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National Energy Savings Potential From Addressing Residential HVAC Installation Problems

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INTRODUCTION

Nationwide, homes which have central air conditioners use an average of 30% of their electricity for cooling. Thus, even though only about two out of every five homes in the United States has central air conditioning,[1] central cooling is responsible for a larger percentage of residential electricity consumption -- 11.4% -- than any other end use except space heating and refrigeration.[2] Moreover, the relative importance of central air conditioner electricity consumption is likely to grow over time because the percentage of homes with central cooling is growing.[3] Heat pumps are much less common than central air conditioners. However, when a heat pump is used to both heat and cool a home it can account for more electricity consumption than all other end uses combined.

Both the government and electric utilities have sponsored a variety of programs to promote efficient central air conditioners and heat pumps over the past decade. These efforts have focused primarily on promoting the sale and purchase of equipment with high efficiency ratings. Beginning in 1992, the federal government made it illegal for any equipment manufacturer to build a central air conditioner or heat pump with a cooling seasonal energy efficiency ratio (SEER) of less than 10. A number of utilities have sponsored rebate, financing and/or other types of programs to promote the sale and purchase of central air conditioners and heat pumps with even higher SEER ratings. More recently, the U.S. Environmental Protection Agency has begun promoting the sale of equipment with ratings of SEER 12 or higher through its Energy Star program. Many of these programs have been very successful, achieving market shares of 50% for SEER 12 equipment (Neme 1998), roughly three times the national average of 18% in 1997.[4]

Efforts to promote the sale and purchase of high efficiency equipment are undoubtedly saving significant amounts of electricity. However, there is a growing body of evidence that suggests that most equipment -- both standard efficiency and high efficiency -- is improperly installed, with significant adverse effects on how efficiently equipment actually works in the home. Indeed, recent studies suggest that the manner in which equipment is installed may have much

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[1] In 1993, 44.5% of all households in the United States had central air conditioning (ARI 1996, Table 29). This includes homes with heat pumps.

[2] Primary and secondary space heating together accounts for 12.3% of total residential electricity consumption; refrigerators account for 13.9%. (EIA 1995).

[3] Saturation of central air conditioning grew from 26.2% to 44.5% between 1980 and 1993. Much of this increase was due to very high saturations -- nearly 80% in single family homes in recent years -- of central cooling in new construction. (ARI 1996, Tables 25 and 29).

[4] Data on national market shares for equipment rated SEER 12 or higher in 1997 were provided to ACEEE by the Air Conditioning and Refrigeration Institute (ARI). These data include the effects of both utility and non-utility efficiency programs. National market shares would be lower if such programs had not been implemented.

greater impact on actual operating efficiency than whether or not it has a high efficiency rating. Improved installation practices also provide numerous non-energy benefits, including improved comfort in the home, reduced maintenance costs and longer equipment life.

The purpose of this paper is to summarize what is known about key installation problems and, based on studies that have already been conducted, quantify the potential benefits of addressing these problems. The paper addresses four key installation issues -- equipment sizing, refrigerant charging, air flow rates, and duct leakage. It should be noted that the principal focus is on cooling energy savings. To calculate national savings potential, we have simplistically assumed that the heating energy savings from improved installation and maintenance of heat pumps are comparable, in percentage terms, to cooling energy savings. The issue of heat pump heating savings potential deserves further, independent investigation and analysis.

ENERGY SAVINGS POTENTIAL BY MEASURE

Equipment Sizing

One of the most important decisions to make when selling or buying a new central air conditioner or heat pump is the decision about how large the unit should be. There are tradeoffs inherent in this decision. On the one hand, a homeowner wants an air conditioner to keep his or her house cool. All other things being equal, the larger the air conditioner, the more likely it is that it will be able to keep a house at a fixed thermostat setting (e.g., 75 degrees Fahrenheit) under even extremely hot outdoor temperatures. On the other hand, an air conditioner capable of meeting a house's cooling load under the most extreme temperature imaginable will be too big for those days when it is hot, but not record-setting hot. As a result, it will repeatedly turn itself "on" and "off" during most of the summer. As noted in a recent article on air conditioner sizing, "air conditioners are very inefficient when they first start operation." (Proctor et al. 1995) Thus, a very large air conditioner that is constantly turning itself "on" and "off" will operate much less efficiently over the course of the entire summer than a smaller unit that averages longer run times. Larger air conditioners are also more expensive, more prone to maintenance problems, shorter lived, noisier, and less effective at removing humidity.

The Air Conditioning Contractors of America (ACCA) and the Air-Conditioning and Refrigeration Institute (ARI) jointly developed guidelines to help contractors strike the appropriate balance when sizing central air conditioners and heat pumps for single family homes. These guidelines are contained in ACCA's *Manual J* (the load calculation manual) and *Manual S* (the sizing manual). One of the fundamental recommendations is that air conditioners should be sized so that they are capable of keeping the house cooled to 75 degrees Fahrenheit during 97.5% of the hours of the summer (i.e. all but the 73 hottest hours of the summer).

Many observers have long believed that Manual J is very conservative in its estimation of cooling loads and that air conditioners sized using Manual J will actually be able to meet cooling loads for more than 97.5% of summer hours. These beliefs were confirmed by a recent study in Arizona which suggested that air conditioners sized using Manual J are large enough to meet the cooling needs of a home in virtually every hour of the summer (Blasnik et al. 1996). ACCA subsequently acknowledged that Manual J is outdated and leads to oversizing, particularly in newer homes.[5] In fact, ACCA is currently in the process of modifying Manual J so that it better reflects the way newer homes have been built. This updating process is expected to take a few years to complete (EDU 1997).

Despite the significant conservatism already built into Manual J, many contractors routinely size residential air conditioners and heat pumps much larger than it would recommend.[6] Indeed, as Table 1 illustrates, eleven different studies conducted in ten different states or regions of the country suggest that the average central air conditioner or heat pump is oversized by about 50% and nearly one ton of capacity compared to Manual J.

