ARI test procedures. Further, the study demonstrated a reduction of about 10% on rated sensible cooling capacity and a similar increase in cooling energy use. Another study of air conditioner indoor coil fouling found that significant fouling typically occurred in most systems, often by about 7.5 years of use. Impacts on SEER at 7.5 years of fouling were estimated at only about 5%, and much greater with marginal systems or in in extreme circumstances. However, this study did not evaluate how the sensible efficiency ratio would be affected—impacts on sensible efficiency would always be larger than on SEER itself (Siegel et al. 2002). Finally, Krafthefter et al. (1987) in laboratory accelerated testing found that found that foiling of indoor coil surfaces could often be associated with 15-20% degradation in performance.

Impacts on heat pump heating performance are likely greater since a reduction in flow cannot pick up additional latent load (as is possible in cooling) and all loss in sensible capacity draws the heat pump system closer to requiring supplemental strip heat. However, in this study we could not estimate heating system impacts given the limited amount of winter heating data in Florida's climate.

Site Characteristics and Research Methods

Study Sample Characteristics

Site and HVAC characteristics and estimated year-to-year degradation are provided in Table 1. Unfortunately, within the project, no data were available on how the cooling systems were maintained or how filter were changed etc., either professionally or by homeowners. Many homeowners are unaware that many systems have two filters – one at the return grille inlet and another at the system filter slot just before the evaporator coil.

Table 1. Site and HVAC Characteristics, Baseline Cooling, and Estimated Degradation Rates

Site #	Living Area (ft^2)	ACH 50	Cooling Energy (kWh)[1]	Avg. Int. Temp. (°F)[2]	Avg. Int. RH[1]	Year AHU/ Comp	Nom. SEER	Size: tons	Duct Leakage (Qn,out)[3]	AHU Replaced Y,N(age)	Max (kW)	Cool Deg. Est. 1&2 (%)[4]
1	2028	13.4	4205	79.2	51.7%	2014	13	3	0.04	Y(11)	3.61	4,2
3	1856	7.9	5480	75.9	57.7%	1993/2010	13	3.5	0.05	N	3.35	15
4	1166	11.5	3200	78.4	50.9%	2000	14	2.5	0.17	N	2.69	-2
5	2328	5.6	10780	77.7	42.0%	2006	13	5	0.10	N	6.89	9
6	1542	8.9	1197	81.8	64.3%	2006	13	3	0.10	N	2.92	20
7[5]	2650	8.3	4602	74.1	50.1%	2013	16	4	0.06	Y(12)	3.88	2,4
8[4]	2134	6.2	2523	77.7	53.2%	2013	17	3	0.05	Y(16)	3.23	15
9	1013	12.9	2767	78.0	57.4%	2011/2006	16	2	N/A	Y(5)	1.96	-3
10[4]	1627	6.0	4319	74.1	45.0%	2013	18	3	0.04	Y(10)	2.65	4, -6
11	1672	10.9	4066	79.7	54.5%	1998/2002	13	3	0.13	N	3.13	16
12	1594	12.0	4366	76.8	57.5%	2000	12	3	0.63	N	3.59	5
13	1052	16.4	2962	78.9	61.3%	2014	15.5	2.5	N/A	Y(14)	2.37	7
14	2016	8.9	3338	77.7	56.3%	2004	14.6	3	N/A	N	3.24	5

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[1] April - October 2013.
[2] April - October 2013.
[3] Duct system leakage normalized to outside; a measurement of duct leakage to non-conditioned space at a test pressure of -25 Pascals divided by the conditioned floor area.
[4] Some sites had multiple years evaluated. 1 is the first set of years compared; 2 is the second set of years compared.
[5] A deep retrofit site which had arbitrary AHU replacement in 2013. For these sites, 2014 rather than 2013 data were used for the baseline daily average cooling energy, interior temperature, and interior RH.

