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# The impacts of duct design on life cycle costs of central residential heating and air-conditioning systems

Brent Stephens*

*Department of Civil, Architectural and Environmental Engineering, Illinois Institute of Technology, Chicago, IL, USA*

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ABSTRACT

Many central residential HVAC systems in the U.S. operate at high external static pressures due to a combination of system restrictions. Undersized and constricted ductwork are thought to be key culprits that lead to excess external static pressures in many systems, although the magnitude of energy impacts associated with restrictive ductwork and the costs or benefits associated with addressing the problem are not well known. Therefore, this work uses annual energy simulations of two typical new single-family homes in two separate climates in the United States (Austin, TX and Chicago, IL) to predict the impacts of various external static pressure ductwork designs from independent HVAC contractors (using both flexible and rigid sheet metal ductwork materials) on annual space conditioning energy use. Results from the simulations are combined with estimates of the initial installation costs of each duct design made by each contractor to evaluate the total life cycle costs or savings of using lower pressure duct designs in the two homes over a 15-year life cycle. Lower pressure ductwork systems generally yielded life cycle cost savings, particularly in homes with PSC blowers and particularly when making comparisons with constant ductwork materials (i.e., comparing flex only or rigid only).



## 1. Introduction

Many central residential heating, ventilating, and air-conditioning (HVAC) systems in the U.S. have substantially higher external static pressures than specified by most standardized test procedures [1] due to a combination of common system restrictions, including high pressure drop filters, cooling coils, heating elements, ductwork, and fittings [2–8]. Among these restrictions, undersized and constricted ductwork is thought to be a key culprit that leads to excess external static pressures, particularly for compressible flexible ductwork materials [9]. Excess static pressures can have negative energy impacts depending on the type of blower motor used in the air handling unit (AHU) and the level of excess static pressure [10,11]. Increasing diameters in duct designs and specifying low-resistance duct materials can reduce system pressures [12] but may also increase the surface area for heat transfer to occur across ductwork installed in unconditioned spaces [13]. Consequently, the combined impacts of duct design details and external static pressures on energy consumption are complex, as the relationships between pressure, fan efficiency, fan power draw, airflow rates, and heating and cooling capacities are not straightforward and depend on the type of blower motor used in the AHU. Additionally, there is a lack of information on the overall life cycle cost implications of lower static pressure duct designs for central residential HVAC systems. Therefore, this work investigates the impacts of various pressure duct designs on factors influencing central residential HVAC energy consumption and uses a combination of energy modeling and life cycle cost analysis to simulate the net life cycle impacts of lower pressure duct designs in residences.

## 2. Background

The energy impacts of varied external static pressures can be categorized generally into (1) direct power draw requirements of the AHU fan, and (2) more complex and indirect relationships between pressure, airflow, delivered sensible and latent capacities, system runtimes, and heat transfer across ductwork surfaces (if ductwork is installed in unconditioned spaces). For direct energy impacts, the fan power draw requirements of any AHU blower are

* Correspondence to: Department of Civil, Architectural and Environmental Engineering, Illinois Institute of Technology, Alumni Memorial Hall Room 212, 3201 South Dearborn Street, Chicago, IL 60616, USA. Tel.: +1 312 567 3356.
*E-mail address:* brent@iit.edu

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determined by system pressure, airflow rates, and fan and motor efficiencies as shown in Eq. (1).

$$W_{fan} = \frac{\Delta P_{system} Q_{fan}}{\eta_{fan} \eta_{motor}} \quad (1)$$

where $W_{fan}$ = power draw of the fan (W); $\Delta P_{system}$ = external system pressure (Pa); $Q_{fan}$ = airflow rate ($m^3\,s^{-1}$); $\eta_{fan}$ = efficiency of the fan (−); and $\eta_{motor}$ = the efficiency of the fan motor (−). Depending on the type of blower motor used, the airflow rate ($Q_{fan}$) and the overall efficiency ($\eta_{fan} \times \eta_{motor}$) will respond differently to a specific external static pressure ($\Delta P_{system}$) and thus will have different impacts on fan power draw.

Permanent split capacitor (PSC) motors have traditionally been the most widely used technology in residential AHU blowers in the U.S. with a market share of approximately 90% as of 2002 [14], although the share has decreased some in recent years. PSC blowers do not incorporate controls to maintain airflow rates at constant rates. Therefore, when excess system pressures are introduced, airflow rates typically decrease [7,8,11]. For most parts along the fan curve, increasing the external static pressure and decreasing airflow rates will reduce the power draw of a PSC blower, although the direction and magnitude of changes in fan power draw also depend on the location along the fan efficiency curve [7].

The overall energy impacts of reduced airflows are more complex. Reducing system airflow rates in systems with PSC blowers will decrease the cooling capacity of vapor compression air-conditioning systems, although changes in sensible and latent capacity are typically nonlinear with flow reductions [11,15]. Decreased sensible capacity will lead to increased energy consumption for space conditioning by increasing the length of system runtime, although very few measurements of these impacts have been made in actual homes. Capturing these effects is important; because the power draw of outdoor compressor-condenser units is typically much larger than the power draw of AHU fans [7,8], even a small increase in system runtime may overwhelm any savings in fan power draw. Complicating things further, reduced airflow rates have also been shown to reduce compressor power draw [11,15], which may offset some of the energy impacts of increased runtimes, depending on the magnitude of each change. For heat pumps, lower airflow rates will generally decrease both heating and cooling capacity as well, although the power draw of outdoor units will typically increase [16].