It is not possible to correct equipment sizing problems without replacing the unit. That is extremely expensive and, therefore, never done. As a result, there are relatively few analyses of the energy benefits that could be realized from proper sizing. One study estimates that every 1% reduction in oversizing will produce an average of 0.2% energy savings over the course of the summer, suggesting the energy savings potential for correcting an average oversizing of 50% is approximately 10% (McClain and Goldberg 1984). Others studies that the savings are smaller, more in the range of 2% to 3% (Proctor et al. 1997, Blasnik et al. 1996)

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[5] When asked about the Arizona study results, ACCA Technical Director Hank Rutowski remarked: 'We know that Manual J oversizes'. (EDU 1997)

[6] Note that Manual J recommends that air source heat pumps, like air conditioners, be sized to meet design cooling loads.

Table 1:
Summary of Studies of A/C Oversizing Compared to Manual J Design Loads

Study Author	State	Existing or New Home?	Sample Size	Avg % Oversizing vs. Man J	Avg Tons Oversizing vs. Man J	Notes
Blasnik et al. 1995a	Nevada	New	30	33%		
Blasnik et al. 1996	Arizona	New	22	48%	1.21	
Giolma et al. 1985	Texas	Both	n.a.	64%		Understates oversizing -- compared to peak day, not Manual J
James et al. 1997	Florida	New	368	23%	0.61	
Katz 1997	Carolinas	New	50		0.81	Median rather than mean value
Kemper 1994	Iowa	New	125	56%	0.98	
Lucas 1992	Pacific NW	Existing	60	44%	0.68	Middle of reported oversizing range (some unclear equip sizes)
Neme et al. 1997	Maryland	New	46	59%	1.11	Manual J calculated for average, composite house
Sherman & Hildebrandt 1998	California	Existing	40	16%	0.30	
VEIC & PEG 1997	New Jersey	New	52	60%	1.58	
Xenergy 1998	New Jersey	Existing	45	70%		Manual J inputs from outdoor measurements, customer surveys
Average				47%	0.91	

Air Flow over the Indoor Coil

Air conditioners are almost universally designed to have 400 cubic feet per minute (CFM) of air flowing across the indoor coil for every ton of cooling capacity (e.g., a 3 ton air conditioner should have 1200 CFM of air flow).[7] This air flow is necessary "to achieve a balance between sensible heat transfer and moisture removal." (Parker et al. 1997) If air flow is too high, the ability to remove humidity from the air is compromised; if air flow is too low, the ability to cool the home is compromised because not enough heat transfer is occurring between the air in the duct system and the refrigerator coils. Very low air flow can lead to icing of the coils, refrigerant flood back, and even compressor failure (Parker et al. 1997).

Over the last seven years, at least twelve different studies of air flow have been conducted. As Table 2 shows, every one of these studies found significant air flow problems. The most common problem is inadequate air flow. Seven studies reported (or provided data sufficient to calculate) the percentage of air conditioner or pump systems tested which had air flow rates of less than 350 CFM per ton, the level commonly recognized as the lower limit of acceptability. These seven studies suggest that an average of 70% of all homes have inadequate air flow. The average of the seven average air flow rates reported (or for which data sufficient to calculate average air flow rates was presented) was 327 CFM per ton, or nearly 20% below manufacturer recommended levels. The fact that most of these studies were of newly built homes makes these results particularly disturbing, as average air flow rates are likely to degrade over time due to inadequate maintenance.

One of the effects of improper air flow is a degradation in equipment operating efficiency. In recent years, three laboratory tests have attempted to quantify the magnitude of these efficiency losses, one conducted by the Florida Solar Energy Center (FSEC) and two conducted at Texas A&M University. The FSEC study reported that "the lower evaporator air flow rates observed in (its) field measurements....might produce a 10% increase in residential cooling energy use over what would have been expected based on rated performance." (Parker et al. 1997) The most recent Texas A&M study also suggested that fixed orifice (i.e. capillary tube) type air conditioners, the most common type of central air conditioner installed in the United States, would experience a 10% loss in efficiency at an air flow rate of 320 CFM per ton. One interesting finding in that work was that the loss in efficiency for the much less common thermal expansion valve (TXV) air conditioner was only 2% at 320 CFM per ton.

As Table 2 shows, several other studies have estimated the combined impact of improper air flow and improper refrigerant charge, usually through sophisticated HVAC system

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[7] 400 CFM per ton is the recommended air flow rate over a wet coil (i.e., when the cooling system is operating). That is equivalent to approximately 425 to 450 CFM per ton across a dry coil (Parker et al. 1997).

modelling. These studies suggest that the average efficiency loss due to both of these problems in combination is between 12% and 32%.

TABLE 2

Table 2:
Summary of Studies on Air Flow over A/C Coils and Energy Savings Potential

Study Author	State	Existing or New Home?	Sample Size	Average Airflow	Airflow <350 cfm	Airflow w/in 10% of 400/ton	Energy Savings Potential	Notes
Blasnik et al. 1995a	NV	New	30	345	50%		8%	Est @ 33% combined charge/air flow correction benefits
Blasnik et al. 1995b	CA	New	10	319	90%			
Blasnik et al. 1996	AZ	New	22	344	64%	29%	10%	Est @ 33% combined charge/air flow correction benefits
Hammarlund et al. 1992	CA	New	12			30%	10%	Single family results
Hammarlund et al. 1992	CA	New	66		76%	14%	12%	Multi-family results
Neme et al. 1997	MD	New	25	340				Average for non-participant homes
Palani et al. 1992	n.a.	n.a.	n.a.				4%	Lab test of EER degradation at 25% reduction in air flow
Parker et al. 1997	FL	Both	27	270	89%	7%	10%	Field measuremnts of flow; lab test of effic loss
Proctor & Pernick 1992	CA	Existing	175		44%			Random sample from PG&E Model Energy Communities Prog.
Proctor 1991	CA	Existing	15			33%		Two-thirds had air flow less than 375 cfm/ton dry coil
Proctor et al., 1995	CA	Existing	30	300	80%	11%		SCE Coachella Valley pilot project
Rodriguez et al. 1995	n.a.	n.a.	n.a.				2%	Lab test of TXV; 2% effic. loss at 320 cfm/ton
Rodriguez et al. 1995	n.a.	n.a.	n.a.				10%	Lab test of Orifice unit; 10% loss at 320 cfm/ton
VEIC/PEG 1997	NJ	New	52	372		30%	7%	Est @ 33% combined charge/air flow correction benefits
Average				327	70%	22%	8%	