Site #	Living Area (ft^2)	ACH 50	Cooling Energy (kWh)[1]	Avg. Int. Temp. (°F)[2]	Avg. Int. RH[1]	Year AHU/ Comp	Nom. SEER	Size: tons	Duct Leakage (Qn,out)[3]	AHU Replaced Y,N(age)	Max (kW)	Cool Deg. Est. 1&2 (%)[4]
15	1359	8.2	2401	80.4	53.7%	1997	13.5	3	0.13	N	3.29	19,8
16	2231	12.7	7212	76.8	60.5%	2002	13.5	4	0.07	N	4.37	N/A
17	1456	8.4	2889	78.7	40.7%	2002	18	3	N/A	Y(14)	2.39	2, 21
18	1802	6.2	4408	75.7	55.4%	2008	14	3	0.05	N	3.29	11, 3
19[4]	2554	6.1	4644	76.3	48.4%	1990/1997	<10	5	0.09	Y(23)	4.70	N/A
21	1628	6.9	6957	77.4	56.5%	2007	13	3.5	0.12	Y(6)	3.97	N/A
22	1743	11.0	3107	80.2	55.6%	2001	12	2.5	0.08	N	3.21	29, 8
23	1946	8.4	6605	76.2	46.1%	2001/2002	14	3.5	0.05	N	4.07	-2
24	1978	9.5	5444	76.1	51.1%	2010	15	3.5	0.09	N	3.72	6, -1
25	1788	4.6	2363	80.9	49.8%	2010	15.5	3.5	0.06	N	2.21	12
26[4]	1502	4.7	3133	74.6	46.0%	2013	17	3	0.04	Y(14)	2.77	8
27	2050	8.0	8993	74.2	43.8%	2008	12	5	0.05	N	5.89	40
28	2622	8.9	3842	80.4	49.9%	1999	10	5	0.06	Y(17)	5.22	21
29	1215	10.2	5064	82.0	54.4%	1985	<10	2.5	0.07	Y(30)	4.17	7
30[4]	1819	5.8	2180	76.8	54.0%	2013	17	3	0.06	Y(10)	2.73	2, 6
33	1752	6.2	5895	77.6	45.4%	2001	12.6	3	0.02	Y(13)	3.43	-1
34	1651	9.3	3624	76.2	53.3%	2011	15	3	0.06	N	2.82	3
35	1625	6.6	8171	77.1	46.3%	1993/1998	<10	3.5	0.08	Y(22)	4.63	0
37[4]	1654	6.6	4283	77.2	44.0%	2013	17	3	0.05	Y(9)	2.94	0
38	1665	6.1	4648	78.1	57.2%	2006	13	3.5	N/A	N	3.93	10
39[4]	1559	6.3	2388	78.2	55.0%	2013	17	3	0.06	Y(7)	2.87	7
40[4]	1983	4.4	2809	75.3	52.1%	2013	17	3	0.04	Y(20)	3.26	-1, -6
41	2471	5.3	4402	75.6	47.4%	2007	18	3.5	0.03	N	3.76	9, -8
42	1666	6.1	7406	75.2	53.3%	2002	10	3	0.04	Y(13)	4.19	16
43	1383	6.5	3693	77.8	43.3%	1999	10	2.5	0.03	N	2.44	3
44	1627	4.7	3539	77.8	48.6%	1998	10	4	0.07	N	3.94	10
45	1299	9.1	4617	78.1	43.5%	2006	13	2.5	0.09	N	3.32	-1
46	2172	6.4	2642	77.7	50.9%	1999	10	3.5	0.03	N	2.08	32
47	1088	5.5	2642	78.3	46.6%	1999/2004	<10	2.5	0.03	Y(15)	3.28	N/A
48	1436	13.2	5353	76.9	44.8%	2006	13	3	0.20	N	3.72	0
49	1749	8.3	6147	73.2	55.5%	2004	17	4	0.09	Y(10)	4.01	1
50	2168	5.5	4699	78.6	56.2%	2005	14	4	0.03	N	3.86	4
51[4]	2233	8.3	3210	78.5	50.7%	2013	16	4	0.06	Y(19)	3.96	5, 3
52	1696	7.0	2626	77.4	53.6%	2012	13	3	0.06	N	3.15	N/A
53	1827	7.1	3713	75.0	50.7%	2012	20.5	3	0.06	N	2.28	15, 2
54	1390	5.3	6738	76.9	48.8%	1999	11	2.5	0.03	N	2.73	-2
55	1980	9.6	3595	78.1	49.4%	2006	14	3	N/A	N	3.16	N/A
56	1000	13.5	4037	79.1	48.2%	2005	10	2.5	0.16	N	3.13	29
57	1406	4.8	2429	77.4	54.9%	2001	13.5	2.3	0.09	Y(14)	2.65	4
58	2020	13.3	4853	78.2	54.6%	2003	13	3.5	N/A	N	3.48	10
59	2298	7.1	4628	79.0	57.2%	2005	18	4	N/A	Y(12)	4.72	14
60	1520	6.6	3852	76.9	52.2%	2006	15.5	3	0.04	N	3.96	8
61	875	12.0	3086	78.5	52.8%	2010	13.5	2.5	0.14	N	4.21	N/A
Median												5.2

