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Energy Impacts of Oversized Residential Air Conditioners—Simulation Study of Retrofit Sequence Impacts

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National Renewable Energy Laboratory

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Technical Report
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Abstract

In this simulation-based study, magnitudes and causes of energy penalties are investigated for oversized residential air conditioners. Oversizing can result from overly conservative sizing of a new air conditioner or out-of-sequence retrofits (installing a new air conditioner first and then later making building improvements that reduce the cooling load). Conventional wisdom states that older, oversized air conditioners have significant energy penalties caused by increased on-off cycling relative to a correctly sized unit. Comparison of simulation results for different scenarios demonstrated that the energy penalty can be significant under certain circumstances. However, this is not primarily the result of increased on-off cycling. Oversizing does cause some additional cycling, but this does not lead to significantly increased energy use because all units already cycle frequently during most cooling season hours when conditions are less extreme than design conditions. However, if off-cycle parasitic power is present and is proportional to cooling capacity, the energy penalty can be significant. Also, oversizing penalties either increase or decrease with duct losses, depending on whether the air conditioner includes off-cycle parasitic power consumption proportional to air conditioner capacity.

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Introduction

Residential retrofits can be substantial investments that affect home energy use for years. Because many retrofits are expensive, homeowners often stage them over months or possibly years. For some retrofits, homeowners don't take action until they face equipment failure. Then they replace a piece of equipment such as an air conditioner immediately and often have little time to plan for the best return on investment or highest energy savings. Air conditioner oversizing results from overly conservative sizing of a new air conditioner or out-of-sequence retrofits (installing a new air conditioner first and then later making building improvements that reduce the cooling load). Homeowners need to have access to the most accurate information available so they understand the energy impacts of decisions made in these situations.

Conventional wisdom suggests that oversized cooling equipment leads to higher energy use because equipment cycling is inefficient (or at least that this was the case with older air conditioners). This reasoning provides impetus for performing intended retrofits before—or simultaneously with—an air conditioner replacement so the new air conditioner can be sized appropriately for the retrofitted load. Otherwise, if an air conditioner is replaced with an identically sized unit, it may not operate as efficiently after the additional retrofits, because the oversizing will lead to additional cycling losses. On the other hand, total duct energy losses are roughly proportional to air conditioner runtime, and a correctly sized system with longer runtime compared to an oversized system would experience more duct losses, potentially offsetting the expected energy penalty from oversizing. Quantitative analysis is necessary to determine if conventional wisdom is accurate and, if so, what are the relative magnitudes of the various effects.

This report describes a simulation-based case study of a typical 1960s vintage home undergoing retrofits including air conditioner replacement, duct improvements, and envelope improvements. *The duct and envelope upgrades reduce the cooling load on the house and provide an opportunity for reducing the size of the air conditioner. Simulations were performed with air conditioners of both the original sizing (oversized) and appropriately downsized (right-sized) for the upgraded house.* Specific questions that are addressed are:

- How much of an air conditioner's energy use is a result of cycling?
- What is the increase in energy use caused by additional cycling from an oversized air conditioner?
- Under what circumstances does oversizing lead to significantly increased energy use?
- How are oversizing energy penalties influenced by the presence of ducts?

This study does not address sizing impacts on air conditioner cost or the dehumidification effects associated with cycling of equipment.

Literature Review

Many researchers have studied the effects of oversizing air-conditioning equipment. A U.S. Department of Energy factsheet presents simulations that show a 13% increase in energy use due to doubling the size of an air conditioner in an energy efficient house (DOE 2002). Proctor et al. (1995) state that oversizing will increase energy use but don't provide estimates on the level of increase. Cummings et al. (1997) collected data on 368 homes in Florida and found 3.7% and 9.3% increases in energy for 20% and 50% oversizing, respectively. The t-value indicated a difference in energy use at the 95% confidence level, but the R^2 of 0.37 suggests that variation among samples (for example through house characteristics or occupant behavior) could play a significant role in the oversizing penalties observed. Sonne et al. (2006) studied three houses in Florida with air conditioner energy use data before and after replacing units with different capacity units that were otherwise identical. This study found mixed results in terms of having any energy penalty. Gorter (2012) states that oversizing leads to higher energy bills but doesn't provide quantitative information. Rhodes et al. (2011) studied installation and design impacts of air conditioner systems on energy use in Austin but did not find that oversizing leads to higher energy for individual houses. An Energy Center of Wisconsin report (2008) showed inconclusive results about the energy impacts of oversizing in two homes, each of which had otherwise identical 2- and 3-ton systems installed. Henderson et al. (2007) performed simulations in hot-humid climates with multiple air conditioner capacities and found that oversizing had very little impact on overall energy use.