Improper charge will typically have a greater impact on system efficiency than inadequate air flow. There are several reasons for this. First, both too much and too little refrigerant lower the temperature drop across the coil, increasing distribution losses for a given amount of cooling in the home. This adverse impact is added to the adverse effect of improper charge on the equipment's operating efficiency. Second, in some cases, increasing fan speed is the approach taken to address inadequate air flow. In such cases, the increase in fan energy use can offset some of the efficiency benefits of improved air flow. Finally, although correcting inadequate air flow increases sensible capacity and efficiency, it reduces latent capacity and efficiency. Sensible capacity and efficiency have a greater impact on energy consumption because thermostats respond to temperature, not humidity. However, as sensible capacity is increased through higher air flow, the moisture in the indoor air will also increase (due to reduced latent capacity). This greater humidity will offset some of the increase in sensible capacity created by improved air flow. It is important to note that these effects are not generally captured by lab tests of equipment efficiency. In summary, we estimate that only about one-third of the combined impact of improper charge and improper air flow is attributable to air flow problems. This suggests that the efficiency loss attributable to air flow problems measured in the field is on the order of 7%.

Refrigerant Charge

Most air conditioners and heat pumps are shipped from the factory charged with enough refrigerant for the compressor and a fixed length and diameter (often either 15 feet or 25 feet) of refrigerant line. HVAC contractors installing new systems are required to either add or remove refrigerant, depending on the actual lineset dimensions between the outdoor unit and indoor coil.

Manufacturers are very specific about the amount of refrigerant that their equipment is designed to use. The right amount of refrigerant in the coils, with the right amount of air flow over the coil, is necessary to achieve the appropriate balance between sensible heat transfer (from the air to the coil) and humidity control. Too much refrigerant can cause floodback, slugging, and premature compressor failure. Too little refrigerant will prevent sufficient cooling of the air passing over the coils. Either condition lowers the efficiency of the equipment.

Over the past seven years, at least seven different studies have examined refrigerant charge. As Table 3 shows, every one of these studies found significant deviations from manufacturer recommended levels. In fact, no study found even half of the systems tested to have correct levels (i.e. within 5% of manufacturer recommendations) of refrigerant. On average, the studies found that refrigerant charge was either too low or too high in approximately three-quarters of the central air conditioners and heat pumps tested. There was no consistent pattern regarding the charging problems. Some studies found that the majority of systems were overcharged, some found that the majority were undercharged and some found some balance between overcharging and undercharging.

Table 3:
Summary of Studies on Refrigerant Charge and Energy Savings Potential

Study Author	State	Existing or New Homes?	Sample Size	Charge correct to mfg spec	% over charge	% unde charge	Energy Savings Potential	Notes
Blasnik et al. 1995a	NV	New	30	35%	5%	59%	17%	Est @ 67% combined charge/air flow correction benefits
Blasnik et al. 1995b	CA	New	10				8%	Est @ 67% combined charge/air flow correction benefits
Blasnik et al. 1996	AZ	New	22	18%	4%	78%	21%	Est @ 67% combined charge/air flow correction benefits
Farzad 1993	n.a.	n.a.	n.a.				5%	Lab test of TXV; 8% loss @20% overchg; 2% loss @20% underchg
Farzad 1993	n.a.	n.a.	n.a.				17%	Lab test of Orifice; 13% loss @20% overchg; 21% loss @ 20% underchg
Hammarlund et al. 1992	CA	New	12				12%	Single family results
Hammarlund et al. 1992	CA	New	66	31%	61%	8%	12%	Multi-family results
Katz 1997	NC/SC	New	22	14%	64%	23%		Charge measured in 22 systems in 13 homes
Proctor & Pernick 1992	CA	Existing	175	44%	33%	23%		Results from PG&E Model Energy Communities Program
Proctor 1991	CA	Existing	15	44%				Fresno homes
Proctor et al. 1995	CA	Existing	30	11%	33%	56%		
Proctor et al. 1997a	NJ	New	52				13%	Est @ 67% combined charge/air flow correction benefits
Rodriguez et al. 1995	n.a.	n.a.	n.a.				5%	Lab test of TXV EER; 5% loss at both 20% overchg & 20% underchg
Rodriguez et al. 1995	n.a.	n.a.	n.a.				15%	Lab test of Orifice EER; 7% loss @20% overchg, 22% loss @ 20% underchg
Average				28%	33%	41%	12%	

As was the case with air flow problems, analyses of energy savings potential can be divided into two categories: modeling of impacts and lab tests. In recent years, two lab tests of the effects of refrigerant charge have been conducted at Texas A&M University. The results of both tests are fairly consistent with each other. They suggest an efficiency loss of about 10% for 20% *overcharging* of fixed orifice-type air conditioners, and an efficiency loss of a little more than 20% for 20% *undercharging* of the same equipment. Assuming an equal distribution of overcharging and undercharging, the average efficiency loss due to improper charge of a fixed orifice air conditioner would be on the order of 15%. As was the case with air flow problems, both lab tests also showed that the efficiency of the less common, thermal expansion valve (TXV) type air conditioners is much less sensitive to levels of refrigerant, at least within the parameters tested (i.e. charge within about 30% of manufacturer specified levels). Assuming an equal distribution of 20% overcharged and 20% undercharged systems, the average efficiency loss from improper charge of a TXV system is approximately 5%.

As discussed above, modeling was commonly conducted to determine the combined impacts of the air flow and charging problems found in the field. Assuming that charging problems are roughly responsible for two-thirds of these combined impacts yields an estimated savings potential of about 13%.