Cooling System Life: A Related Aspect of AC Degradation

The average age of an air conditioning system replacement may give a meaningful indication about the rates of cooling degradation. In Florida, being without air conditioning in summer is intolerable for almost all households. On the other hand, the cost of replacing an air conditioner or heat hump is typically \$5000 - \$9000—so large an investment that many homeowners attempt to delay it for as long as possible. What are the most common types of problems? Karger and Carpenter (1978) surveyed 511 failed air conditioners and found that simple electrical failures (e.g. contractors) (31%) were the most common reason for service, but that true failure and replacement was associated with refrigerant problems (17%) or compressor failure (14%) and failed outdoor fans (12%). Similarly, Lewis (1987) surveyed 492 heat pump dealers and found that refrigerant leaks were found in 19% of failed units, while failed compressors or motors were 16% and other mechanical components at 12%.

Within the study, we tracked the status of the air conditioning systems in 46 study households without arbitrary replacement. (Ten homes within a deep retrofit segment had their central HVAC system arbitrarily replaced). A total of 12 of 46 systems were replaced over the monitoring period during the period the systems were tracked, which averaged 4.5 years. The median age of the air handler unit at the time of replacement was 13.5 years. A histogram of average system age (air handler), shows that 86% of systems were less than 16 years old, with a very rapid drop off beyond 15 years.

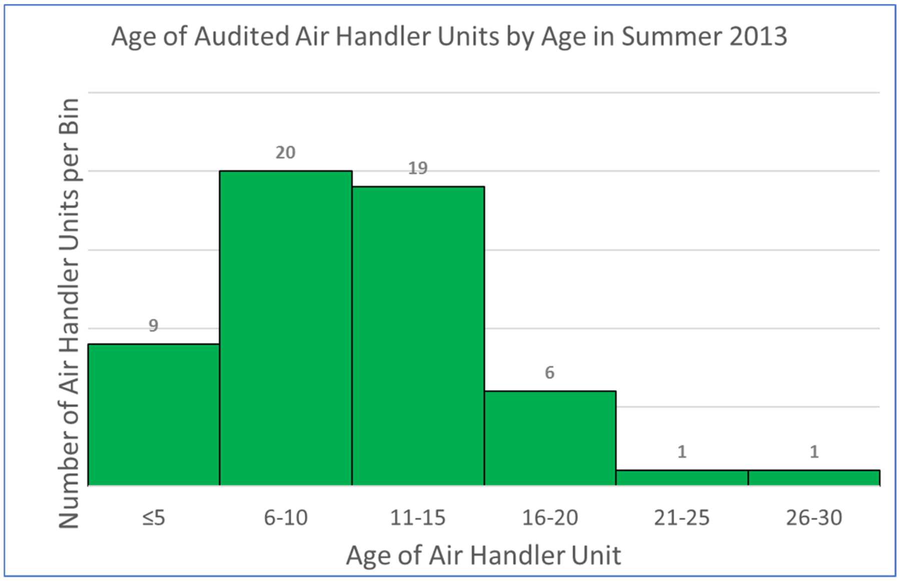

Figure 1. Histogram of AC system life as found in 56 homes.

Evaluating the sample of homes that had no intervention, we found median compressor age was 9 years in 2013 and the average air handler unit was somewhat older at 9.5 years. This indicates a typical system life of about 18 years – close to air conditioner service industry estimates (Kostora 2016). Six systems had mismatched compressors and air handlers, indicative of compressor failure and replacement. Compressor replacement is much less costly than replacing the entire system. However, such mismatched systems often have implications for efficiency. In any case, the typical replacement at 14 - 18 years along with the severe drop-off in system life after 15 years was significant in that it likely indicates the point at which the system can no longer provide suitable cooling. The longevity of AC units is also related to the mean time to failure (MTTF) of cooling equipment (Birolini 2013). The arithmetic mean of the 14.3-year life of the 12 units replaced in our study would indicate an MTTF failure rate of 7.0% – greater than the degradation rate found in our evaluation.