Modeling

Air Conditioner Cycling

In simulation programs such as DOE-2 and EnergyPlus (DOE 2013), air conditioner cycling is modeled using average performance degradation effects of cycling over a given time step rather than modeling individual on-off cycles. A detailed derivation of the following model, and references, are given in Henderson (2000).The modeling begins with a part load ratio, *PLR*, sometimes called a cooling load factor, *CLF*

$$PLR = \frac{sensible\ cooling\ load}{steady - state\ sensible\ cooling\ capacity}$$

PLR is used to calculate the part load fraction, *PLF*, sometimes referred to as the part load factor or part load function

$$PLF = \frac{part\ load\ efficiency}{steady - state\ efficiency}$$

A simple and common method for relating *PLF* to *PLR* is through a concept called the degradation coefficient, C_D. The value of C_D is typically between 0.05 (lower cycling loss) and 0.25 (higher cycling loss); the values used in this study for the particular air conditioner units simulated are between 0.07 and 0.2. Modern, single-stage air conditioners tend to have C_D values around 0.07.

$$PLF = 1 - C_D(1 - PLR)$$

EnergyPlus defines the runtime fraction, *RTF* as follows

$$RTF \equiv \frac{PLR}{PLF} = \frac{PLR}{1 - C_D(1 - PLR)}$$

Thus, cyclic losses are accounted for by increasing the required air conditioner runtime to meet the building load. The cooling energy consumption is

$$E = RTF * \frac{Cooling\ Capacity}{COP}$$

The difference in energy consumption between two air conditioners, one right sized (RS) and one oversized (OS), is then

$$Oversizing\ Penalty = RTF_{OS}\left(\frac{Cooling\ Capacity}{COP}\right)_{OS} - RTF_{RS}\left(\frac{Cooling\ Capacity}{COP}\right)_{RS}$$

The rated cooling capacities and the *PLR* of the two units can be related by a capacity ratio, *CR*

$$CR \equiv \frac{Cooling\ Capacity_{OS}}{Cooling\ Capacity_{RS}} = \frac{PLR_{RS}}{PLR_{OS}}$$

Substituting into the oversizing penalty equation above and assuming the COP of the air conditioners is identical

$$Oversizing\ Penalty = PLR_{RS}\left(\frac{1}{PLF_{OS}} - \frac{1}{PLF_{RS}}\right)\left(\frac{Cooling\ Capacity_{RS}}{COP}\right)$$

The percent energy penalty is then

$$\%\ Oversizing\ Penalty = 100 * \frac{Oversizing\ Penalty}{E_{RS}}$$

$$= 100 * \frac{PLR_{RS}\left(\frac{1}{PLF_{OS}} - \frac{1}{PLF_{RS}}\right)\left(\frac{Cooling\ Capacity_{RS}}{COP}\right)}{RTF_{RS} * \left(\frac{Cooling\ Capacity_{RS}}{COP}\right)}$$

$$= 100 * PLF_{RS}\left(\frac{1}{PLF_{OS}} - \frac{1}{PLF_{RS}}\right)$$

$$= 100 * \left(\frac{PLF_{RS}}{PLF_{OS}} - 1\right)$$

Figure 1 plots the *PLF* as a function of *PLR* for the bounding values of C_D used in this study. A value of 0.2 can be interpreted as meaning that the degradation in performance with infinitesimal load (*PLR* ~0) is 20% lower than if the unit operates continuously (*PLR* =1); a value of 0.07 means performance would degrade by 7% under the same infinitesimal load. In simulation, a *PLR* near zero is possible depending on the load; as a practical matter, this extreme is almost never encountered. Minimum hourly *PLR* values are typically around 0.1. The exact value is controlled by the thermostat, which often has a minimum on-time of approximately 5 minutes. This means that either the air conditioner does not turn on at all, *PLR* = 0, or if it turns on just once during an hour the *PLR* is 0.083 if the on-time is exactly 5 minutes. If most hours of the year have *PLR* values well away from the extremes, the degradation caused by cycling with very poor performance (C_D = 0.2) will be substantially less than 20% and with very good performance (C_D = 0.07) will be substantially less than 7%.

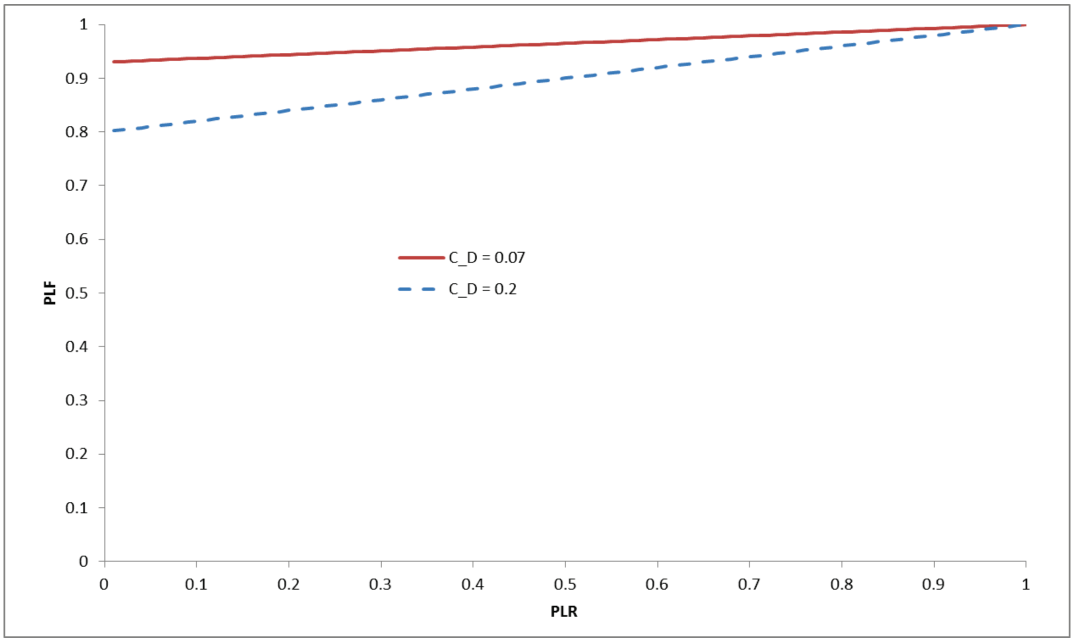

Figure 1. Linear model for *PLF* as a function of *PLR*. This assumes that there are no parasitic power draws or that they are accounted for separately.

