Ducts in the Attic? What Were They Thinking?

Dave Roberts and Jon Winkler, National Renewable Energy Laboratory[1]

ABSTRACT

As energy-efficiency efforts focus increasingly on existing homes, we scratch our heads about construction decisions made 30, 40, 50-years ago and ask: "What were they thinking?" A logical follow-on question is: "What will folks think in 2050 about the homes we're building today?" This question can lead to a lively discussion, but the current practice that we find most alarming is placing ducts in the attic.

In this paper, we explore through literature and analysis the impact duct location has on cooling load, peak demand, and energy cost in hot climates. For a typical new home in these climates, we estimate that locating ducts in attics rather than inside conditioned space increases the cooling load 0.5 to 1 ton, increases cooling costs 15% and increases demand by 0.75 kW. The aggregate demand to service duct loss in homes built in Houston, Las Vegas, and Phoenix during the period 2000 through 2009 is estimated to be 700 MW.

We present options for building homes with ducts in conditioned space and demonstrate that these options compare favorably with other common approaches to achieving electricity peak demand and consumption savings in homes.

Background

Heat exchangers are designed to transfer as much heat as possible from one fluid to another. The heat exchanger we commonly find in a solar storage tank is an immersed coiled tube; we move solar heated water through the tube and it heats the water in the tank. In a good solar storage system, we place the coil at the bottom of the tank and strive for temperature stratification in the tank so we bring the hottest water in the system (from the collectors) in contact with the coldest water in the system (from the cold-water mains, settled at the bottom of the storage tank).

This is oddly similar to the configuration we see in many homes being built in cooling-dominated climates – we place tubes (with hundreds of square feet of surface area) carrying the coldest fluid in the system (55°F air leaving the air-conditioning unit) immersed in the hottest fluid in the system (150°F attic air). The only difference is, in this system we ***don't*** want heat exchange. Heat exchange is a bad thing because we don't need to cool the attic air (it's outside our enclosure) and we certainly don't want to heat the air we just paid the electric utility to cool. So, to overcome this serious design flaw we create energy codes that require us to put some goop on joints and wrap an inch or so of insulation around the tubes. Feels a bit like bubble gum and a

---

[1] **Authorization for Alliance employees only**

The Alliance for Sustainable Energy, LLC (Alliance) is the manager and operator of the National Renewable Energy Laboratory (NREL).

bandage – MacGyver would be proud. In fact it reminds us of some of the old homes we see where someone stuffed wadded-up newspapers into the walls or poured sawdust on the attic floor in an attempt to improve on construction practices of the time. You can almost hear the old-timer as he's working to "fix" things – "What the heck were they thinking Myrtle?"

Figure 1. Ducts in an Unconditioned, Vented Attic

Source: ducts.lbl.gov. Used by permission of LBL.

We know placing ducts in a vented, unconditioned attic is a bad idea because we've modeled it (Siegel, Walker & Sherman 2000; Walker 2001; Hendron et al. 2002; Hedrick 2003b; Kinney 2005). We know it's a bad idea because we've measured it (Jump, Walker & Modera 1996; Hedrick 2003a). In fact, we know even when it is done pretty well (which is rare), it reduces system efficiency by about 20% – not a trivial number. People spend big bucks trying to save 20%. Or even bigger bucks to produce that amount of electricity with sexy solar panels. And the worst part is that it's a pretty permanent situation. Fifty years from now, after we've evolved to the point where we agree this is a bad idea, it will be really hard to change things. It's kind of like figuring out how to go back and insulate walls in millions of homes built in the first half of the 20th century. Actually, it's worse than that.

And here's what's really strange. Electric utilities hand out money for things that have far less impact. They might give you $500 to upgrade to a SEER 15 air conditioner because it's cheaper than building a new power plant. We'll take it! Then we'll take our fancy SEER 15 air conditioner (which will probably last 15 years or so and is really easy to upgrade) and hook it up to a lousy delivery system (which will likely be around for 100 years and is really hard to improve), effectively turning it into a SEER 12 unit (Neal 1998).

Most of us agree it's better and cheaper to reduce demand than to increase supply. So let's see what it saves, what it's worth, and what it costs to move ducts inside the building enclosure, and compare that to other popular efficiency measures that electric utilities commonly pay for.

What It Saves

Savings Reported from Previous Studies and Reports

Table 1 provides an overview of the energy, demand, and cost savings estimated from some earlier studies. Long and short of it – ducts in attics are about 80% efficient at best, add ½ to 1 ton to the cooling load, and increase peak demand by about 1 kW.