We performed a statistical evaluation of possible factors influencing the age of air conditioners encountered at the beginning of the study. A stepwise regression of system age predicted by annual hours of runtime, system size, the equipment SEER, and the average interior temperature produced the following model and bulleted findings:

$$Age = -8.855883 - \underset{[t = -6.18]}{1.3919(SEER)} + \underset{[t = 1.49]}{0.468388(Tint)}. \qquad [2]$$

$R^2 = 0.54$
Number of observations = 49

Where:

Age is the age of AHU and Tint is interior temperature in degrees Fahrenheit.

- Lower SEER systems tended to be older—an expected finding.
- Lower interior temperatures maintained (also associated with increased operating hours) were correlated with a shorter system life. Every degree below a high setpoint of 82°F the thermostat was maintained was associated with about a half year reduction in system life expectancy.
- Ignoring interior temperature, one finds operating hours to be significant. This indicates lower maintained interior temperatures and operating hours are strongly related.

Time-Related Degradation in Air Conditioning Performance

We used an established method to analyze possible degradation influences in the 56 PDR homes based on response to weather (ASHRAE 2002; Haberl et al. 2005). Figure 2 illustrates this method applied to Site 11, which indicates an approximate 70°F balance point.

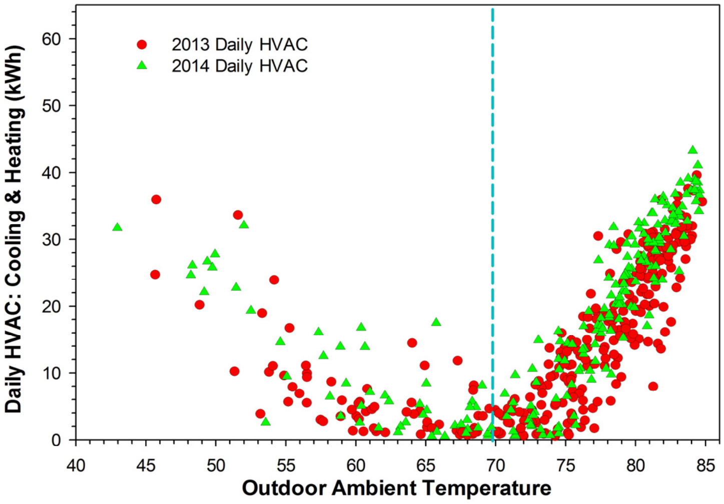

Figure 2. Site 11 daily HVAC kWh over a two-year long period plotted against outdoor temperature.

The plot includes about two years of data, up to the point where a smart thermostat was installed in 2014. Regression evaluation reveals:

Baseline Year Cooling: (Tamb>70°F): $AC = -172.93 + 2.432(Tamb).$ [3]
2^{nd} Year Cooling: $AC = -201.35 + 2.832(Tamb).$ [4]

Where:

AC is daily kWh for cooling, and Tamb is the ambient outdoor average temperature.

Cooling for a summer day averaging 80°F with the 70°F balance point was 21.6 kWh/day in the baseline condition installations and 25.2 kWh in the post year period for an estimated 16.7% (3.6 kWh/day) apparent degradation.

In our evaluation we applied the stronger of two models: either ambient air temperature or the indoor to outdoor temperature difference to predict cooling energy use. Using this analytical approach, we found that cooling related air conditioning performance falls between 3-7% per year, on average. This suggests that mechanical cooling system performance degrades over time in a measurable fashion if tracked by weather-related influences. Next, we illustrate both models with an AC system of a 2001 vintage (both indoor and outdoor unit). Figure 3 plots cooling use against the daily outdoor temperature and against the indoor to outdoor temperature differential for 2013 and 2014.