Electronically commutated motors (ECMs), also known as brushless permanent magnet motors (BPMs), utilize variable speed motors and drives that are designed to maintain constant or near-constant airflow rates across a wide range of external static pressures [17]. ECM blowers typically also have a much higher electric conversion efficiency than PSC blowers across a wider range of airflow rates [3,18–20]. In these systems, an increase in system pressure will generally result in an increase in fan power draw and thus fan energy consumption in order to maintain the same (or nearly the same) airflow rate [21], depending on the sophistication of control systems utilized [22]. The absolute magnitude of power draw will still usually be lower than a PSC motor because of typically higher efficiencies at most airflow rates, depending on the magnitude of the pressure increase. Because ECM blowers adjust to maintain airflow rates, altering duct system pressures will not drastically impact indirect energy consumption by altering system runtimes; energy impacts are primarily derived from direct fan power impacts. However, overall space conditioning energy impacts can still be more complex and may vary by climate. For example, at higher fan power draws at higher pressures, more excess heat will be rejected into the airstream, which may increase cooling energy requirements but may also decrease heating energy requirements [23].

Given the complexity of these relationships between external static pressure, airflow rates, fan power draws, fan efficiencies, sensible and latent capacities, system runtimes, and the combined impacts on space conditioning energy consumption, we have conducted a modeling effort to explore the overall impacts on energy consumption and life cycle costs of various duct designs in two typical single-family homes in both hot and cold U.S. climates: Chicago, IL, and Austin, TX. Three external static pressures ($\Delta P_{system}$) were initially specified as design targets (low, medium, and high) in each home and independent HVAC contractors provided ductwork designs and cost estimates for each duct system in each home as if they were to actually perform the design and installation. Details of the duct designs and system configurations (including two types of ductwork materials, rigid and flex) at the various external pressures were combined with typical fan and system curves for air-handling equipment to provide inputs for whole building energy analysis in order to explore these complex relationships in the two model homes.

## 3. Methodology

The following sections describe the selection of model homes; determinations of inputs for target system pressures, airflow rates, and fan power draws; estimation of duct UA values from the contractors' designs; the energy simulation procedures; and methods for conducting life cycle cost analyses. More details are described in the full project report [24].

### 3.1. Model home selection

House plans for (i) a typical one-story single-family home with an unconditioned basement in the Midwestern U.S. (Chicago, IL) and (ii) a typical one-story slab-on-grade single-family home in the Southern U.S. (Austin, TX) were first identified by an independent residential HVAC contractor in each location. The homes were designed to meet or exceed most minimum energy code requirements in both locations according to the 2009 International Energy Conservation Code (IECC). Relevant building characteristics are described in detail in Table 1. These homes are considered to be generally consistent with new residential construction practices in each location.

### 3.2. Pressure, airflow, and fan power determinations

The smaller Chicago home was chosen to have a nominal airflow rate of 2040 $m^3\,h^{-1}$ with ducts installed in the unconditioned basement and the larger Austin home had a nominal airflow rate of 2720 $m^3\,h^{-1}$ with ducts installed in the unconditioned attic. We then specified a range of three target external static pressures ($\Delta P_{system}$) to explore based on the size of each system, defined as "low," "medium," and "high" static pressures herein. These pressures were chosen to accurately reflect a wide, albeit realistic, range observed in real homes in the field and to represent the total pressure introduced by a combination of ductwork, coils, filters, supply registers, and return grilles. Table 2 summarizes the total external static pressures associated with each targeted design: 125, 200, and 275 Pa were used as the low, medium, and high pressures in the Chicago home and 138, 213, and 288 Pa were used in the larger Austin home. Table 2 also shows the external static pressures introduced by ducts alone after assuming 87 Pa is introduced by the combination of filters (25 Pa), coils (40 Pa), and registers, grilles, and dampers (22 Pa). These assumptions are widely used in ACCA Manual D calculations [25]. Although the system pressures identified in Table 2 are higher than standard industry assumptions and test conditions [1], they actually compare very well with existing measurements of pressures in real homes across the U.S. For example,