Table 1. Sampling of Measured and Predicted Savings from Previous Studies

Reference	Type	Highlights
Jump, Walker & Modera 1996	Measured	Average distribution system efficiency of 76% after repair in Sacramento, CA.
Siegel, Walker & Sherman 2000	Modeled	Predicts 1.0 kW electric demand savings and 55% daily energy savings when moving typical new duct system from vented attic to cathedralized attic space and reducing A/C sizing in Sacramento, CA.
Walker 2001	Modeled	Shows distribution system efficiencies of ~75% for R-4.2, 10% leakage duct system in attics during cooling season in Sacramento and Phoenix.
Hendron et al. 2002	Modeled	At duct leakage levels allowed under 2009 IECC, modeling indicates about 20% cooling energy savings and 1.0 kW of demand reduction from cathedralizing attic in Las Vegas.
Hedrick 2003a	Measured	Measured duct leakage-to-outside averaged 29 cfm25 in 16 CA homes with ducts inside conditioned space – some using drop ceilings, some with cathedralized attics – a fraction of the leakage allowed by code and commonly found in new homes with ducts in the attic.
Hedrick 2003b	Modeled	California statewide average energy savings for a 2-story, single-family home is predicted to be 3,400 kWh/year from moving ducts inside conditioned space. Associated predicted demand savings ranged from 0.8 to 3.3 kW, depending on climate.
Kinney 2005	Modeled	Predicts about \$220 to \$240 in annual energy cost savings when reducing duct leakage to outside from 30% to 4% and reducing conductive losses using R-30 insulation (essentially moving ducts inside conditioned space) in Phoenix and Las Vegas.

Our Analysis

We looked at three cooling-dominated climates (Houston, Phoenix, and Las Vegas) where standard construction practice is to place ducts in the attic. In the first part of the analysis we used ASHRAE Standard 152-2004 (ASHRAE 2004) calculation procedures to estimate the energy penalty associated with locating the ducts in the attic. We then used an annual building simulation tool (BEopt 0.9 software[2]) to estimate the annual energy savings and peak demand reduction associated with relocating the ducts to conditioned space.

---

[2] The BEopt software tool was developed at NREL to identify optimal building energy designs aimed at minimizing the total of the amortized cost of improvements and the cost of energy. It produces designs that minimize combined construction and energy costs by using the DOE-2.2 and TRNSYS energy simulation programs to automate a sequential search technique for locating least-cost solutions on a path toward net zero energy. The software and underlying methodology are described in detail by Christensen et al. (2005, 2006) and Horowitz et al. (2008).

The prototypical house used in our analysis is a 2-story, 2500 sq. ft., slab-on-grade home with R-13 walls, R-30 vented attic, and 0.3 solar heat gain coefficient (SHGC) windows. The house has a SEER 13 air-conditioner, gas furnace, complies with ASHRAE Standard 62.2 for ventilation requirements, and is assumed to be fairly tight with a 0.0003 specific leakage area (SLA). The ducts are located in the vented[3] attic and assumed to be well insulated and well sealed with R-8 insulation and 5.5% leakage on the supply side and 4.5% leakage on the return side. This duct system, characterized in the BEopt software as "tight," can be considered pretty well constructed, exceeding the minimum requirements of the 2009 IECC.

ASHRAE Standard 152-2004 establishes a methodology for calculating the distribution system efficiency (DSE)[4] of a ducted system. We used appropriate cooling system capacities and air flow rates for our example home and Standard 152 procedures to calculate DSEs for the three locations. The results are shown in Table 2.

Table 2. ASHRAE Standard 152 Calculated Distribution System Efficiency

	Houston	**Phoenix**	**Las Vegas**
Equipment Cooling Capacity (kBtu/hr)	36.0	48.0	42.0
Cooling Fan Flow (cfm)	1200	1600	1400
Cooling Supply Duct Leakage (cfm)	66	88	77
Cooling Return Duct Leakage (cfm)	54	72	63
Cooling Design DSE	71%	72%	73%
Cooing Seasonal DSE	79%	82%	81%

The average DSE for the three locations on the design day, which would be considered the day of the season when cooling demand is highest, is 72%. This means that on the hottest day of the summer, 28% of the air-conditioner output is ultimately lost. Over the entire cooling season the average loss in cooling capacity is 20%. So in a climate where the air-conditioner is likely used for eight to nine months of the year, 20% of the cooling produced by the air-conditioner is simply thrown away by the distribution system.

The obvious alternative is to place the ducts in conditioned space. Here, most of the air leakage and thermal losses of the distribution system would go into cooling the living space. The end result is that the cooling system design load, energy consumption, and peak demand imposed on the utility are reduced.