Henderson (1991) presents a more physical interpretation of C_D by relating it to the time constant of the air conditioner and the per-hour cycling rate of the air conditioner. A typical time constant at the time that paper was published was around 80 seconds. The maximum cycling rate of the air conditioner depends on the physical characteristics of the building and on the thermostat. A cycling rate of 3.125 cycles per hour corresponds well with a C_D = 0.25 with a time constant of 76 seconds (Henderson 1999). A lower maximum cycling rate, or a smaller time constant, results in cycling performance that is comparable to lower C_D values.

Parasitic Power

The above formula for calculating *PLF* assumes either there is no off-cycle parasitic power consumption in the air conditioner or that this energy consumption is accounted for separately in the simulation.

A commonly used modification to the *PLF* correlation includes off-cycle parasitic losses directly (Henderson et al. 2000). This approach is introduced here because it is a well-known method from the literature and it clearly illustrates the effects of off-cycle parasitic power draw on *PLF*.

An example of a parasitic loss is a crankcase heater on the air conditioner. It is used to keep the oil in the compressor warm so that it does not absorb refrigerant when the air conditioner is not operating; it is standard equipment on a heat pump and can be used on an air conditioner as well. Crankcase heaters and their control strategies vary by air conditioner manufacturer, vintage, and price point. A crankcase heater typically operates when the air conditioner compressor is not running and, if thermostatically controlled, when the temperature of the compressor discharge line temperature is below a set point such as 65°F.

Parasitic power can be represented as a fraction of unit operating power

$$pr = \frac{Parasitic\ power}{Power\ draw\ when\ operating}$$

This can be used to formulate a modified part load fraction that includes parasitic power effects, *PLF'* (Henderson 1999)

$$PLF' = \frac{PLR}{\left(\frac{PLR}{PLF} + \left(1 - \frac{PLR}{PLF}\right) pr\right)}$$

If *pr* is constant, parasitic power losses are proportional to operating power consumption. For a given system efficiency this is proportional to capacity. If *pr* is zero, *PLF'* reduces to *PLF* from the linear correlation above. The lower *PLR* values that result from oversizing and the consequent lower runtime fractions mean the parasitic power is a larger wattage as well as being "on" for more time. This combination can lead to an oversizing energy penalty even if C_D is zero.

Figure 2 shows the PLF' correlation with two different *pr* values, a linear correlation for comparison, as well as a curve that is representative of the simulations in this study that have parasitic losses. The *pr* values are the bounding values considered by Henderson et al. (1999) for "good" (*pr* 0.01) and "bad" (*pr* 0.03) air conditioner units. The curve that is representative of simulations in this study is for 20 W/ton of nominal cooling capacity of parasitic power and COP 3.07 (corresponding to a SEER 10 unit), which gives a *pr* of 0.02. Note that for *PLR* values above approximately 0.5, parasitic power draws of this magnitude result in minor differences with the linear model.

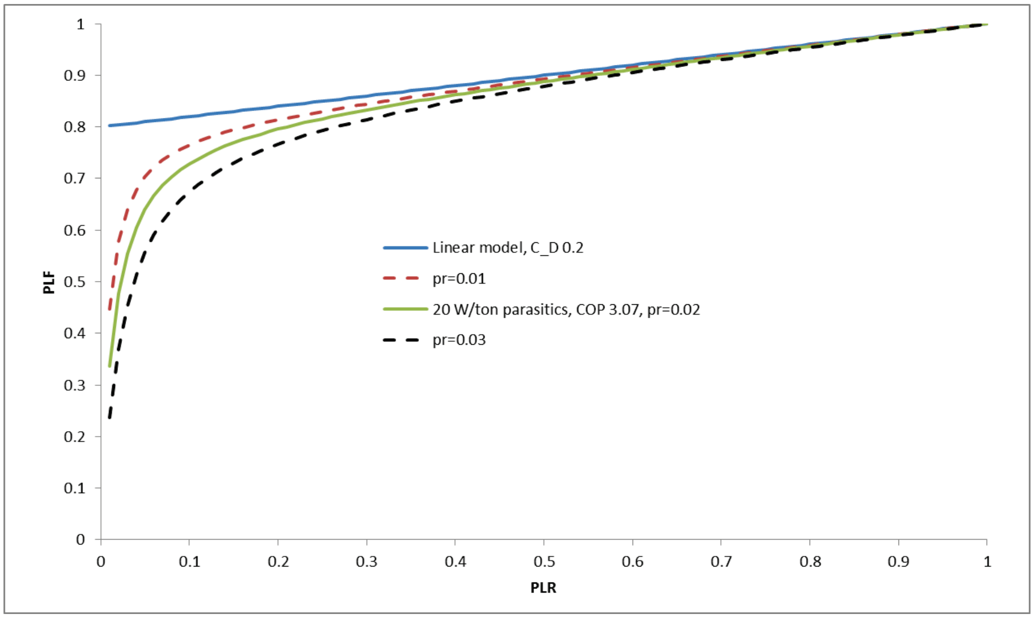

Figure 2. *PLF*' including parasitic power draws. The linear *PLF* model is included for reference.