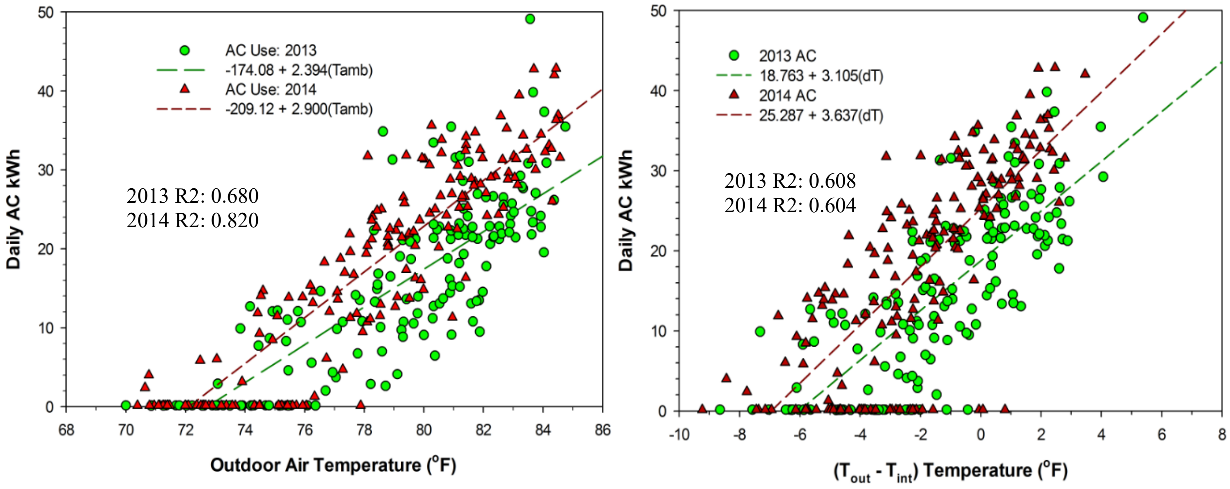

Figure 3. Degradation in cooling performance at Site 22 from 2013 to 2014 v. outdoor temperature & outdoor to indoor temperature difference.

The data show apparent degradation of the AC performance in 2014 against 2013, regardless of examination method—either by cooling energy use against ambient air temperature, or against indoor to outdoor temperature difference. Not only was this seen in Site 22, but in most sites where it could be examined—a trend of increasing consumption from one year to the next, even controlling for weather and interior temperature preferences.

The specific method by which sites are evaluated:

- Organize sub-metered HVAC data and estimate daily average kWh/day
- Obtain nearest weather station records for the location

- Eliminate zero and near zero cooling energy use values
- Obtain interior temperatures from a data logger (or smart thermostat)
- Regress daily average cooling energy consumption against outdoor temperature for the one-year baseline period
- For cooling, regress for outdoor temperatures >65°F; then increment up or down by one degree for each regression (e.g. 66°F /64°F) until R^2 is maximized. This temperature is the cooling balance point. The same procedure can be done for heating at <65°F.)
- Regress cooling energy consumption against outdoor to inside temperature difference
- Choose superior model based on R^2
- Evaluate model over different periods based on changes with building to be examined (e.g. degradation, insulation, new air conditioner)
- Estimate impacts of various influences by applying regression results to weather data and/or interior temperatures

Note that in the absence of HVAC kWh/day, heat pump runtime multiplied by estimated maximum runtime kW (typically capacity [Btu/hr]/EER) can be used to create surrogate energy estimates. HVAC runtime is typically available from smart thermostats.

Analysis and Discussion

Not surprisingly, while the degradation phenomenon was very significant as evidenced by Analysis of Variance (ANOVA) and regression against system age, we found the data very noisy with outliers. This was anticipated as even with interior to exterior temperature difference, changes in internal heat gains from appliances and occupancy and behavior (opening windows etc.) can produce either exaggerated or contradictory results in some cases. Also, some units may slowly degrade in performance while others may experience sudden failure. When we binned the data on air handler age, we found the medians descriptive of system degradation relative to age (see Figure 4). The air handler age was significant to the degradation rate at 95% confidence level.