To estimate reductions in annual cooling energy usage, peak load, and peak demand, BEopt 0.9 software was used to simulate the prototype house over the course of an entire year, in the three climates previously mentioned, with the ducts first located in the attic and then moved to the living space. In BEopt, ducts in living space are assumed to have a DSE of 100% (an admittedly optimistic assumption and difficult to achieve in practice). Table 3 shows the percent reduction from the baseline case (ducts in the attic) to the case with the ducts located in conditioned space.

---

[3] Attic vent area set to 1 sq. ft. per 300 sq. ft. of attic floor area.

[4] Modera (1993) provides a pretty clear definition of DSE: *the ratio of the energy that would be consumed by a house using a given piece of heating or cooling equipment, to the energy consumed by that house with the thermal distribution system connected to that same piece of equipment.*

Table 3. Savings Due to Moving Ducts Inside Living Space

	Houston	Phoenix	Las Vegas
Reduction in Required A/C Capacity	24%	24%	23%
Reduction in Annual Cooling Electricity Usage	17%	16%	14%
Reduction in Peak Cooling Demand	22%	23%	22%

Let's take a closer look at what these savings mean. On average (for this particular home), the cooling system can be reduced by nearly 0.8 tons of capacity. The capital cost savings associated with this capacity reduction will be realized every time the air-conditioning unit is replaced, (about every 15 years), because the ductwork will be used for the life of the home. According to the Energy Information Agency, the average price of electricity in these three cities during 2009 was 12.13 ¢/kWh (EIA 2009), meaning on average the homeowner would save more than $80 per year to cool their home. (This does not include additional savings attributed to heating the home during the winter.) The peak demand placed on the utility, which occurs on the hottest day of the year, is also reduced on average by more than 0.75 kW. These savings ultimately reduce the need to construct additional generation and distribution capacity as new homes are added to the utility system. Time-of-use rates, likely to become more common with the advent of smart grid technologies, will increase the cost of running air-conditioning units during periods of peak demand, further bolstering our case for moving ducts out of the attic.

What It Costs

There are several approaches to building homes in cooling-dominated climates with ducts located inside the enclosure: (1) cathedralizing the attic – moving the thermal and air barrier from the attic floor to the roof deck; (2) using drop ceilings and soffits below the attic floor; (3) in 2-story homes, using the space between floors; and (4) using a scissor-truss to create a plenum below the attic and above the living space. The fourth approach is not widely used. The first three have been used by quite a few builders so there is a fair bit of cost data in the literature. Ultimately, the best approach, and associated cost, will depend on each builder's current construction practices.

Figure 2. Schematics of Four Approaches to Moving Ducts Inside Conditioned Space

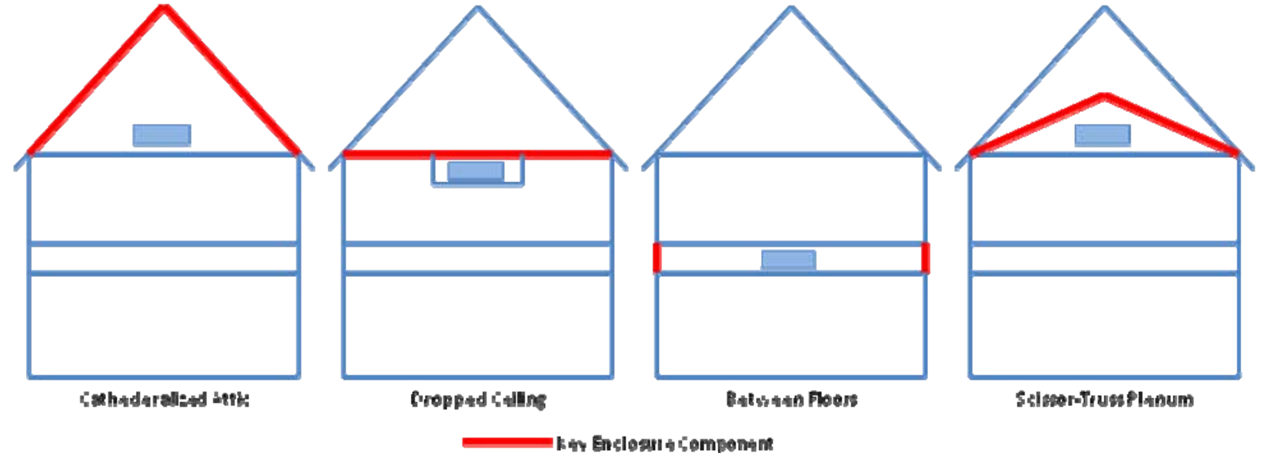


Figure 3. Examples of Dropped Ceiling and Between Floor Locations during Construction


Dropped Ceiling

Between Floors

Source: Janet Mcilvane, FSEC (left) (used by permission of FSEC) and IBACOS, Inc. (right) (NREL PIX 14234).