**Table 1**
Baseline characteristics of each IECC 2009 compliant home in each location.

| | Austin, TX | Chicago, IL |
|---|---|---|
| Floor area ($m^2$) | 293 | 195 |
| Orientation | Front door faces southeast | Front door faces east |
| Floor construction | Slab on grade | Full unconditioned basement R-SI 5.28 floor insulation |
| Number of bedrooms | 3 | 3 |
| Number of bathrooms | 2 | 2 |
| Exterior materials | Stucco and stone exterior | Brick veneer |
| Wall insulation ($m^2\,K\,W^{-1}$) | R-SI 3.35 in 5 cm × 15 cm studs | R-SI 3.70 in 5 cm × 15 cm studs |
| Attic insulation ($m^2\,K\,W^{-1}$) | R-SI 6.69 in roof deck | R-SI 6.69 in roof deck |
| Window *U*-value ($W\,m^{-2}\,K$) | 2.0 | 2.0 |
| Window SHGC | 0.30 | 0.55 |
| Window area, F B L R ($m^2$) | 8.3, 18.6, 11.1, 3.3 | 4.5, 10.4, 0.8, 1.1 |
| Duct/AHU location | Unconditioned attic | Unfinished basement |
| Duct insulation ($m^2\,K\,W^{-1}$) | R-SI 1.06 | R-SI 1.06 |
| Duct leakage (%) | 10% | 10% |
| Envelope airtightness | 7 $ACH_{50}$ | 7 $ACH_{50}$ |
| Modeled HVAC equipment | 1-stage heat pump<br>4.76 rated COP cooling<br>3.91 rated COP heating | 1-stage DX AC unit<br>4.76 rated COP cooling<br>92.5% AFUE gas furnace |
| Nominal AHU airflow rate ($m^3\,h^{-1}$) | 2040 @ 125 Pa | 2720 @ 125 Pa |
| Nominal cooling capacity (kW)* | 14.1 kW (SHR = 0.74) | 10.6 kW (SHR = 0.74) |
| Nominal heating capacity (kW)* | 14.1 kW (+2.93 kW suppl.) | 19.9 kW |

* Model system capacities reflect values modeled at the nominal (highest) airflow rate assumed for each home.

in a study of 60 new homes in California, total external pressures during cooling periods ranged from ∼75 to ∼300 Pa [26]. Similarly high static pressures were also measured in other recent field studies [6–8,27,28]. Thus our target design pressures for low, medium, and high static pressure duct designs are considered realistic across the U.S. residential building stock.

The specified pressures and home plans were then used by each of the independent HVAC contractors in performing ACCA Manual D calculations to size and specify different ductwork designs to achieve each external pressure in each home [25]. Each contractor provided their designs along with a cost estimate for the design and installation of each duct system in each homes as if they were to actually perform the installation. Duct designs were also made for each target pressure using two different duct materials: (1) flex ductwork and (2) rigid sheet metal ductwork. Both contractors performed duct designs and cost estimates for each home; therefore, their results capture regional variations in material selections, labor costs, and construction practices for both homes. Each contractor provided a total of 12 duct designs and cost estimates covering the two homes, each with three pressures and two duct materials. These designs captured real life variability in duct diameters, layouts, lengths, and materials that real contractors would use to achieve the target low, medium, or high external static pressures.

The low, medium, and high external static pressures were then used to estimate the impacts of system pressures on fan airflow rates, fan efficiencies, and fan power draws in each home, treating PSC and ECM blowers separately, which were then used as inputs to annual building energy simulations in EnergyPlus [29]. Data were selected for these inputs to be as widely representative of residential HVAC equipment as possible by relying on “virtual models” from a large summary of manufacturer fan data provided in Appendix 7-F of the *Technical Support Document* for the *Energy Efficiency Program for Consumer Products: Residential Central Air Conditioners, Heat Pumps, and Furnaces* [21].

Representative fan curves (airflow vs. pressure) and fan power curves (power vs. pressure) for a range of single-stage virtual model furnaces with both PSC and ECM blowers are shown in Fig. 1. The target low, medium, and high static pressures are marked on each graph for both homes. These virtual models show that excess static pressures indeed decrease airflow rates and fan power draw with PSC blowers. Conversely, the representative ECM blowers respond to excess pressure by maintaining near-constant flows, with fan power draw increasing almost linearly with airflow. Curve fits to the data in the technical support document were used to extend the range of external pressures beyond the scale shown in the original figures.

For both PSC and ECM blowers, nominal airflows of 2040 and 2720 $m^3\,h^{-1}$ are assumed to be achieved in the Chicago and Austin homes at the lowest external static pressures of 125 and 138 Pa, respectively. Increases in external static pressure to the medium pressure scenarios of 200 Pa (in Chicago) and 213 Pa (in Austin) are expected to yield 20 and 18% reductions in flow for the PSC blowers and 3 and 1% reductions in flow for ECM blowers, respectively. Similarly, increases in external static pressure to the high values of 275 Pa (Chicago) and 288 Pa (Austin) yield 48 and 43% reductions in flow for PSC blowers and 8 and 2% reductions in flow for ECM blowers, relative to the low pressure cases.

For the Chicago home, these flow changes correspond to as much as a 41% reduction in fan power draw (PSC) and as much as a 42% increase in fan power draw (ECM) at the highest pressure relative to the lowest pressure. At the highest pressure the PSC blower will actually draw less power than the ECM blower. Similarly for the Austin home, the highest pressure yields a 36% decrease in fan power draw by the PSC blower and a 55% increase in fan power draw by the ECM blower relative to the lowest pressure scenario; power draw is approximately equal for both blowers at the highest pressure. These pressure, flow, and power draw changes are generally consistent not only with manufacturer data but with data from other laboratory and field tests [7,8,11,20,27], and thus should be considered generally representative of the range of equipment and operational conditions observed in homes across the country. The absolute values of the full range of pressure, airflow, fan power draw, and fan efficiency inputs for each simulation case in both homes are shown in Table 2. Once airflow and fan power draw impacts in response to the defined target static pressures were identified, those data were then used as inputs to EnergyPlus, which utilized built-in polynomial functions that calculate heating and cooling capacity, COP (which is the inverse of the energy input ratio, EIR), and outdoor unit power draw as a function airflow rates using generic air-conditioning, heat pump, and furnace models.