Duct Leakage

The effectiveness of a central air conditioner or heat pump in cooling or heating a home is a function of both the efficacy of the equipment itself and the ducts through which cool air is delivered in the summer and warm air is delivered in the winter. The most advanced central air conditioner or heat pump -- even if properly sized and installed with the right amount of air flow and refrigerant -- will not operate efficiently if the duct system is poorly designed and installed.

There are many aspects to good duct design and installation. Perhaps the most commonly studied is duct sealing. As Table 4 shows, there have been at least 19 studies of duct leakage and its effects on electric HVAC efficiency during the past eight years. Every single one of these studies have found significant levels of duct leakage to the outside of the house, with average leakage rates ranging from 193 to 397 cubic feet per minute at 25 Pascals of pressure difference between the inside and outside of the ducts (CFM_{25}). The average of the various study results was 270 CFM_{25}. Interestingly, the studies do not suggest that ducts in new homes are less leaky than ducts in existing homes.

CFM_{25} is commonly used as a metric for duct leakage because the pressures created when the air handler of an air conditioner is "on" are typically close to 25 Pascals. Thus, the duct leakage measured at CFM_{25} is a rough approximation of duct leakage to and from the outdoors when the air conditioning is operating.

Table 4:
Summary of Studies on Duct Leakage Rates and Energy Savings Potential

Study Author	State	Existing or New Homes?	Sample Size	Duct Leakage Outside cfm25	Energy Savings Potential %	Comments
Blasnik et al. 1995a	NV	New	30	253	26%	Savings modelled and include benefits of increasing duct insulation
Blasnik et al. 1995b	CA	New	10	292	25%	Savings modelled and include benefits of increasing duct insulation
Blasnik et al. 1996	AZ	New	22	193	11%	Savings modelled based on reducing leakage to 3% of system air flow
Cummings et al. 1990	FL	Existing	24		18%	Savings measured after duct repair
Hammarlund et al. 1992	CA	New	12		24%	Single family buildings - average of heating (18%) and cooling (30%) savings
Hammarlund et al. 1992	CA	New	66		6%	Multi-family buildings - heating cooling savings both 6%
Jump et al. 1996	CA	Existing	24		18%	Builds on earlier Jump & Modera work
Katz 1997	Carolinas	New	96	360		Not sure if total leakage or leakage to outside
Modera & Jump 1995	CA	Existing	3		19%	Heating savings from sealing and insulating ducts on 3 heat pump systems
Neme et al. 1997	MD	New	25	204	12%	Savings for sealing & insulation, modelled from actual prog performance
Palmiter & Francisco 1994	Northwest	Existing	22	287	16%	cfm50 converted to cfm25, savings from 6 homes w/avg pre-cfm25 of 356
Penn 1993	FL	Existing	10,620		17%	Est. cooling savings reported in Home Energy -- no details on study
Proctor & Pernick 1992	CA	Existing	1,000	246	18%	Savings modelled, model estimates supported by subsequent sub-metering
Proctor 1991	CA	Existing	15	276	18%	Measured cooling savings in 15 Fresno homes
Proctor et al 1995		Existing	30	397		15% savings (best contractor =22%) for multiple measures, incl. duct repair
Proctor et al 1997a	NJ	New	52	299	20%	Savings modelled based on reducing leakage to 3% of system air flow
Siegel et al. 1996	OR	Existing	8	241	16%	results for manuf. homes, cfm50 converted to cfm25, savings are for heating
Treidler & Modera 1996	MD	?	4		9%	Simulations of savings from homes w/ducts in basements
Vigil 1993	NC	Existing	82	188	13%	cfm50 converted to cfm25, savings estimated from 5-home billing analysis
Average				270	17%	

As Table 4 shows, the potential energy savings from sealing ducts are substantial. Most studies suggest savings potential of between 15% and 20%. Recent analysis suggests that some of the older savings estimates may be too high. Nevertheless, it is probably reasonable to assume that savings of 10% in existing homes and 15% in new homes are achievable using the traditional duct sealing technique of hand-applying sealant to seams, holes and other sources of leakage. The savings potential in new homes is higher because some leaks which can be sealed at the time the ducts are being installed will become inaccessible after construction has been completed.

Recent commercialization of a new technology for sealing leaks "from the inside" may offer the potential for even greater savings, particularly in existing homes. The Aeroseal technology blows an aerosol of adhesive particles into the duct system (after registers are sealed and the HVAC equipment is isolated from the duct system). With the ducts under pressure, the adhesive particles are deposited at leakage points in the system, ultimately "closing" holes in the system.[8] This technology appears capable of greater sealing than traditional duct sealing techniques. Indeed, in a field test of 47 homes in Florida the Aeroseal technology sealed approximately 80% of the leakage it encountered (Modera et al. 1996). A subsequent field test on 23 homes in six northeastern and midwestern states produced similar results (Modera et al. 1997).

PEAK DEMAND SAVINGS POTENTIAL BY MEASURE

A recent study suggests that estimating peak demand impacts of efforts to improve cooling efficiency requires analysis of the different ways in which air conditioners are being used at the time of system peak. Virtually every utility will have at least some air conditioners operating in each of the following four "mode of operation" categories (Peterson and Proctor 1998):

1. *Constant Off* -- the air conditioner is off during the peak hour. This may be because a customer is on vacation. Another possible explanation is that a customer left the home immediately prior to the peak hour and turned their thermostats up before leaving.

2. *Cycling* -- the air conditioner is operating during the peak hour, but not continuously. This type of operation is often related to the presence of an oversized air conditioner. Alternatively, a customer could have moved the thermostat setting up immediately prior to the peak hour, but not far enough up to prevent the air conditioner from coming on for at least part of the hour.

3. *Could Cycle* -- the air conditioner is running continuously during the peak hour, but could begin cycling if the cooling load on the house were reduced. The capacity of an air conditioner in this group is fairly closely matched to the demand placed on it by the load on the house and the customer's thermostat setting.[9]

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[8] There is a limit to the size of a hole that the Aeroseal process is capable of sealing. It is generally advisable to seal large leaks (i.e. greater than 3/8 inch across) by hand.

[9] This does not necessarily mean that the air conditioner is properly sized for "design" conditions specified by Manual J.