Kerr (2008) provides an overview of an approach taken by two production builders in the Northwest. Both used space between the first and second floors (one used open-web trusses) and added furnace closets to get the air handler into conditioned space. The estimated cost to make the change was $500.

Lubliner et al. (2008) report stipulated costs of $650 for utility programs in the Northwest developing demand-side programs that encourage relocation of the duct system to the conditioned space. They state that one production builder in the Northwest added $675 to the price of its homes to cover this cost.

Hedrick (2003b) estimated additional construction costs for approaches 1, 2, and 4 using three methods of estimation for various house sizes. Cost estimates for approach 4, the plenum truss, were quite high, approaching $4000. The costs for approaches 1 and 2, however, ranged from $800 downward to a ***saving*** of $800 for single-family homes. This did not include the savings from downsizing the air conditioner, furnace and air-handling unit, which were estimated to be $1100 to drop from a 4-ton to a 3.5-ton unit or from a 3.5-ton unit to a 3-ton unit.

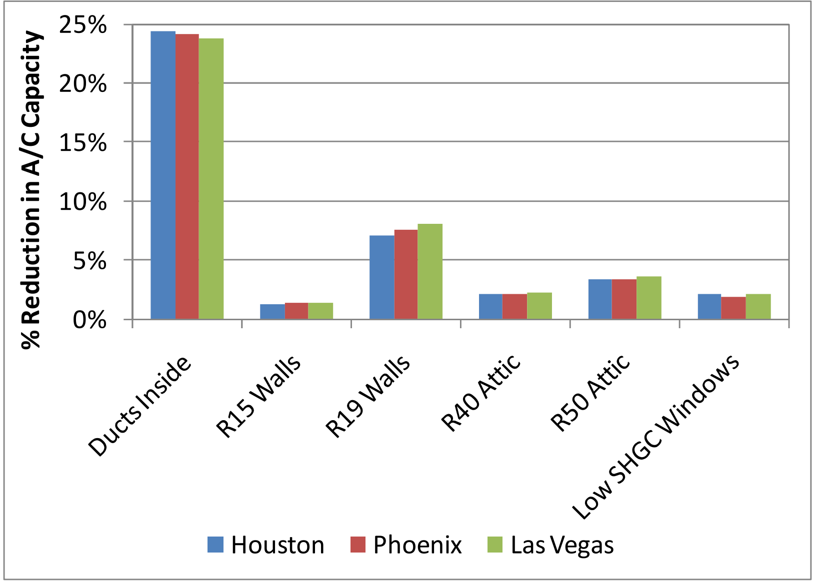
DOE (2010) reports that Tommy Williams Homes in Gainesville, Florida used ducts in conditioned space to meet the Builders Challenge program requirements and produce a net-zero energy home. Ken Fonorrow (2010), the builder’s home energy rater, reports the estimated additional cost to move the ducts into dropped ceilings is $800, not including savings associated with downsizing the air-conditioner.

How It Compares

The easiest way to put the savings attributed to relocating ducts to conditioned space into perspective is to compare it to other energy efficiency upgrades (most of which are often given more attention in energy codes and utility programs than the relocation of ductwork). We used BEopt to compare moving the ducts into the conditioned space to upgrading the wall R-value, upgrading the attic floor R-value, using low SHGC windows, and installing a higher SEER air-conditioner.