### 3.3. Duct UA values

Duct surface areas and duct UA values were also estimated for each modeled scenario based on the contractor duct designs

**Table 2**
Summary of pressure, flow, fan efficiency, fan power, and duct UA inputs for the EnergyPlus simulations.

| Home | Duct type | Blower type | Duct pressure (Pa) | Total pressure (Pa) | Airflow rate ($m^3 h^{-1}$) | Fan efficiency (%) | Fan power draw (W) | Duct UA ($W K^{-1}$) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Chicago contractor | | Austin contractor | |
| | | | | | | | | Supply | Return | Supply | Return |
| | | | 38 | 125 | 2040 | 0.16 | 449 | 119 | 59 | 87 | 0.7 |
| Chicago home | | PSC | 113 | 200 | 1638 | 0.25 | 369 | 90 | 48 | 70 | 0.3 |
| Ducts in basement | | | 188 | 275 | 1056 | 0.30 | 265 | 85 | 44 | 76 | 0.3 |
| | Flex | | 38 | 125 | 2040 | 0.27 | 260 | 119 | 59 | 87 | 0.7 |
| 2040 $m^3 h^{-1}$ airflow nominal | | ECM | 113 | 200 | 1975 | 0.33 | 330 | 90 | 48 | 70 | 0.3 |
| | | | 188 | 275 | 1875 | 0.39 | 369 | 85 | 44 | 76 | 0.3 |
| | | | 38 | 125 | 2040 | 0.16 | 449 | 74 | 35 | 61 | 0.3 |
| 10.6 kW AC unit | | PSC | 113 | 200 | 1638 | 0.25 | 369 | 58 | 27 | 60 | 0.3 |
| | | | 188 | 275 | 1056 | 0.30 | 265 | 57 | 27 | 60 | 0.3 |
| 19.9 kW | Rigid Metal | | 38 | 125 | 2040 | 0.27 | 260 | 74 | 35 | 61 | 0.3 |
| Gas furnace | | ECM | 113 | 200 | 1975 | 0.33 | 330 | 58 | 27 | 60 | 0.3 |
| | | | 188 | 275 | 1875 | 0.39 | 369 | 57 | 27 | 60 | 0.3 |
| | | | 50 | 138 | 2720 | 0.18 | 573 | 171 | 58 | 105 | 22 |
| | | PSC | 125 | 213 | 2236 | 0.27 | 482 | 139 | 57 | 100 | 20 |
| Austin home | Flex | | 200 | 288 | 1557 | 0.34 | 369 | 137 | 57 | 97 | 20 |
| | | | 50 | 138 | 2720 | 0.32 | 329 | 171 | 58 | 105 | 22 |
| Ducts in attic | | ECM | 125 | 213 | 2701 | 0.37 | 427 | 139 | 57 | 100 | 20 |
| | | | 200 | 288 | 2660 | 0.42 | 510 | 137 | 57 | 97 | 20 |
| 2720 $m^3 h^{-1}$ airflow nominal | | | 50 | 138 | 2720 | 0.18 | 573 | 83 | 49 | 108 | 0.9 |
| | | PSC | 125 | 213 | 2236 | 0.27 | 482 | 71 | 45 | 98 | 0.9 |
| | | | 200 | 288 | 1557 | 0.34 | 369 | 66 | 44 | 97 | 0.9 |
| 14.1 kW heat pump | Rigid Metal | | 50 | 138 | 2720 | 0.32 | 329 | 83 | 49 | 108 | 0.9 |
| | | ECM | 125 | 213 | 2701 | 0.37 | 427 | 71 | 45 | 98 | 0.9 |
| | | | 200 | 288 | 2660 | 0.42 | 510 | 66 | 44 | 97 | 0.9 |