4. *Continuous On* -- the air conditioner is running continuously during the peak hour and would continue to do so even if cooling loads were reduced significantly. Some air conditioners in this group may be undersized relative to the load on the home at the time of peak. Alternatively, this condition may be caused by a customer decision to turn down the thermostat immediately prior to the peak hour.

The distribution of air conditioners across these four categories will vary from utility to utility, depending on demographics, the time of day at which system peak occurs and other factors. Analysis of data from six different studies suggest that a reasonable assumption of the average national distribution may be as follows (Peterson and Proctor 1998):

Constant Off	15%
Cycling	60%
Could Cycle	5%
Continuous On	20%

Sizing

Downsizing of equipment, like all other efficiency measures, will not produce any peak demand savings from units in the "Constant Off" mode. Small savings from units in "Cycling" mode will result from longer equipment run times. As noted above, this is the most common mode of operation so it is most indicative of the type of savings that will be realized. Substantial peak demand savings -- equal to the reduction in unit kW draw during operation -- will be provided from the last two categories. However, only about 25% of all households fall into these two categories. On average, proper sizing will provide moderate levels of peak demand savings.

Air Flow

Increasing air flow to levels recommended by manufacturers will also not provide any peak demand savings from units in the "Constant Off" mode. Small savings will be provided from units in both the "Cycling" and "Could Cycle" modes of operation. Although increasing air flow will increase the watt draw of the fan motor and compressor, it will increase capacity by even more. Thus, increased watt draw will be more than offset by decreased run time, producing small peak demand savings from units that are or could be cycling. In contrast, units that are in "Constant On" mode will, by definition, not be able to offset increased watt-draw with decreased run time. For these units, increasing air flow will actually increase peak hour consumption. On average, increasing system air flow will provide very limited, if any, peak demand savings.

Refrigerant Charge

The peak demand impacts of incorrect charge depend on whether the unit is undercharged or overcharged. The peak impacts of correcting undercharging are similar to those of correcting inadequate air flow. Correcting undercharging increases both watt draw and capacity. However, the capacity increases faster than watt draw. Thus, for units that are cycling or close to cycling, correcting undercharging will provide small peak demand savings; for units that are continuously running, correcting undercharging will actually increase peak demand. On average, correcting undercharging will provide very little, if any, peak demand savings.

In contrast, overcharged units have a high watt draw and a low capacity. When overcharging is corrected, watt draw decreases and capacity increases. This provides moderate peak demand savings both when the unit is cycling and when it is running continuously, though the savings will be a little higher if the unit is already cycling. Thus, correcting overcharging can be expected to provide moderate demand savings on average.

Duct Leakage

Duct sealing reduces cooling load, thereby reducing run time and peak demands from air conditioners that are either already cycling or could be cycling. The reduction in load on a unit that is running continuously will not affect kW draw. Because duct leakage often represents a substantial portion of the cooling load, and most customers' air conditioners are cycling at the time of system peak, duct sealing should provide substantial peak demand savings. Correcting return duct leakage has more dramatic effects on peak draw than on energy use, as the magnitude of return duct leakage is considerably higher near peak draw times.

Summary

Table 5 provides a quick summary of the peak demand effects of each combination of installation efficiency measure and equipment mode of operation at the time of system peak.

Table 5: Peak Impacts by Equipment Operating Mode[10]

Measure	Equipment Operating Mode			
	Constant Off	Cycling	Could Cycle	Constant On
Equipment Downsizing	None	Small	Large	Large
Increase Air Flow	None	Small	Very Small	Negative
Correct Undercharging	None	Small	Very Small	Negative
Correct Overcharging	None	Moderate	Moderate	Moderate
Duct Sealing	None	Large	Moderate	None

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[10] This table is adapted from a similar table presented in Peterson and Proctor, p. 1.262.

CUMULATIVE SAVINGS POTENTIAL

Interactive Effects

Thus far, this paper has examined the savings potential for treating or correcting each of four different installation problem in isolation. These estimates are summarized in Table 6 below.

Table 6:
Summary of Savings Potential
from Four HVAC Installation Measures

Measure	Energy Savings Potential	Peak Demand Savings Potential
Proper Sizing	2% to 10%	Moderate
Ensure Proper Air Flow	7%	Very Small
Proper Charging	13%	Small
Duct Sealing	10% to 15%	Large

It is important to note that the savings estimates for each of the four measures are not additive. There are a number of interactive effects which must be addressed in the development of an estimate of savings for *simultaneously* correcting or treating all four installation problems. The discussion above has alluded to some of these interactions. What follows is a brief summary of some key interactions to consider.

Sizing Interactions

Oversizing often masks a number of other installation problems, particularly improper charge and significant duct leakage. Correctly sizing an air conditioner will make these other installation problems more apparent, particularly when outdoor conditions become severe. This provides a necessary and missing feedback mechanism to the home owner about the performance of their unit.

Downsizing an oversized air conditioner will generally make it easier to obtain proper air flow, though care must be taken to minimize the duct surface area. It also generally decreases duct system efficiency. Other key interactions are largely related to peak demand impacts. As air conditioners are downsized, the fraction of units operating continuously at the time of peak increases and the fraction that are cycling at the time of peak decreases. In general, this will reduce the peak demand benefits of proper charging, ensuring proper air flow, and reducing duct leakage.

Distribution Efficiency Interactions

The distribution efficiency is highly interactive with other installation variables. The primary interaction occurs through the temperature change across the coil. The larger the change across the coil the higher the distribution efficiency, all else being equal.

As noted above, when improper refrigerant charge is corrected, the temperature change across the coil increases. This improves the distribution efficiency at the same time that it improves equipment efficiency.

The savings from duct sealing and correcting inadequate air flow can be interactive in another important way. Because of undersized return ducts, some air conditioners or heat pumps may receive enough air flow over the coil only because the return ducts are leaky. If these ducts are sealed, at least some of the efficiency benefits of reduced leakage may be offset by efficiency losses due to inadequate air flow. In new construction, the answer to such problems is simple: design the duct system so that it has adequate return capacity when the ducts are sealed. However, in existing homes, the options may be more limited if the homeowner is not willing to pay for modifications to the duct system. Where there are single returns, increasing return duct sizes may not be very difficult or expense. In other cases, return duct modifications may be more complex.