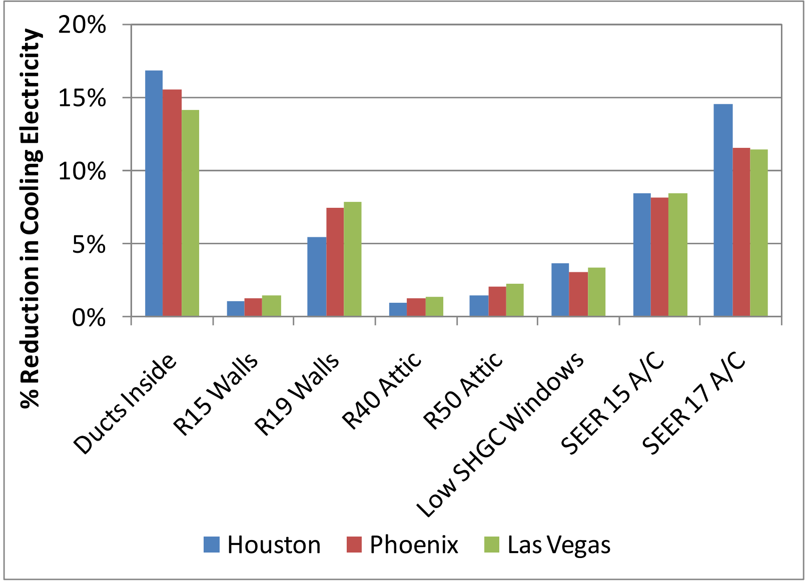
Of the energy efficiency upgrades included in the analysis, moving the ducts into conditioned space led to the most significant reduction in the required air-conditioner capacity. Incrementally enhancing the building envelope over the prototype home slightly reduces the need for cooling, but not significantly compared to relocating the ducts. Upgrading the SEER rating of the air-conditioner does nothing to dramatically influence the air-conditioner capacity and only decreases the amount of energy required to provide a certain amount of cooling, thus the effect of SEER was not included in Figure 4.

Figure 4. Reduction in Required Cooling Capacity for Various Efficiency Upgrades



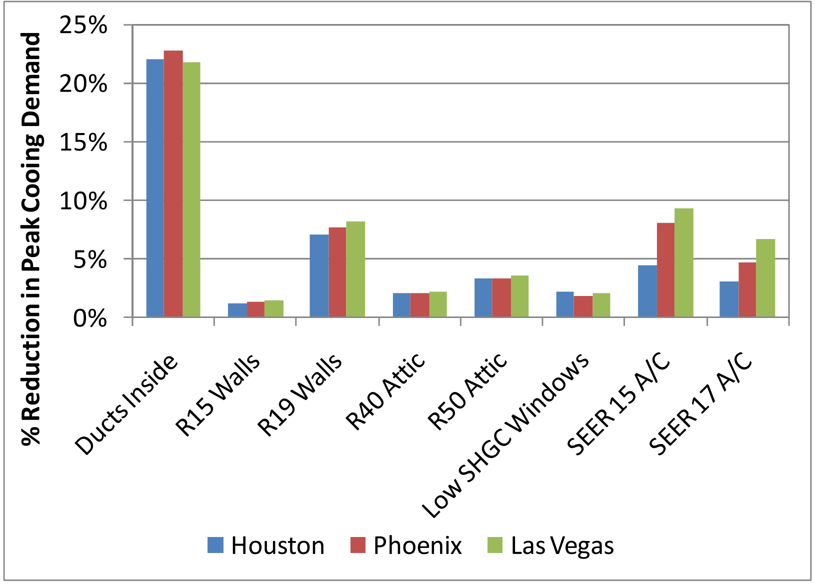
In terms of the amount of electricity required to cool the home over the course of the year, relocating the ducts slightly out performs upgrading to even a SEER 17 air-conditioner (see Figure 5). However, relocating the ductwork is a one-time expense that is amortized into the cost of the mortgage. The air-conditioning unit, by contrast, is an upgrade that will need to be repurchased. Again, incrementally enhancing the building envelope goes only so far to reduce the energy consumption required to cool the home.

Figure 5. Reduction in Cooling Electricity Usage for Various Efficiency Upgrades



Relocating the ducts to conditioned space reduces peak demand far more than any other energy efficiency upgrade included in the analysis (see Figure 6). The SEER 15 air-conditioner reduces peak demand more than the SEER 17 air-conditioner, which is contrary to expectations, because the SEER 17 unit is a two-speed unit and can operate at low stage to save energy when the cooling load is not as high, the energy efficiency ratio (EER) for the SEER 17 unit at stage 2 cooling is slightly lower than that for the SEER 15 unit. Thus, on the hottest of days the SEER 17 unit will draw more power. Upgrading the attic insulation levels and windows does little to reduce demand. R-19 walls show modest improvement over the R-13 walls.