The power ratios (pr) of 0.01 and 0.03 are representative of "good" and "bad" air conditioner units from Henderson (1999). The modeling approach used in this analysis is based on specifying parasitic power as a function of air conditioner capacity only. The 20 W/ton of nominal cooling capacity of parasitic power and COP 3.07 (SEER 10) correspond to a pr of approximately 0.02. For the range of SEER values simulated here, the pr values are 0.017–0.027.

Ducts

Ducts have an important impact on air conditioner performance. Location (conditioned space versus unconditioned space such as an attic), leakage, and conduction losses all have substantial effects on air conditioner performance. All ducts were assumed to be in the attic for this study.

The leakage was specified as a percentage of total airflow, so there is no correction for lower operating pressures caused by downsizing the air conditioner and leaving the ducts at the original size.

The fan efficiency is modeled as constant; it is not a function of pressure or flow rate. Higher efficiency air conditioner units have more efficient fans, but for any individual unit the efficiency is constant. The fan flow rate per unit capacity (CFM/ton) is constant over all units considered in this study.

Duct conduction losses are calculated using the log-mean temperature-difference model, which uses the air handler supply temperature, $T_{air\ handler}$, the air temperature in the duct location, T_{attic}, (all ducts were assumed to be in the attic), and the overall heat transfer coefficient, UA

$$Q_{cond} = UA\left(\frac{(T_{air\ handler} - T_{attic}) - (T_{register} - T_{attic})}{\ln\left(\frac{T_{air\ handler} - T_{attic}}{T_{register} - T_{attic}}\right)}\right)$$

The UA is based on the duct insulation R-value, R_{Ducts}, an exterior film resistance that was assumed to be 1.7 Btu/(h-°F-ft^2) (ASHRAE 1989) and the exterior surface area of the ducts, A. The interior film coefficient is assumed infinite such that the inner wall of the ducts is at the same temperature as the supply air.

$$UA = \frac{A}{R_{Ducts} + 1.7}$$

Simulations

Simulations were performed using BEopt 2.0 with EnergyPlus v8.0 as the simulation engine with TMY3 weather data for Houston, Texas.

Scenarios

Two retrofit-sequence scenarios are included in the analysis.

1. Right-sized (RS)—Air conditioner replacement is appropriately sized for the load after all retrofits are completed.
2. Oversized (OS)—Air conditioner replacement is the same capacity as the original unit and is oversized after retrofits are completed.

In both cases, post-retrofit buildings are simulated. Pre-retrofit simulations were not required since the comparisons are between different sized air conditioners, not between buildings with different characteristics.

Important house characteristics are presented in Table 1. The structure is a 1,280-ft^2 1960s vintage house with operation based on the Building America House Simulation Protocol (Hendron and Engebrecht 2010).

Table 1. House Characteristics

Characteristic	Pre-Retrofit	Post-Retrofit
Floor area	1,280 ft2	
Foundation	Slab on grade	
Windows	Double-pane, clear glazing, U 0.76, SHGC 0.67	
Infiltration	15 ACH50	3 ACH50
Attic insulation	R-11 blown cellulose	R-30 blown cellulose
Walls	Uninsulated 2×4 walls 16 in. o.c.	R-13 2×4 walls 16 in. o.c.
Ducts, in attic	R-4, 20% leakage	R-8, 2.5% leakage
Air conditioner	SEER 10	Each of the following was considered for all scenarios SEER 10 SEER 13 SEER 16, single speed SEER 16, two speed

Air Conditioner Sizing

The simulation results in Table 2 provided the air conditioner sizing for subsequent simulations; they are not directly related to further simulations except for sizing. The units are sized according to the implementation of ACCA Manual J in BEopt. Simulations for each pertinent combination of house characteristics were performed with and without parasitic losses to isolate the effects on annual energy use. Note that subsequent simulations only considered two duct options: none or upgraded. Later simulations that had 6.5 ton capacity systems assumed upgraded ducts.

Table 2. Simulated Air Conditioner Cooling Capacity

Ducts	Envelope	Capacity (tons)	Capacity Ratio
None	Original	3.5	1.8
None	Upgraded	2	
Original	Original	6.5	2.2
Upgraded	Upgraded	3	

Results

Annual Energy Simulation Results

Table 3 shows total annual cooling energy, including fan energy, for the retrofit scenarios simulated with upgraded ducts and without ducts, different air conditioner sizing and characteristics, and parasitic power losses.