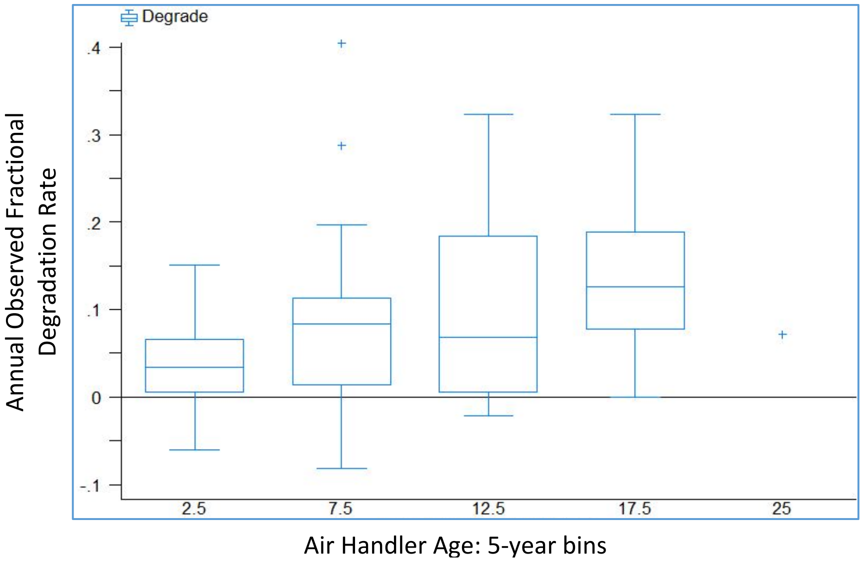

Figure 4. Boxplot of estimated degradation Rates in 50 monitored homes; Medians: (0-5 Yrs: 0.034 5-10: 0.083; 10-15: 0.068; 20+: 0.125).

We conducted an exploratory analysis of the data (some sites had multiple years evaluated) and discovered that degradation was not only associated with the air handler age, but also more strongly with the size (tons) and SEER of the equipment. Higher SEER equipment appeared more resilient to degradation while larger equipment appeared to suffer greater degradation rates. However, we were cautious of collinearity as the newer equipment generally had higher SEERs. Only after an analysis of covariance did we establish that SEER remained significant after controlling for equipment age.

Based on the coarse data on degradation with outliers, we used a robust regression with an iterative bi-weights advocated by Huber (1964) as implemented into the *Stata* statistical analysis software. Regression results from are presented in Figures 5.

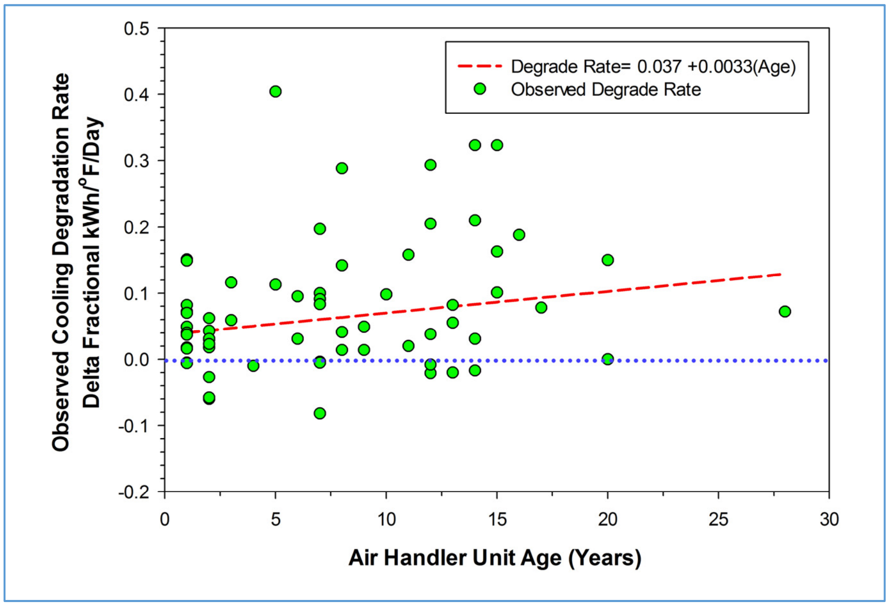

Figure 5. Estimated cooling efficiency degradation by age of equipment per site over a one-year period. Plot symbols are the SEER of the evaluated systems.

Note that that coefficient of determination, or R^2 should be ignored in the evaluation of the degradation estimates (while the t-statistics for the coefficients remain relevant). This is because we fully expect that much of the variation in the degradation estimates shown in Figure 5 are spurious and due to differences in internal gains and occupancy and behavior from year to year. Others are extreme and real—sudden loss of refrigerant, or progressive failure of systems fans. However, examining the data one is not only struck by the obvious scatter in estimates relative to system age, but also by the fact that *the great majority of the 64 estimated degradation values are above zero (87%). Few estimates are at zero or below. This suggests that degradation is a real phenomenon although air handler age poorly describes observed differences.* Equation 5 presents the robust model for regressing AC degradation against AHU age.

$$Degrade = 0.0370074 + 0.0032956(Age). \qquad [5]$$

$$[t = 1.91]$$

Number of observations = 64

Where:

Degrade is the cooling efficiency degradation, and Age is the age of the AHU.