Figure 6. Reduction in Peak Cooling Demand for Various Efficiency Upgrades

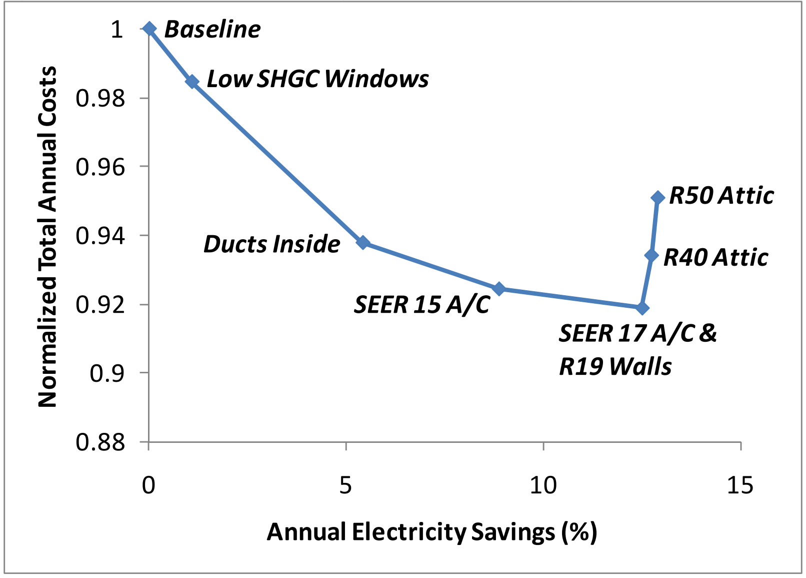


Selecting energy efficiency upgrades should be based not only on the potential savings but on the expected total cost, including the initial capital cost, energy bill savings, and replacement cost after a given number of years. BEopt was selected to perform this analysis, in part, because it is well suited to optimize the order in which these upgrades should be selected. Only the results for Houston are shown in Figure 7, but the results for the other two cities display similar trends. The total normalized cost relative to the baseline is plotted on the y-axis and the annual electricity savings on the x-axis. Total normalized cost includes the amortized incremental capital cost of the energy efficiency measure, including replacements during the 30-year mortgage, and the associated energy cost savings. Values less than 1.0 indicate energy cost savings are greater than the incremental mortgage and replacement costs.

The first selected energy efficiency measure is upgrading to low SHGC windows, because this option has the most negative slope relative the baseline point. However, the annual energy savings are minimal (1%). Moving the ducts inside is the next preferred option. The percent energy savings per unit cost are slightly higher than upgrading windows, but moving the ducts has the most dramatic effect on annual energy savings. The next preferred option is to upgrade to a more efficient SEER 15 air-conditioner. As can be expected, the electric consumption is most cost-effectively lowered by moving the ducts inside and upgrading the windows before upgrading the air-conditioner.

The final three points deal with wall and attic insulation levels. R-15 walls do not show as a preferred option because of their small incremental benefit over the code R-13 walls and the fact that R-19 walls reduce the framing factor by moving to 2x6 studs spaced 24 inches on center. There is little energy savings associated with higher attic insulation values in these cooling-dominated climates.

Figure 7. Optimized Energy Efficiency Upgrades for Phoenix



A Utility Perspective

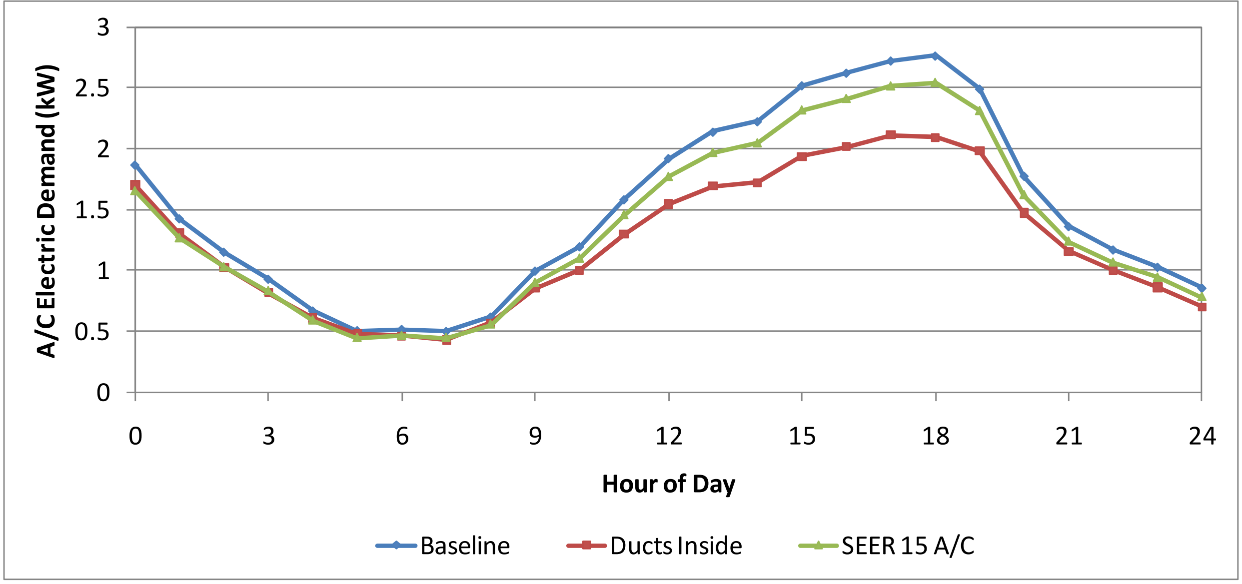
Most electric utilities have programs aimed at reducing system peak demand or overall electrical consumption. The programs generally involve utility investment in energy efficiency measures. In buildings this usually comes in the form of payments for specific technologies (e.g., compact fluorescent lamps) or performance targets (e.g., ENERGY STAR Qualified Home). The size of the payments or rebates is usually based, in part, on the avoided cost to the utility of generating a kilowatt-hour of electrical energy or building the next kilowatt of capacity.