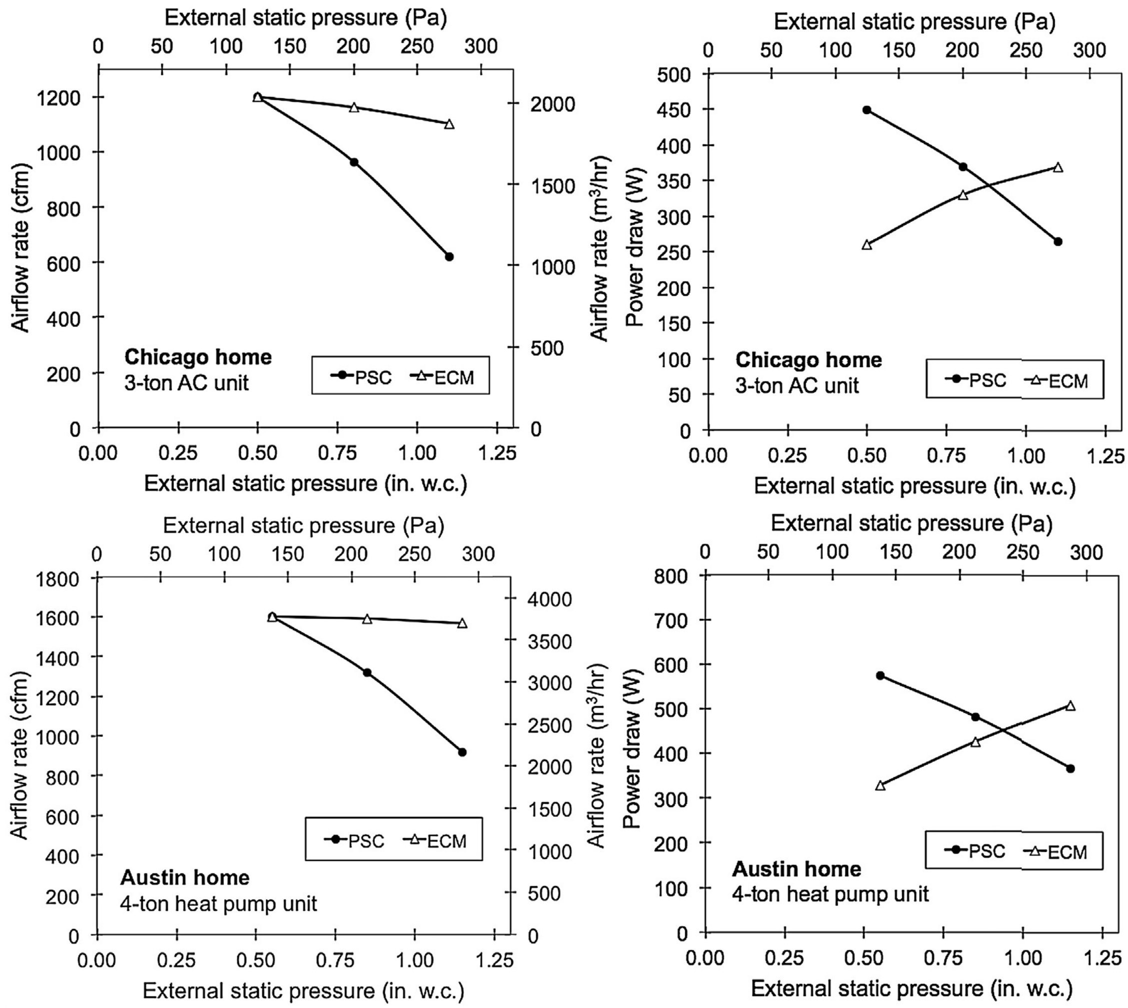


**Fig. 1.** Fan airflow rate and power draw inputs utilized at each of the low, medium, and high external static pressures in this work for both PSC and ECM blowers.

to capture indirect energy impacts of heat transfer across ducts installed in unconditioned spaces [13,30,31]. Although duct insulation values were constant in both homes and in all scenarios (R-SI 1.06 $m^2\,K\,W^{-1}$), the surface areas of supply and return ductwork varied according to each duct design, which affects the overall UA values for ductwork. Supply and return ductwork surface areas of each ductwork design were estimated manually based on the size and shape of ductwork provided by the contractors (i.e., by calculating the surface area of a cylinder of the same length and diameter as each duct run). Those values were converted into UA values for each scenario based on ductwork with U = 0.94 $W\,m^{-2}\,K$.

The ductwork designs for lower external static pressures from the contractors generally utilized greater diameter ductwork that was typically running similar lengths (the greater diameter allows for lower resistance for an equivalent length). Therefore, the external surface area of ductwork was typically higher for the lower static pressure designs, although there was considerable variability between the two contractors' designs. Designs by the Chicago contractor resulted in UA values for ductwork that were typically 20–30% higher for the lower pressure (larger diameter) duct systems relative to the highest pressure (smaller diameter) duct systems; designs by the Austin contractor resulted in UA values that were between 2 and 15% higher for the lower pressure systems. Additionally, the Austin contractor tended to use more efficient duct designs in terms of material; their duct UA values were often 20–40% lower than the Chicago contractors. For example, the Austin contractor relied on flexible duct trunks and branches to achieve the desired pressure for each scenario while the Chicago contractor utilized a radial flex duct design where each branch began at the AHU (this is often referred to "ductopus" configuration as the branches resemble the tentacles of a cephalopod).

### 3.4. Energy simulation procedures

A total of 48 annual energy simulations were performed in EnergyPlus Version 8.1.0 using the appropriate (Chicago and Austin) typical meteorological year (TMY3) data and all of the combinations of input scenarios covering the two contractors' duct designs and UA values, three levels of external static pressure, two types of AHU blowers, and the two homes in the two climates. BEopt Version 2.1.0.0 was first used to generate EnergyPlus input files (IDF files) for each of the two homes based on geometry and the basic inputs from Table 1. All inputs related to occupant activity, such as natural ventilation (i.e., window opening) during mild weather and appliance, lighting, and miscellaneous load profiles, were chosen as the default values in BEopt, which relies on the well-established inputs in the Building America House Simulation Protocols.