Table 3. Total Cooling Electricity (kWh/yr)

(blue represents lower values, red represents higher values)

Ducts Present	Capacity (tons)		Capacity Ratio	Parasitic Power (W)	SEER 10 CD = 0.2	SEER 13 CD = 0.07	SEER 16 CD = 0.07	SEER 16 2spd CD = 0.11
No	2	RS	1.8	0	3638	2704	2185	2115
	3.5	OS		0	3783	2737	2210	2173
No	2	RS	1.8	40	3928	3000	2481	2394
	3.5	OS		70	4334	3294	2768	2714
Yes	3	RS	2.2	0	4026	2928	2367	2364
	6.5	OS		0	4066	2885	2331	2335
Yes	3	RS	2.2	60	4485	3395	2835	2810
	6.5	OS		130	5137	3965	3412	3397

Cycling Losses in Right-Sized Air Conditioners

Table 4 shows, as a theoretical reference, results for air conditioners with no cycling losses ($C_D = 0$).

Table 4. Total Cooling Electricity (kWh/yr) Without Cycling Losses

(blue represents lower values, red represents higher values)

Ducts Present	Capacity (tons)	Parasitic Power (W)	SEER 10 $C_D = 0.0$	SEER 13 $C_D = 0.0$	SEER 16 $C_D = 0.0$	SEER 16 2spd $C_D = 0.0$
No	2	0	3157	2578	2087	2001
Yes	3	0	3387	2766	2238	2192

Table 5 shows cycling losses for right-sized air conditioners (without off-cycle parasitic power consumption). The values are calculated by subtracting the theoretical no-cycling values in Table 4 from the corresponding simulation result in Table 3, using the no-cycling values as the reference for the percentages. Significant cycling losses occur even with right-sized air conditioners, because most hours with cooling have relatively low loads compared to the air conditioner capacity, which is determined using the design cooling load.

Table 5. Cycling Losses (%) With Right-Sized Air Conditioners

(blue represents lower values, red represents higher values)

Ducts Present	Capacity (tons)	Parasitic Power (W)	SEER 10 $C_D = 0.0$	SEER 13 $C_D = 0.0$	SEER 16 $C_D = 0.0$	SEER 16 2spd $C_D = 0.0$
No	2	0	15%	5%	5%	6%
Yes	3	0	19%	6%	6%	8%

Oversizing Penalties Without Off-Cycle Parasitic Power Consumption

Table 6 shows air conditioner oversizing penalties (without off-cycle parasitic power consumption). The values are calculated from results rows 1-2 and 5-6 in Table 6 by subtracting right-sized energy values from the oversized energy values for each scenario, using right-sized values as the reference for the percentages. Without off-cycle parasitic losses, oversizing penalties range from –2% to 4% for capacity ratios of 1.8 and 2.2. When off-cycle parasitic power consumption proportional to air conditioner capacity is not present, oversizing penalties are not very significant (and are even negative in some cases because of reductions in duct losses).

Table 6. Oversizing Penalties (%) Without Off-Cycle Parasitic Power Consumption

(blue represents lower values, red represents higher values)

Ducts Present	Capacity Ratio	Parasitic Power	SEER 10 $C_D = 0.2$	SEER 13 $C_D = 0.07$	SEER 16 $C_D = 0.07$	SEER 16 2spd $C_D = 0.11$
No	1.8	None	4%	1%	1%	3%
Yes	2.2		1%	–1%	–2%	–1%

Oversizing causes additional cycling beyond what occurs in right-sized air conditioners during part-load conditions, but there are diminishing effects on efficiency. With a C_D value of 0.2, for example, an hour when the right-sized *PLR* is 0.4 has efficiency degradation of 12% (*PLF* of 0.88); an oversized (by a factor of 2) unit has a *PLR* of 0.2 and efficiency degradation of 16% (*PLF* of 0.84). As described previously the hourly oversizing penalty is calculated as the difference between the reciprocals of the *PLF* values multiplied by the original *PLF*, approximately 5% in this example. An annual oversizing penalty depends on aggregation across hourly results with many *PLR* values.

In cases with duct losses (the second row of Table 6) penalties are lower, because oversizing reduces annual duct losses (see the description in the Oversizing Penalties with Duct Losses section below).

Oversizing Penalties With Off-Cycle Parasitic Power Consumption

Table 7 shows oversizing energy penalties in cases with off-cycle parasitic power consumption proportional to air conditioner capacity. The values are calculated from results rows 3-4 and 7-8 in Table 7 by subtracting right-sized energy values from the oversized energy values for each scenario, using right-sized values as the reference for the percentages. With off-cycle parasitic losses, oversizing penalties range from 10% to 21% for capacity ratios of 1.8 and 2.2.

Table 7. Oversizing Penalties (%) With Off-Cycle Parasitic Power Consumption

(blue represents lower values, red represents higher values)

Ducts Present	Parasitic Power	Capacity Ratio	SEER 10 C_D = 0.2	SEER 13 C_D = 0.07	SEER 16 C_D = 0.07	SEER 16 2spd C_D = 0.11
No	20 W/ton	1.8	10%	10%	12%	13%
Yes		2.2	15%	17%	20%	21%

The oversizing penalties are significantly larger when off-cycle parasitic power consumption is proportional to air conditioner capacity. Oversizing leads to higher parasitic power and more off-cycle time and, therefore, increased off-cycle parasitic energy consumption. The oversizing energy penalty is a moderately strong function of SEER; the higher percent penalties at higher SEER values are due to the lower overall energy use in the more efficient systems compared to the parasitic energy consumption.