Peak demand for utilities in cooling-dominated climates is generally driven by air-conditioning. Demand-side programs from these utilities tend to target air-conditioning, paying incentives for measures that reduce cooling during periods of system peak. Common measures include low solar heat gain windows, high-efficiency air conditioners, and direct load control. In existing homes, measures might include solar screens, duct insulation and sealing, and air conditioner tune-ups. We could not find any utility that offers direct incentives to design and build homes with ducts in conditioned space.

Our analysis indicates payments to incentivize builders to move ducts out of attics would be a wise investment for utilities in cooling-dominated climates. For example APS, an electric utility serving the Phoenix area, will pay $425 for a SEER 14 air-conditioner (APS 2010). Figure 6 shows moving the ducts inside will save more than twice the peak demand as the air-conditioner, so one might conclude that APS could pay an $800 incentive for a builder to move the ducts. Similarly, CenterPoint and Entergy, two utilities serving the Houston area, will pay $477/kW and $0.16/kWh for duct sealing in existing homes (DSIRE, 2009). Based on our estimates of demand and energy savings for Houston, similar rebates might total $380 for moving a duct system from the attic into conditioned space in new homes. And finally, according to the DSIRE website (2009), NV Energy, which serves the Las Vegas market, was paying $280 to upgrade to a SEER 14, 4-ton air conditioner in 2009. Again, referring to the results in Figure 6, one might conclude that a $500 rebate for homebuilders would be appropriate for moving the ducts.

The BEopt simulations results in Figure 8 emphasize the impact of shaving peak demand. The high demand associated with air-conditioning generally occurs over the span of only a few hours in the evening. The additional capacity required by the electric utility to meet the peak cooling demand is being fully utilized for several hours of the day on the hottest days of the year. Thus, the demand offset by relocating the ducts to conditioned space in new construction will ultimately reduce the need for additional installed capacity and improve the load factor for the electric utility.

Figure 8. Cooling Demand Profile during Day of Peak Demand for Houston



The accumulation of potential savings is startling. According to the U.S. Census Bureau (2010), approximately 930,000 single-family homes were built between 2000 and 2009 in the combined markets of Houston, Phoenix, and Las Vegas. Assuming all these homes were constructed with ductwork in the attic, and using our savings estimate of 0.75 kW per home, nearly 700 MW of new installed capacity could have been avoided if all these homes had been built with ducts inside conditioned space.

Summary

Building a home in a hot climate with ducts located in the attic is a bad idea. Moving the ducts inside the thermal enclosure during construction is relative inexpensive and will reduce electric consumption for cooling about 15%, will reduce demand by about 0.75 kW, and will reduce needed cooling capacity by 0.5 to 1 tons. Spending money to move the ducts inside is a better investment than other commonly incented energy efficiency measures.

References

[APS] Arizona Public Service. 2010. **APS Green Choice Residential AC Rebate Program** http://www.aps.com/main/green/choice/choice_3.html?source=prgj. Phoenix, Ariz.: Arizona Public Service.

[ASHRAE] American Society of Heating, Refrigerating, and Air-Conditioning Engineers. 2004. **Standard 152-2004 -- Method of Test for Determining the Design and Seasonal Efficiencies of Residential Thermal Distribution Systems (ANSI Approved).** Atlanta, Ga.: American Society of Heating, Refrigerating, and Air-Conditioning Engineers.

CenterPoint Energy. 2010. **Residential Standard Offer Program.** http://www.centerpointenergy.com/services/electricity/residential/energyefficiencyprograms/residentialstandardoffer/. Houston, Tex.: CenterPoint Energy, Inc.