The age term is significant at the 90% level. Annual degradation is about 3.7% but increasing slowly at about 0.3% per year. We postulate that the best way to understand this degradation, based on research on the likely phenomenon involved—coil fouling and refrigerant loss—is by losses to cooling capacity.

As the losses are cumulative from one year to the next, the relationship above as applied to Equation [1][6] would suggest that a machine which started out with a cooling capacity of three tons (36,000 Btu/hour) would see capacity drop by about 20% after five years, 40% after ten years, and 60% after fifteen years. In large part, this would also explain the life of systems. Beyond twelve years many systems have lost half of their cooling capacity. However, since most systems are oversized on installation by at 20-60% relative to actual cooling loads (James et al. 1997) and have at a minimum half a ton of additional capacity, the shortfall over time would not be typically noticed until after ten years except for households that desire lower summer interior temperatures. Not surprisingly, our statistical analysis finds that system life is strongly associated with average maintained temperature inside; those preferring cooler temperatures will need to replace systems more often.

Exploratory analysis using ordinary least squares (OLS) also found that the degradation rate is poorly described by the available factors but appears most strongly associated with both system size (larger systems degrading more quickly) and with SEER—the highest SEER systems degrading more slowly. Equation 6 presents resulting model regressing AC degradation against SEER and system size.

$$\begin{array}{c} \mathit{Degrade} = 0.1297971 - \underset{[t = 2.10]}{0.0388729(\mathit{Tons})} + \underset{[t = -3.05]}{0.0123086(\mathit{SEER})}. \end{array} \qquad [6]$$

Number of observations = 64

Where:

Degrade is the cooling efficiency degradation and Tons is the nominal system size.

The terms are significant at a 95% level or higher. The average size of the equipment evaluated was 3.21 tons (range: 2-5 tons) and efficiency averaged 14.36 Btu/Wh. The degradation rate of the lowest SEER equipment (SEER 9 Btu/Wh) appeared to suffer more degradation each year—although SEER is also associated with age itself as new equipment tends to be more efficient. We used another robust multiple regression procedure, median regression, to estimate the relationship between system degradation and SEER, system nominal tons and system age in years with the results in Equation 7. (Note that neither R^2 nor the t-statistic are meaningful for a median regression which does not have a normal distribution.)

$$\mathit{Degrade} = -0.0454 + 0.00269(\mathit{Age}) + 0.030\ (\mathit{Tons}) - 0.00127(\mathit{SEER}). \qquad [7]$$

Number of observations = 64

Where:

Degradation is the cooling efficiency degradation, Age is the age of the AHU, and Tons is the nominal system size.

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[6] $SEER_{degrade} = SEER_{nominal} * (1- M)^{Age}$

One will note that the result is not so different from the OLS treatment although the coefficient for SEER is much smaller. The combined model is intriguing as it shows that for each ton increase in system size degradation increases by 3% per year. Meanwhile, for a three-ton machine, annual degradation would be reduced by about 1% per year for a SEER 20 vs. a SEER 10 system. Figure 6 shows the relationship with the observed behavior that smaller HVAC equipment has superior performance after a twelve-year period than a larger system. As this study is preliminary, these estimates should be considered in a tentative fashion.