Changes in Oversizing Penalties With Ducts Present

In the presence of duct losses (before and after retrofit) the larger oversizing capacity ratios seen in Table 4 would be expected to cause more cycling and larger oversizing penalties.

However, without off-cycle parasitic power consumption, oversizing penalties are reduced in the presence of ducts as indicated by Table 6. Conduction heat transfer through the duct walls is approximately proportional to the runtime of the unit. Oversized units run for shorter times and hence have lower losses relative to right-sized units.

Off-cycle parasitic power consumption proportional to air conditioner capacity presents a tradeoff between (1) increased parasitic power consumption resulting from the larger capacity ratio caused by duct losses at design conditions; and (2) reduced duct losses during operation resulting from shorter runtimes in the case with the oversized system. Under these circumstances the oversizing penalty increases in the presence of ducts, as indicated in Table 7.

Conclusions

Residential retrofits can be substantial investments that affect home energy use for years. Because many retrofits are expensive, homeowners often stage them over months or possibly years. Homeowners need to have access to the most accurate information so they can understand the energy impacts of retrofits in these situations.

This report describes a numerical case study of a typical 1960s vintage home in Houston, TX that begins when the air conditioner is replaced. To analyze choices that homeowners or their contractors might consider, scenarios were simulated that also included duct and envelope improvements. These upgrades reduce the cooling load on the house and, if implemented at the same time the air conditioner is replaced, provide an opportunity for reducing the size of the air conditioner.

Comparison of simulation results for different scenarios demonstrated that the energy penalty caused by an oversized air conditioner can be significant. However, the penalty is not due to unit cycling efficiency but rather to off-cycle parasitic power consumption. If the parasitic power is proportional to cooling capacity, the losses are substantial and support the conventional wisdom that having an oversized air conditioner results in an energy penalty.

Specific questions that are addressed are:

- How much of an air conditioner's energy use is a result of cycling?

  In many climates even a right-sized, single-speed air conditioner experiences significant cycling because loads during many cooling season hours are low relative to loads at design conditions. Older air conditioners are sensitive to cycling and could have up to 15% increased energy use. Newer air conditioners are less sensitive and experience only single-digit increases in energy use.

- What is the increase in energy use caused by additional cycling from an oversized air conditioner?

  Oversizing does cause additional cycling, but this does not lead to significant increased energy use because there are diminishing impacts after the seasonal cycling effect described above.

- Under what circumstances does oversizing lead to significantly increased energy use?

  With off-cycle parasitic power consumption proportional to air conditioner capacity (from components such as controls and crankcase heaters) oversizing leads to significant additional energy use, because oversized units are off more of the time.

- How are oversizing energy penalties influenced by the presence of ducts?

  Without off-cycle parasitic power consumption, oversizing penalties are reduced in the presence of duct losses. With off-cycle parasitic power consumption proportional to air *conditioner capacity, on the other hand, oversizing penalties increase when ducts are present.*

Comparison of the simulated scenarios demonstrated that the oversizing penalty is significant if there are parasitic power losses. However, the penalty is not due to unit cycling efficiency as conventional wisdom might suggest.

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Appendix: Effects of Part Load Ratio

The relatively small impact of oversizing on annual energy use from Figure 3 can be better understood by looking at the individual effects of C_D and the part load fraction models described above.

Figure 3 is a convenient graphical method for understanding the physical and mathematical trends associated with oversizing and cycling of equipment; it is not a substitute for using whole-building simulations to determine changes in annual cooling energy due to equipment sizing. The load graphs are histograms of the total cooling load at each *PLR* over a year using TMY3 weather data for Houston. The air conditioner is a SEER 10 unit with no parasitic losses, 2 tons for the right-sized unit and 3.5 tons for the oversized unit, a capacity ratio of approximately 1.8. The part load fraction (*PLF*) is the fractional decrease in efficiency including cycling losses. A *PLF* of 1 means the unit operates at steady state efficiency; which occurs when the unit operates continuously (*PLR* = 1). A *PLF* of 0.9 means the unit operates at 90% of steady state efficiency, etc. The vertical lines are a graphical aid to help translate between the load histograms and the *PLF* curve over every *PLR*. The relative positions of the vertical lines are proportional to the capacity ratio. For example, with a 1.8x capacity ratio, if the vertical line corresponding to the right-sized system is at a *PLR* of 0.4, the vertical line corresponding to the oversized system will be at 0.22. This ratio is constant over every *PLR*.