Distribution efficiency can also be affected by equipment sizing. Reducing the size of the air conditioner without changing any other variables (total air flow, relative charge, duct leakage, duct area and duct insulation) would reduce the temperature change across the coil and reduce distribution efficiency.

Air Flow and Charging Interactions

Within the range normally found on residential air conditioners, the effects of charge and air flow are mildly dependent on each other. On a TXV unit, for example, the savings associated with correcting a 30% undercharge were approximately 12% when the air flow was correct and 9% when the air flow was low (Proctor 1998).

Cumulative Savings Potential Adjusted for Interactive Effects

At least four studies have attempted to develop estimates of total savings possible from addressing all four installation issues discussed above. These studies suggest that it should be possible to realize average energy savings on the order of 30% to 40%.[11] Estimates of peak demand savings range more widely, from about 15% to 30%.[12]

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[11] One report estimated 30% savings potential (Proctor et al. 1997a). A second estimated 33% to 37% (Proctor et al., 1997b). Both the third (Blasnik et al. 1996) and fourth (Neal 1998) estimated 41%.

[12] One report suggested 13% (Proctor et al., NPCS 1997), a second 14% to 20% (Proctor et al.,

Most of these studies assessed savings potential from equipment installations in new construction. The savings potential from installations in existing homes can be expected to be lower largely because of constraints associated with the existing duct system. For example, it is usually not possible to achieve the same level of duct leakage reductions in existing homes because portions of the duct system are often inaccessible. It may also be very difficult to obtain the correct level of air flow over the coil. Moreover, even when that is possible, it may require adjustments (e.g. increasing fan speed) which offset some of the energy benefits of improved air flow. The savings possible from addressing installation problems on a retrofit basis will be even lower than those associated with new installations in existing homes. A service technician can do nothing about the size of the air conditioner. Also, typical service calls do not allow the time required to properly seal ducts. Table 7 provides an estimate of the cumulative savings potential under the three scenarios discussed here – equipment installations, a comprehensive retrofit, and a service call.

Table 7:
Cumulative Energy and Peak Demand Savings Potential
from Addressing Typical Sizing and Installation Problems

Scenario	Installation Issues Addressed	KWh Savings Potential	System Peak kW Savings Potential[13]
Equipment Installation[14]	Sizing, Charge, Air Flow, and Duct Leakage	24 to 35%	14% to 25%
Comprehensive Retrofit	Charge, Air Flow, and Duct Leakage	24%	14%
Service Call	Charge and Air Flow	17%	7%

One useful way to think about the magnitude of these savings potentials is to compare them to what would be achieved through other efficiency upgrades. For example, as one recently

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PSE&G 1997), and the third 35% (Blasnik et al.). Note that the 35% savings estimate was for a region in which virtually all air conditioners were operating at the time of system peak and the vast majority (85%) were cycling. These usage patterns, which are different from most other utility peak usage patterns which have been analyzed (Peterson and Proctor 1998), are the most conducive to substantial peak demand reductions from improved installation practices.

[13] Peak demand savings potential is estimated assuming a late afternoon or early evening peak (i.e. hour ending 5 pm or hour ending 6 pm).

[14] Equipment installations can be divided into two major categories: installations in existing homes and new construction. The lower end of the savings potenial shown here is for installations in existing homes. The upper end is for new construction.

published paper nicely demonstrates, the energy impacts of improving installation practices can be effectively communicated as external adjustments to SEER ratings (Neal 1998). The energy savings potential estimated in this paper for installations in new homes (the high end of the equipment installation scenario savings range), for example, are comparable to the savings that would be realized from upgrading a SEER 10 piece of equipment to a SEER 15.4.

NATIONAL SAVINGS POTENTIAL

The potential for energy and peak demand savings at the regional and national levels was estimated for the same three scenarios discussed above X a service call scenario, a comprehensive retrofit scenario, and a good installation practices scenario. The service call scenario includes checking and adjusting refrigerant charge and airflow as part of a regular service call. Few technicians currently check and adjust these parameters, but with proper training, procedures and inducements, they could do so. The comprehensive retrofit scenario goes beyond the service call scenario in that it also includes duct sealing. While few HVAC contractors currently do duct sealing, many contractors could be trained to offer these services for which they would charge an additional fee. The good installation practices scenario applies only to new equipment (new construction and replacement) and includes proper equipment sizing in addition to the practices included in the comprehensive retrofit scenario.

To estimate the impacts of these different scenarios, we constructed a simple computer spreadsheet model that uses regional data from the 1990 and 1993 Residential Energy Consumption Survey (RECS) compiled and published by the U.S. Department of Energy's Energy Information Administration (EIA 1993 and EIA 1995).[15] RECS includes air conditioner and heat pump saturation and energy use data for nine different regions of the country. By comparing data from the 1990 and 1993 surveys, annual growth rates in the air conditioner stock can be calculated. Using data on air conditioner and heat pump stock, growth rates, and energy use, our model estimates air conditioner and heat pump energy use in 2010. We chose 2010 as our analysis frame because it is close enough to be of interest to policy-makers and program planners but far enough away that a new installation and maintenance practices initiative could have an impact. Our estimates of 2010 energy use were then calibrated with each other and with EIA’s 1998 Annual Energy Outlook (EIA 1997), which required modest reductions in the growth rates for air conditioners and heat pumps.

The model then estimates energy (kWh) savings in 2010 by multiplying air conditioner and heat pump energy use in 2010 by the average savings achieved by each scenario and by the estimated penetration rate over the 2000-2010 period of good installation and maintenance services. Penetration rates were estimated based on our estimate of what could be achieved by aggressive programs operating throughout the country. Such programs might include contractor training,

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[15] EIA has conducted a 1996 RECS survey but data are still being analyzed and are not yet publicly available yet.

marketing of educational messages to consumers, promotion of effective contractor certification efforts, and/or financial incentives.