Once all available inputs were selected in BEopt, a single simulation for each home was run in order to generate an EnergyPlus input (IDF) file. The IDF file was copied for each home and the results of the initial simulation were discarded because not all inputs were accurate at this stage. The IDF file was then directly edited using a simple text editor to vary input parameters to reflect each simulation case. Rated airflow rates for HVAC equipment and duct sizes were kept at the maximum (nominal, or lowest pressure) value for each simulation case, but the design and specified airflow rates were adjusted in each case (and capacities and EIR were adjusted automatically within EnergyPlus using built-in algorithms). Airflow rates were changed in each of the following sections of the IDF files: `AirLoopHVAC:UnitaryHeatCool`, `Fan:OnOff`, `AirTerminal:SingleDuct:Uncontrolled`, and `Branch`. Fan pressure and efficiency were also changed for each case (in the `Fan:OnOff` section of the IDF file), which governs fan power draw in the simulations. Finally, duct UA values were adjusted for each case in a separate section of the IDF file that is created by BEopt (`EnergyManagementSystem:Program`).

The homes were modeled without a dedicated outdoor air supply or heat recovery system. Thermostat set points were 24.4 °C in the summer and 21.1 °C in the winter. The same airflow rates were assumed for both heating and cooling modes for simplicity. Important EnergyPlus outputs for the Chicago home included annual electric use for the AHU fan and outdoor condenser–compressor unit, as well as annual natural gas usage for the furnace. Similar annual outputs for the Austin home included electric use for the AHU fan and heat pump during both heating and cooling modes. In this work, "cooling energy" refers to the energy used by the compressor unit; "heating energy" refers to energy used by either the furnace or the heat pump unit during heating mode; "fan energy" refers to the total amount of energy used by the AHU fan during both heating and cooling modes; and total "HVAC energy" refers to the combination of fan, compressor, and furnace energy use. These annual outputs were first used to explore impacts of blower types and duct designs on total HVAC energy use and costs on an annual basis using baseline energy cost estimates. The same results were also used to explore life cycle costs, using methods described below.

### 3.5. Life cycle cost estimation

Estimates of annual HVAC energy consumption and costs were summed over an assumed 15-year lifetime of the HVAC equipment to determine the estimated total lifetime HVAC energy consumption of each configuration. A 15-year lifetime was chosen as the life cycle length because although ductwork materials should last much longer, the actual systems modeled herein (and all of their associated capacity and efficiency inputs) are likely to be replaced within 15 years. However, a 30-year lifespan was also later considered to explore sensitivity to this assumption, although it still does not include equipment replacement costs because the efficiency and capital costs of equipment available 15 years from now are unknown. National average residential electricity rates and natural gas costs were used in both homes. Natural gas costs were assumed to remain constant at the 10-year residential average of $11 USD per GJ, primarily because of recent decreases in gas costs that disrupt any clear trend in costs and because of historical difficulty in accurately forecasting natural gas prices [32]. Nominal electricity costs were assumed to be $0.118 USD per kWh in the present year [33], increasing at a nominal rate of 2.0% per year, or 0.3% in real (2011) dollars [34].

To explore the upfront costs and life cycle operational costs or benefits of each duct design scenario, we first compared differences in upfront costs between each duct design to differences in cumulative energy costs summed over 15 years of life, accounting for both increases in energy costs and inflation. This allowed for a comparison between the excess costs of a design to any added benefit (in terms of operational energy cost savings) or added cost (in terms of additional operational energy costs required) over the assumed lifespan of 15 years. The highest pressure (i.e., 275 or 288 Pa) ductwork design was first used as the reference case for other scenarios to compare to, treating rigid and flex ductwork materials separately. The analysis was performed separately for PSC and ECM fans because we have not attempted to capture differences in initial costs for these fan types. An additional comparison was also made across both flex and metal ductwork to capture the costs and benefits of using different pressure ductwork designs with different materials, although this analysis is somewhat limited as described in a later section.

The results from the cost-benefit analysis above were also converted into a net present value (NPV) as another way to compare life cycle costs and benefits associated with investment in the various ductwork designs. The annual NPV was estimated for each scenario according to Eq. (2), which follows a procedure outlined in the 2012 Supplement to NIST Handbook 135 *Life-Cycle Costing Manual for the Federal Energy Management Program* [35].

$$\mathrm{NPV}_n = \frac{\Delta C_n}{(1+d)^n} \tag{2}$$

where $\Delta C_n$ = the difference in annual energy cost for space conditioning between a particular duct design configuration and the baseline configuration in year $n$; $d$ = the discount rate (assumed 3.5% based on a 3.0% real rate excluding inflation and a 0.5% long-term average inflation rate, as described in Rushing et al. [35]); and $n$ = the year of analysis. The total NPV over the course of a 15-year life cycle was then estimated according to Eq. (3).

$$\mathrm{NPV}_{lifecycle} = \sum_{n=0}^{15} \mathrm{NPV}_n \tag{3}$$

where $\mathrm{NPV}_{lifecycle}$ is the sum of the $\mathrm{NPV}_n$ for each of the 15 assumed years of the design life cycle, including the cost of implementation of ductwork in year 0. This yields the total NPV, which can be used to evaluate whether or not an investment will be beneficial or costly over its lifetime compared to a reference scenario. In this work, a positive life cycle NPV describes an investment in which life cycle benefits exceed costs relative to the highest pressure reference scenarios (i.e., positive NPV = savings). Conversely, a negative NPV describes an investment in which costs exceed benefits over the duration of the design life cycle (i.e., negative NPV = excess costs).