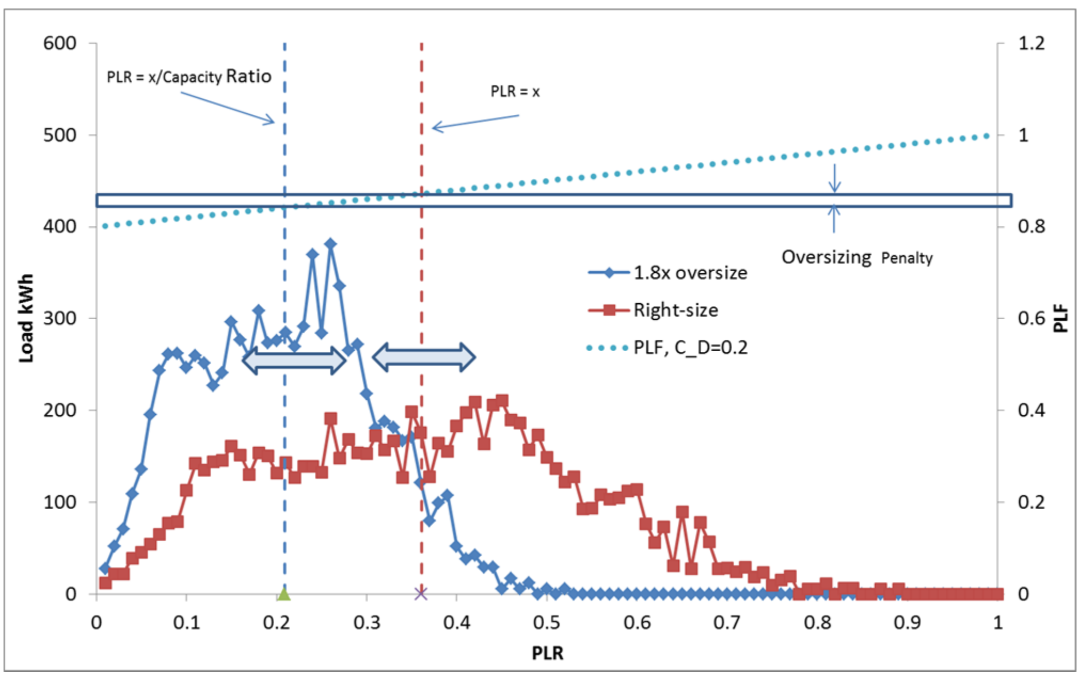

Figure 3. Histogram of loads for a right-sized unit and a 1.8x oversized unit. Dotted lines represent the *PLR* where the *PLF* is being calculated.

This calculation occurs for every PLR. The effect on energy use can be weighted by the load at each PLR to gauge the annual oversizing impact e.g., the oversizing penalty at high loads is more important than the oversizing penalty at smaller loads.

The difference in the value of *PLF* where it intersects the two vertical lines (the graph gives an example of *PLR* 0.36 for right sized and 0.21 for oversized, which correspond to the load-weighted average annual *PLR* for each capacity) is representative of the decrease in system efficiency from additional cycling from oversizing, a 3% decrease in this situation. This does not equate directly to a 3% increase in energy usage; however, it is indicative of the change in energy consumption due to oversizing.

There can be significant cycling losses in both correctly sized and oversized systems because most hours of the year are spent at relatively low loads compared to design-condition loads; however, the impact of additional cycling from oversizing is more modest.

Reduced Cycling Losses in Newer Air Conditioners

Figure 4 is similar to Figure 3 except the load histograms are removed for clarity and another *PLF* curve is added which has a different cycling degradation coefficient. The cycling performance of equipment has improved significantly from 1990's levels to today. SEER 10 units sold in the 1990s had a C_D ~0.2 whereas modern units can have a value closer to 0.07 (Cutler et al. 2013). Figure 4 shows the reduction in *PLF* due to oversizing with a capacity ratio of 1.8 at a right-sized *PLR* = 0.36 for C_D of 0.2 (poor cycling performance) is ~3% and for C_D of 0.07 (good cycling performance) it is ~1%. Cooling energy is not proportional to *PLF* but rather to the runtime fraction (*RTF*), however, *PLF* does represent a decrease in unit efficiency due to cycling. Therefore, Figure 4 provides a useful baseline when considering the effect of cycling performance on the energy penalty due to oversizing for both good and bad cycling performance.

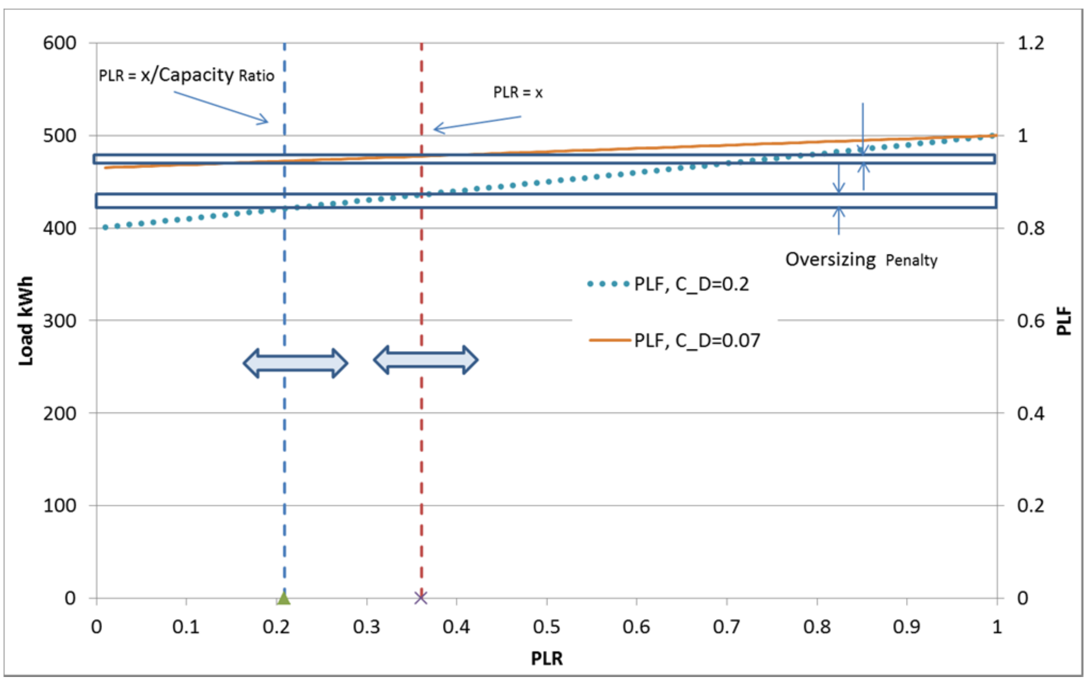

Figure 4. *PLF* for two different cycling degradation coefficients.
The vertical lines are translated over every *PLR*.