For the service call scenario, we estimate that 5% of homes could be served in 2000 and 2001 (a two-year period to allow for program ramp-up), an additional 5% in 2002, etc., leading to 50% cumulative penetration in 2010. For the comprehensive retrofit scenario, we estimate that the training required to build a duct sealing infrastructure will necessitate a longer ramp-up period, resulting in a cumulative penetration rate of 30% by 2010. For the good installation practices scenario, we estimated that programs could serve 5% of units installed in 2000, 10% of units installed in 2001, etc., leading to an average penetration of 30% of units installed throughout the 2000-2010 period (with a lower proportion served in the early years and a higher proportion in the latter years).

National data on the coincident summer peak demand impacts of air conditioning are not readily available. Thus, coincident peak demand impacts were estimated by multiplying regional air conditioning energy use by ratios of air conditioning coincident peak to annual air conditioning energy use. These ratios were developed using RECS and end-use metering data from different regions of the country. For regions where peak demand data were not available, we extrapolated from other regions, adjusting for climatic differences. Due to the fact that coincident peak demand estimates are based on such limited data, our savings estimates should be considered very approximate.

Table 8 summarizes the results of our analysis. Additional details can be found in Appendix A: National Scenario Analyses.

Table 8:
Achievable National Energy and Peak Demand Savings
From Improved HVAC Maintenance and Installation Practices

Scenario	Energy Savings (Terawatt-hours)	Coincident Peak Demand Savings (Gigawatts)
Service Call	17,600	19.6
Comprehensive Retrofit	14,950	39.2
Good Installation Practices	14,510	41.0

It should be noted that these scenarios overlap in part and in part are independent. For example, the service call and retrofit scenarios overlap because the retrofit scenario essentially includes the measures addressed by service calls, though the lower projected penetration rate for the retrofit scenario means that there are unique savings in the service call scenario. Similarly, the retrofit and good installation practices scenarios overlap, in that a portion of the savings from each scenario are included in the other. However, these two scenarios also include unique savings. Thus, programs designed to promote improved practices both at the time of new installations and during maintenance or retrofit applications could produce savings larger than estimated for any one scenario, but less than the sum of the savings estimated each scenario.

It should also be noted that the above figures represent an estimate of the achievable conservation potential from these programs. The technical savings potential, which is based on 100% penetration of all measures, will be two to three times greater than the achievable savings potential, depending on the scenario.[16]

ENVIRONMENTAL BENEFITS

Fossil fuel combustion associated with electricity production is widely recognized as one of the leading contributors to several major environmental problems. Thus, end-use efficiency improvements resulting from improved HVAC maintenance and installation practices will improve environmental conditions.

We have attempted to quantify several of the key environmental benefits, focusing on the impacts on air emissions of carbon dioxide, sulfur dioxide and nitrogen oxides. Carbon dioxide emissions are critically important contributor to global warming, sulfur dioxide is the major contributor to acid rain and nitrogen oxides are contributors to both acid rain and ground-level ozone (commonly known as smog). National reductions in the emissions of these pollutants that would result from improved HVAC maintenance and installation practices were calculated based on kWh savings from each of the three scenarios discussed above and emissions/kWh ratios for the three pollutants. These ratios were derived from EIA=s 1998 Annual Energy Outlook (EIA 1997). The results are presented in Table 9.

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[16] Specifically, the technical savings potential for 2010 is 35,300 GWh, 51,900 GWh, and 62,700 GWh for the service call, retrofit, and good installation practices scenarios respectively.

Table 9:
U.S. Emission Reductions from Improved HVAC Maintenance & Installation Practices[17]

Scenario	CO_2 Emissions Reductions (Million Metric Tons)	SO_2 Emission Reductions (Ktons)	NO_x Emission Reductions (Ktons)
Service Call	14.1	54	34
Comprehensive Retrofit	12.0	45	29
Good Installation Practices	11.6	44	28

CONCLUSIONS

Numerous studies from across the country conclusively demonstrate that most HVAC systems are sized and installed incorrectly. The potential benefits of improved HVAC maintenance and installation practices are substantial. For example, the average energy savings from improved service calls – 17% -- are as great as the savings from upgrading equipment efficiency ratings from the minimum level required by federal law (SEER 10) to levels promoted by EPA's Energy Star program and numerous utilities (SEER 12). Savings potential for improved installations in new construction – 35% -- are roughly twice what would be achieved from such equipment efficiency improvements. Moreover, although not discussed in detail here, there are substantial non-energy benefits associated with improved HVAC equipment maintenance and installation practices. These include improved comfort, quieter system operation, lower equipment maintenance costs and longer equipment life.

Unfortunately, the barriers to improving HVAC maintenance and installation practices also appear to be substantial. Thus, the challenge facing government, utilities, efficiency advocates, leaders in the HVAC industry and others interested in this issue is to devise strategies that enable both consumers and HVAC contractors to benefit from improving practices. An effective strategy will require a long term, concerted effort that builds on the successes of recent pilot studies.

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[17] Reductions are based on projected 2010 emissions of 0.218 million metric tons (MMT) of carbon per TWh (0.8 MMT of CO_2 per TWh), 3.03 thousand tons of SO_2/TWh and 1.94 thousand tons of Nox/TWh. These figures are based on the simplifying assumption that energy savings will displace coal, gas and oil generation in proportion to their projected contribution to the national 2010 generating mix (EIA 1997).