## 4. Results

### 4.1. Initial costs of duct designs

Table 3 shows the initial design and installation cost estimates for each duct design and installation in each home from both HVAC contractors. These estimates provide the starting point for differences in installation costs to which differences in annual energy savings (or excess costs) are compared for each configuration. For both the Austin and Chicago home duct designs by the Chicago contractor, lower pressure ducts were consistently more expensive than higher pressure duct designs. For example, the lowest pressure flex duct would cost approximately $150 USD more than the highest pressure flex duct (~3% higher) in the Chicago home; the same comparison yields an excess cost of $1250 in the Austin home (~26% higher costs). Similarly, the lowest pressure sheet metal duct was estimated to cost $1650 more than the highest pressure metal duct (~19% higher) in the Chicago home and $900 more (~8% higher) in the Austin home. These differences are attributed to both differences in ductwork material (between flex and rigid) and labor to perform the installations.

For both the Austin and Chicago home duct designs by the Austin contractor, differences between lower pressure and higher pressure duct costs were not as straightforward. For example, the lowest pressure flex duct would cost approximately $119 *less* than the highest pressure flex duct in the Chicago home; the same comparison yields an excess cost of only $68 in the Austin home. The medium pressure duct design even had the highest cost in one set

**Table 3**
Duct design and installation cost estimates from the hired contractors.

| Duct material | Duct pressure (Pa) | Total external static pressure (Pa) | Initial design and installation cost | |
|---|---|---|---|---|
| | | | Chicago contractor | Austin contractor |
| | | | Chicago home | |
| Flex duct | 38 | 125 | $4,970 | $3,784 |
| | 113 | 200 | $4,870 | $3,665 |
| | 188 | 275 | $4,820 | $3,903 |
| Rigid sheet metal | 38 | 125 | $10,470 | $7,370 |
| | 113 | 200 | $8,970 | $7,423 |
| | 188 | 275 | $8,820 | $7,361 |
| | | | Austin home | |
| Flex duct | 50 | 138 | $6,110 | $4,182 |
| | 125 | 213 | $5,360 | $4,160 |
| | 200 | 288 | $4,860 | $4,114 |
| Rigid sheet metal | 50 | 138 | $11,410 | $7,324 |
| | 125 | 213 | $10,910 | $7,160 |
| | 200 | 288 | $10,510 | $7,132 |

of designs. Similarly, the lowest pressure sheet metal duct was estimated to cost only $9 more than the highest pressure metal duct in the Chicago home and only $192 more in the Austin home. These differences are attributed to a combination of differences in ductwork material (between flex and rigid), the design diameters of ductwork runs, and the labor requirements for installation.

Obviously the two contractors delivered very different designs and cost estimates to meet the same goals, which is important to capture in the analysis herein. Overall, duct design and installation is estimated to cost less for the smaller Chicago home according to both contractors, which is intuitive for the smaller amount of materials involved. Also, for both contractors, rigid sheet metal ductwork is estimated to cost substantially more than flex duct for all scenarios, as much as $6000 more for some equivalent configurations. This large excess initial cost is due not only to differences in materials but in estimates of the more intensive level of labor required to install rigid ductwork relative to flexible ductwork. Finally, it is important to note that the design and installation estimates from the Austin contractor were consistently lower for all configurations, primarily reflecting differences in labor and material costs between Austin, TX and Chicago, IL.

### 4.2. Annual energy simulation results

A full table of results from all 48 simulations for both homes with duct designs from both contractors is shown in Table 4. Results are limited to annual energy use for space conditioning (i.e., "HVAC energy"), including heating, cooling, and fan energy in each case. Other non-HVAC energy consumption is excluded from these results because they are unaffected by the input variables used herein, although it should be noted that heating energy accounted for ∼68–73% of the total amount of predicted natural gas usage in the Chicago home, on average, while fan and cooling energy accounted for only ∼8 and ∼6% of total electricity usage, respectively, across all scenarios and duct designs by both contractors. Space conditioning energy use accounted for only 36–47% of the total amount of predicted electricity usage in the Austin home, depending on configuration.

#### 4.2.1. Chicago home energy simulation results

The relative comparison of annual (i) heating energy, (ii) fan energy, (iii) cooling energy, and (iv) total HVAC energy costs estimated for the baseline (present) year between each of the three static pressures for each duct system and fan type for the Chicago home based on both the Chicago and Austin contractors duct designs is shown in Fig. 2.

*4.2.1.1. PSC blowers.* Relative differences in energy use among design duct pressures were similar among rigid and flex ductwork in the Chicago home using both contractors' designs. For PSC blowers and both ductwork types, cooling energy increased by approximately 7% when moving from low pressure to medium pressure duct systems and increased approximately 26–27% when moving from low pressure to high pressure duct systems. Both reflect increases in system runtimes at airflow rates that are 20 and 48% lower, respectively. Lower airflow rates led to lower cooling capacities at these higher pressures, although the increase in runtime is not as large as decreased airflow rates for a number of reasons, including nonlinear reductions in sensible capacity, reduced compressor power draw at the lower airflow rates, less reject heat added to the airstream for the PSC blowers, and lower conductive losses through ductwork with typically lower surface areas and thus lower UA values.