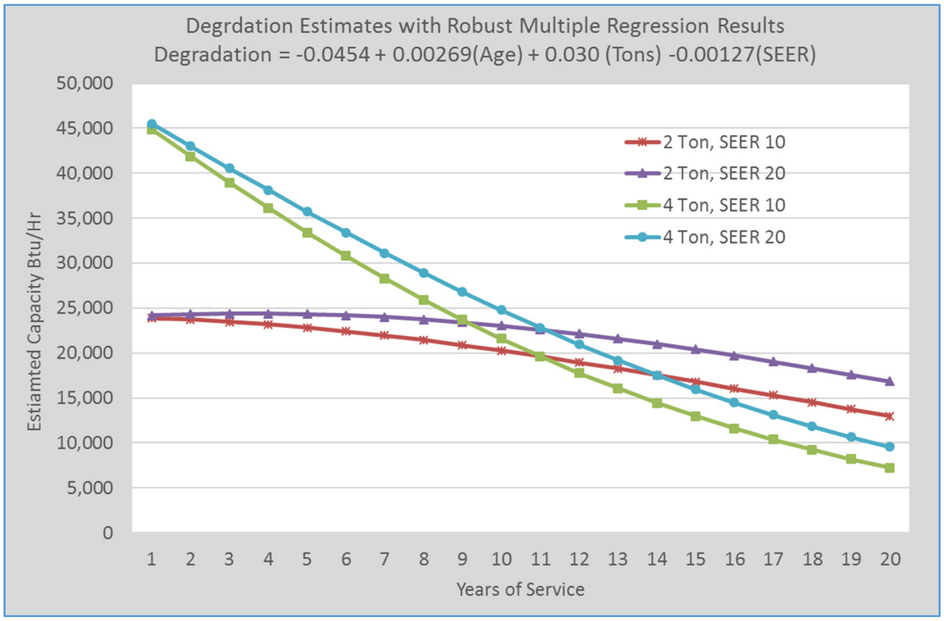

Figure 6: Estimated degradation for two and four-ton cooling systems of SEER 10 and 20 over a 20-year period.

Conclusions

An evaluation of air conditioning system performance degradation was conducted in 56 heavily monitored Florida homes. The assessment showed that cooling efficiency degradation can be readily observed as well as some of the influences involved. A statistical efficiency tracking method was developed that allows insight into the rate of annual degradation, even with data showing a high degree of variation. Previous metrics developed for the U.S. DOE had estimated degradation rates of about 3% for unmaintained systems (Hendron 2006). Our estimate is higher, albeit in Florida which is known for its intense use of space cooling (often>1,500 hours per year). The degradation rate was linked to the likelihood of system replacement as well as a preference for lower interior temperatures. The reason for the progressive decline of cooling performance is not determined in the study although earlier research suggests coil fouling and refrigerant charge problems likely play roles in the phenomenon. Filter maintenance could be another important factor.

The median degradation rate estimated in the study was 5.2% per year which would represent 216 kWh/year as measured in the baseline sample of cooling energy intensity in 2013. Among the 46 monitored homes where systems were not arbitrarily replaced, a dozen systems were replaced over the course of the 4.5 years of the study. Median study mechanical system life was estimated at 14-17 years. The likelihood that a system would be replaced over the course of the study was linked to the observed degradation rate (significant at a 90% confidence level).

Beyond equipment age, degradation was also found to be more influenced by system size and the seasonal energy efficiency ratio (SEER). System size appeared to be the largest factor; higher capacity systems being driven to maintain lower temperatures appear to degrade more quickly and have shorter life expectancy. We speculate that this could be because such systems must operate at must higher air flow rates which may increase filter loading and coil fouling rates for return registers that are frequently undersized for large equipment.

Higher SEER equipment appeared to have lower rates of degradation. This is not altogether unexpected as higher SEER equipment is designed to modulate and operate efficiently at lower coil air flows that might be produced from coil fouling. Also, the common use of thermal expansion valves (TXV) in such equipment generally makes the equipment more forgiving to undercharged system refrigerant levels (Farzad and O'Neal 1993; Mowris et al. 2004).

We also note that factors associated with cooling system use intensity – such as low preferred interior temperatures – are linked to degradation rate and system life. Thus, the building energy measures which reduce the intensity of cooling system use will likely reduce cooling system degradation rates. Also, since measures such as better insulation, more efficient windows and a tighter envelope are all statistically linked with cooling system hours, they are desirable since space conditioning system life may be improved. Further, the strategy of using a supplemental mini-split heat pump to reduce the load on the central space cooling system may have advantageous effects on system life (Sutherland et al. 2016). The most robust system with lowest degradation potential: an efficient building served by a small, high efficiency heat pump.

Future Application

The analytical methods developed here can potentially be added to applications (apps) running on smart thermostats to track heat pump performance. Such thermostats intrinsically have system runtime, interior temperature and broadband weather available which would allow necessary calculations. These apps could run constantly in the background using data from each added day along with recursive evaluation to estimate the changing behavior of the home and HVAC system. This could allow tracking of system degradation that might suggest filter changes, service calls or improvements to the system. This also facilitates intervention before equipment failure for advance selection of more efficient systems. Users could add notes regarding major changes to the home or its occupancy via the app (e.g. added ceiling insulation). Such influences could automatically be evaluated over time advising households on best courses of action.

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