The ratio of the PLR for the two lines is the inverse of the capacity ratio (i.e. a 1.8x oversizing means the right-sized line has a PLR 1.8 times greater than the PLR of the oversized unit). The difference in the value of PLF where it intersects the two vertical lines represents the decrease in system efficiency from oversizing. A smaller cycling degradation coefficient, CD, reduces the impact of oversizing on PLF and hence on cooling energy used.

Oversizing With and Without Off-Cycle Parasitic Power

Figure 5 shows that the oversizing energy penalty depends heavily on whether there are parasitic power losses. The largest parasitic power draw on air conditioner units is a crankcase heater. These are standard equipment on heat pumps, which operate in colder conditions than air conditioner units; however, they may or may not be present on any particular air conditioner, depending on the age, manufacturer, capacity, performance, etc. A common method to control these heaters, if they exist, is to have the heater turn on if two conditions are satisfied: (1) the air conditioner is not operating; and (2) a reference temperature, typically the outdoor temperature at the condenser, is below a specified value. In the simulations where crankcase heaters were used in this study, the reference temperature was set arbitrarily high such that the heaters turned on whenever the air conditioner was off. This provides a sort of worst-case scenario in terms of maximizing the energy penalty associated with oversizing the unit.

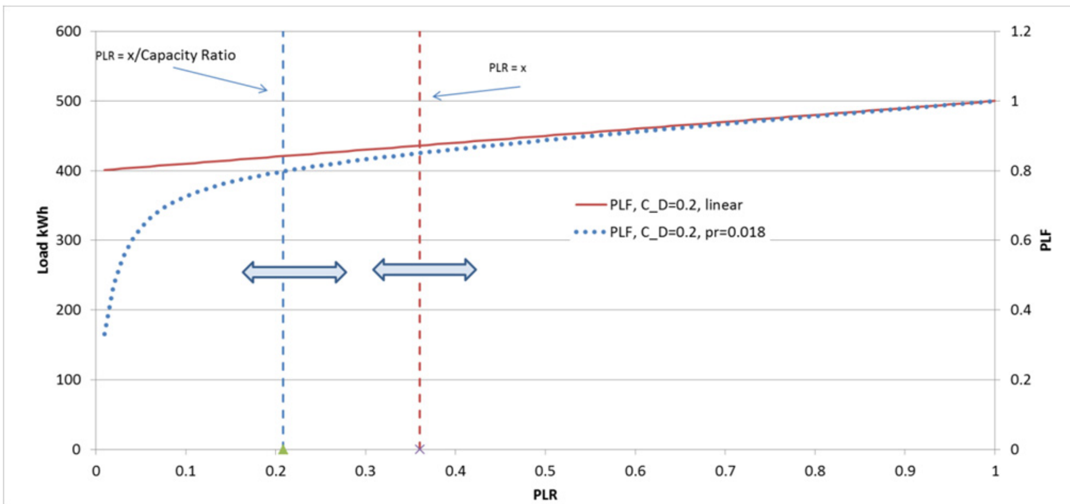

Figure 5. Comparison of *PLF* curves with (nonlinear) and without (linear) parasitic losses.

The difference in PLF for each curve between the two vertical lines gives an idea on the oversizing penalty; this penalty should be evaluated over all PLR for which there is a load. For the nonlinear curve, there are substantial parasitic losses at PLR = 0 that do not affect PLF but do contribute to the annual oversizing penalty. For all PLR values, the parasitic loss curve (nonlinear) has a higher oversizing penalty. The effect is more pronounced at lower PLR values.

Figure 5 shows two *PLF* curves, one with and one without parasitic losses included; both curves have $C_D = 0.2$. The difference in *PLF* for each curve between the two vertical lines gives an idea of the oversizing penalty; this should be evaluated over all *PLRs* to get an approximate annual oversizing penalty. For all *PLR* values, the curve with parasitic losses (nonlinear) can be seen to have a steeper slope that will result in a higher oversizing penalty. The effect is more pronounced at lower *PLR* values. For the non-linear curve, there are substantial parasitic losses at *PLR* = 0 that do not affect the *PLF* curve but do contribute to the annual oversizing penalty. These losses at *PLR*=0 occur when the air conditioner does not turn on during a simulation time step (1 hour for all simulations in this study). Because the air conditioner did not turn on, the *PLR* and hence *PLF* = 0, however, the parasitic losses still occurred during the entire hour and must be accounted for when calculating annual energy use and oversizing energy penalty. There are a large number of hours during the year for which *PLR* = 0, the parasitic losses during these times are the dominant factor in the oversizing penalty.