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National Analysis of Potential Energy and Coincident Peak Demand Savings from Improved Air Conditioner and Heat Pump Maintenance & Installation Practices

Service Call Scenario (includes proper charge and flow)

Region	1993 A/C Stock (millions)	1993 HP Stock (millions)	Annual Growth Rate	Average kWh/Unit		2010 Elec. Use (GWh)	Average Elec. Savings	Penetration by 2010	2010 Savings (GWH)	Ratio Summer Peak Use to Avg. Use	~Peak Demand in 2010 Due to A/C (MW)	Average Peak Demand Savings	Summer Coincident Peak Savings (MW)
				- Cooling	- Heating								
New England	0.6	0.2	4.4%	1658	4970	3,600	17%	50%	310	0.00163	5,900	7%	410
Middle Atlantic	3.2	0.4	4.4%	1555	5272	15,000	17%	50%	1,280	0.00174	26,100	7%	1,830
Great Lakes Region	6.7	0.5	3.4%	1456	6903	23,000	17%	50%	1,960	0.00185	42,600	7%	2,980
Northern Plains	3.8	0.4	3.4%	1594	5894	14,700	17%	50%	1,250	0.00169	24,900	7%	1,740
South Atlantic	11.1	2.6	3.2%	2708	3171	65,000	17%	50%	5,530	0.00125	81,000	7%	5,670
Tennessee Valley	3.4	0.8	3.2%	2923	5197	23,400	17%	50%	1,990	0.00115	27,000	7%	1,890
South Central	6.9	1.0	3.2%	3454	3789	46,900	17%	50%	3,990	0.00098	45,800	7%	3,210
Mountain	1.7	0.4	1.0%	1964	3662	5,800	17%	50%	490	0.00138	8,000	7%	560
Pacific	3.5	1.3	1.0%	1070	3823	10,100	17%	50%	860	0.00187	18,900	7%	1,320
TOTAL	40.9	7.5				207,500			17,660		280,200		19,600

Retrofit Scenario (includes proper charge and flow as well as duct sealing)

Region	1993 A/C Stock (millions)	1993 HP Stock (millions)	Annual Growth Rate	Average kWh/Unit		2010 Elec. Use (GWh)	Average Elec. Savings	Penetration by 2010	2010 Savings (TWh)	Ratio Summer Peak Use to Avg. Use	~Peak Demand in 2010 Due to A/C (MW)	Average Peak Demand Savings	Summer Coincident Peak Savings (MW)
				- Cooling	- Heating								
New England	0.6	0.2	4.4%	1658	4970	3,600	24%	30%	260	0.00163	5,900	14%	830
Middle Atlantic	3.2	0.4	4.4%	1555	5272	15,000	24%	30%	1,080	0.00174	26,100	14%	3,650
Great Lakes Region	6.7	0.5	3.4%	1456	6903	23,000	24%	30%	1,660	0.00185	42,600	14%	5,960
Northern Plains	3.8	0.4	3.4%	1594	5894	14,700	24%	30%	1,060	0.00169	24,900	14%	3,490
South Atlantic	11.1	2.6	3.2%	2708	3171	65,000	24%	30%	4,680	0.00125	81,000	14%	11,340
Tennessee Valley	3.4	0.8	3.2%	2923	5197	23,400	24%	30%	1,680	0.00115	27,000	14%	3,780
South Central	6.9	1.0	3.2%	3454	3789	46,900	24%	30%	3,380	0.00098	45,800	14%	6,410
Mountain	1.7	0.4	1.0%	1964	3662	5,800	24%	30%	420	0.00138	8,000	14%	1,120
Pacific	3.5	1.3	1.0%	1070	3823	10,100	24%	30%	730	0.00187	18,900	14%	2,650
TOTAL	40.9	7.5				207,500			14,950		280,200		39,200

National Analysis of Potential Energy and Coincident Peak Demand Savings from Improved Air Conditioner and Heat Pump Maintenance & Installation Practices

Good Installation Scenario (includes proper charge and airflow, duct sealing and proper sizing)

Region	Annual Sales		Average kWh/Unit		Elec. Use in 2010 of units installed 2000-2010 (GWh)	Average Elec. Savings	Penetration by 2010	2010 Savings (GWH)	Ratio Summer Peak Use to Avg. Use	~Peak Demand in 2010 Due to A/C (MW)	Average Peak Demand Savings	Summer Coincident Peak Savings (MW)
	A/C (1000s)	HP (1000s)	- Cooling	- Heating								
New Construction												
New England	19	5	1658	4970	600	35%	30%	60	0.00163	1,000	25%	250
Middle Atlantic	99	13	1555	5272	2,500	35%	30%	260	0.00174	4,300	25%	1,080
Great Lakes Region	168	13	1456	6903	3,700	35%	30%	390	0.00185	6,900	25%	1,730
Northern Plains	95	10	1594	5894	2,300	35%	30%	240	0.00169	3,900	25%	980
South Atlantic	358	188	2708	3171	17,200	35%	30%	1,810	0.00125	21,400	25%	5,350
Tennessee Valley	110	54	2923	5197	6,600	35%	30%	690	0.00115	7,600	25%	1,900
South Central	222	73	3454	3789	11,500	35%	30%	1,210	0.00098	11,200	25%	2,800
Mountain	53	11	1964	3662	1,600	35%	30%	170	0.00138	2,200	25%	550
Pacific	108	32	1070	3823	2,600	35%	30%	270	0.00187	4,900	25%	1,230
Sub-Total	1232	399			48,600			5,100		63,400		15,900
Existing Homes												
New England	67	21	1658	4970	2,400	24%	30%	170	0.00163	3,900	14%	550
Middle Atlantic	358	60	1555	5272	9,600	24%	30%	690	0.00174	16,700	14%	2,340
Great Lakes Region	698	63	1456	6903	16,000	24%	30%	1,150	0.00185	29,700	14%	4,160
Northern Plains	396	51	1594	5894	10,300	24%	30%	740	0.00169	17,400	14%	2,440
South Atlantic	1046	215	2708	3171	38,600	24%	30%	2,780	0.00125	48,100	14%	6,730
Tennessee Valley	320	62	2923	5197	13,800	24%	30%	990	0.00115	15,900	14%	2,230
South Central	650	84	3454	3789	28,200	24%	30%	2,030	0.00098	27,600	14%	3,860
Mountain	115	40	1964	3662	4,100	24%	30%	300	0.00138	5,600	14%	780
Pacific	236	120	1070	3823	7,800	24%	30%	560	0.00187	14,600	14%	2,040
Sub-Total	3886	715			130,800			9,410		179,500		25,100
TOTAL	5,118	1,114			179,400			14,510		242,900		41,000