Christensen, C., S. Horowitz, T. Givler, A. Courtney, and G. Barker. 2005. **BEopt: Software for Identifying Optimal Building Designs on the Path to Zero Net Energy**. Golden, Colo.: National Renewable Energy Laboratory, NREL/CP-550-37733.

Christensen, C. R. Anderson, S. Horowitz, A. Courtney, and J. Spencer. 2006. **BEopt Software for Building Energy Optimization: Features and Capabilities.** Golden, Colo.: National Renewable Energy Laboratory, NREL/TP-550-39929.

[DOE] Department of Energy. 2010. Tommy Williams Homes Zero Energy Home Longleaf. Washington D.C.: U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Building Technology Program.

[DSIRE] **Database of State Incentives for Renewables & Efficiency.** 2009. www.dsireusa.org. Raleigh, N.C.: N.C. Solar Center / N.C. State University / College of Engineering.

[EIA] Energy Information Administration. 2009. **Average Retail Price of Electricity to Ultimate Customers by End-Use Sector, by State**. http://www.eia.doe.gov/cneaf/electricity/epm/table5_6_b.html. Washington D.C.: U.S. Energy Information Administration.

Fonorow, Ken (Florida HERO). 2010. Personal communication. March 1.

Hedrick, R. 2003a. **Residential Duct Placement Field Test and Research Reports**. Sacramento, Calif.: California Energy Commission 500-03-082-A-29.

Hedrick, R. 2003b. **Costs & Savings for Houses Built With Ducts In Conditioned Space: Technical Information Report**. Sacramento, Calif.: California Energy Commission 500-03-082-A-31.

Hendron, R., R. Anderson, P. Reeves, & E. Hancock. 2002. **Thermal Performance of Unvented Attics in Hot-Dry Climates**. Golden, Colo.: National Renewable Energy Laboratory, NREL/TP-550-30839.

Horowitz, S. C. Christensen, M. Brandemuehl, and M. Krarti. 2008. **Enhanced Sequential Search Methodology for Identifying Cost-Optimal Building Pathways**. Golden, Colo.: National Renewable Energy Laboratory, NREL/CP-550-43238.

[ICC] International Code Council. 2009. **International Energy Conservation Code**. Country Club Hills, Ill.: International Code Council, Inc.

Jump, D., I. Walker, and M. Modera. 1996. "**Field Measurements of Efficiency and Duct Retrofit Effectiveness in Residential Forced Air Distribution Systems**." In *Proceedings of the ACEEE 1996 Summer Study on Energy Efficiency in Buildings*, 1.147-1.155. Washington, D.C.: American Council for an Energy Efficient Economy.

Kerr, R. 2008. "**Green Production Building—Moving Ducts Inside**." In *Home Energy* May/June 2008. Berkeley, Calif.: Home Energy Magazine.

Neal, L. 1998. "**Field Adjusted SEER [SEERFA]. Residential Buildings: Technologies, Design, and Performance Analysis**." In *Proceedings of the ACEEE 1998 Summer Study on Energy Efficiency in Buildings*, 1.197-1.209. Washington, D.C.: American Council for an Energy Efficient Economy.

Lubliner, M., R. Kerr, A. Gordon, and C. Murray. 2008. "**Moving Ducts Inside: Big Builders, Scientists Find Common Ground**." In *Proceedings of the ACEEE 2008 Summer Study on Energy Efficiency in Buildings*, 1.152-1.163. Washington, D.C.: American Council for an Energy Efficient Economy.

Modera, M. 1993. "**One Size Fits All: A Thermal Distribution Efficiency Standard**." In *Home Energy* September/October 1993. Berkeley, Calif.: Home Energy Magazine.

Kinney, L. 2005. **Duct Systems in Southwestern Homes: Problems and Opportunities.** Boulder, Colo.: Southwest Energy Efficiency Project.

Siegel, J., I. Walker, and M. Sherman. 2000. "**Delivering Tons to the Register: Energy Efficient Design and Operation of Residential Cooling Systems**." In *Proceedings of the 2000 ACEEE Summer Study on Energy Efficiency in Buildings*, 1 295-306. Washington, D.C.: American Council for an Energy Efficient Economy.

U.S. Census Bureau. 2010. **Housing Units Authorized By Building Permits Table 3 – Metropolitan Areas.** http://www.census.gov/const/www/C40/table3.html. Washington, D.C.: U.S Census Bureau.

Walker, I. 2001. **Sensitivity of Forced Air Distribution System Efficiency to Climate, Duct Location, Air Leakage and Insulation**. Berkeley, Calif.: Lawrence Berkeley National Laboratory, LBNL–43371.