Annual fan energy did not change when moving from low to medium pressure scenarios with the Chicago contractor's duct designs but decreased 2% with the Austin contractor's designs. Annual fan energy then increased by 11–14% when moving to the highest pressure PSC + flex system, suggesting that any reductions in fan power draw observed at moderately increased static pressures were overwhelmed by longer system runtimes. Similar changes of −1% and +10–11% were also predicted for the PSC + rigid system. Annual heating energy increased 3–5% for both PSC + flex and PSC + rigid systems at the highest pressures using both contractors' designs; changes in heating energy were negligible for the medium pressure systems.

Total HVAC energy costs in the baseline year were estimated to be between ∼0.2% lower and 0.4% higher for each of the PSC + flex scenarios with medium pressure ducts compared to low pressure ducts (the same medium pressure comparison resulted in baseline HVAC energy costs between 0.2 and 1.6% higher for PSC + rigid scenarios, depending on contractor design). Total HVAC energy costs in the baseline year for the high pressure PSC + flex duct systems were estimated to be between 5.4 and 6.9% higher compared to the low pressure systems (again depending on contractor design), and between 5.1 and 6.7% higher for the high pressure PSC + rigid systems. Overall, these results suggest that for PSC blowers in this home, the use of the lowest pressure duct designs could likely save approximately 5–7% in total annual HVAC energy costs relative to the highest pressure designs.

**Table 4**
Annual energy simulation results for both homes using both contractors' designs.

| Home | Duct type | Blower type | Total pressure (Pa) | Airflow rate ($m^3\ h^{-1}$) | Chicago contractor | | | Austin contractor | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Cooling energy (kWh) | Fan energy (kWh) | Heating energy (GJ) | Cooling energy (kWh) | Fan energy (kWh) | Heating energy (GJ) |
| Chicago home | | | 125 | 2040 | 631 | 556 | 66.45 | 619 | 542 | 64.31 |
| | | PSC | 200 | 1638 | 672 | 539 | 66.06 | 661 | 531 | 64.28 |
| Ducts in basement | Flex | | 275 | 1056 | 792 | 603 | 68.49 | 786 | 600 | 67.22 |
| | | | 125 | 2040 | 622 | 328 | 67.10 | 611 | 319 | 64.94 |
| $2040\ m^3\ h^{-1}$ airflow nominal | | ECM | 200 | 1975 | 622 | 417 | 65.34 | 614 | 411 | 63.80 |
| | | | 275 | 1875 | 633 | 481 | 65.11 | 631 | 478 | 64.21 |
| | | | 125 | 2040 | 614 | 536 | 63.84 | 611 | 531 | 62.80 |
| 10.6 kW AC unit | | PSC | 200 | 1638 | 656 | 522 | 63.70 | 656 | 525 | 63.57 |
| | Metal | | 275 | 1056 | 767 | 578 | 65.62 | 769 | 583 | 65.59 |
| 19.9 kW Gas furnace | | | 125 | 2040 | 606 | 317 | 64.46 | 603 | 314 | 63.41 |
| | | ECM | 200 | 1975 | 608 | 406 | 63.31 | 611 | 406 | 63.19 |
| | | | 275 | 1875 | 622 | 469 | 63.26 | 625 | 472 | 63.20 |
| | | | Total pressure (Pa) | Airflow rate ($m^3\ h^{-1}$) | Chicago contractor | | | Austin contractor | | |
| | | | | | Cooling energy (kWh) | Fan energy (kWh) | Heating energy (kWh) | Cooling energy (kWh) | Fan energy (kWh) | Heating energy (kWh) |
| | | | 138 | 2720 | 2797 | 964 | 2261 | 2342 | 808 | 1822 |
| Austin home | | PSC | 213 | 2236 | 2789 | 817 | 2369 | 2461 | 722 | 2042 |
| | | | 288 | 1557 | 3183 | 719 | 3244 | 2753 | 622 | 2722 |
| Ducts in attic | Flex | | 138 | 2720 | 2747 | 539 | 2311 | 2303 | 453 | 1856 |
| | | ECM | 213 | 2701 | 2578 | 672 | 2100 | 2294 | 597 | 1819 |
| $2720\ m^3\ h^{-1}$ airflow nominal | | | 288 | 2660 | 2594 | 789 | 2094 | 2303 | 700 | 1808 |
| | | | 138 | 2720 | 2267 | 786 | 1756 | 2325 | 803 | 1803 |
| | | PSC | 213 | 2236 | 2325 | 683 | 1906 | 2417 | 708 | 1997 |
| | | | 288 | 1557 | 2717 | 617 | 2697 | 2717 | 617 | 2697 |
| 14.1 kW heat pump | Metal | | 138 | 2720 | 2231 | 442 | 1789 | 2286 | 450 | 1836 |
| | | ECM | 213 | 2701 | 2183 | 569 | 1717 | 2256 | 586 | 1778 |
| | | | 288 | 2660 | 2178 | 664 | 1694 | 2272 | 692 | 1778 |

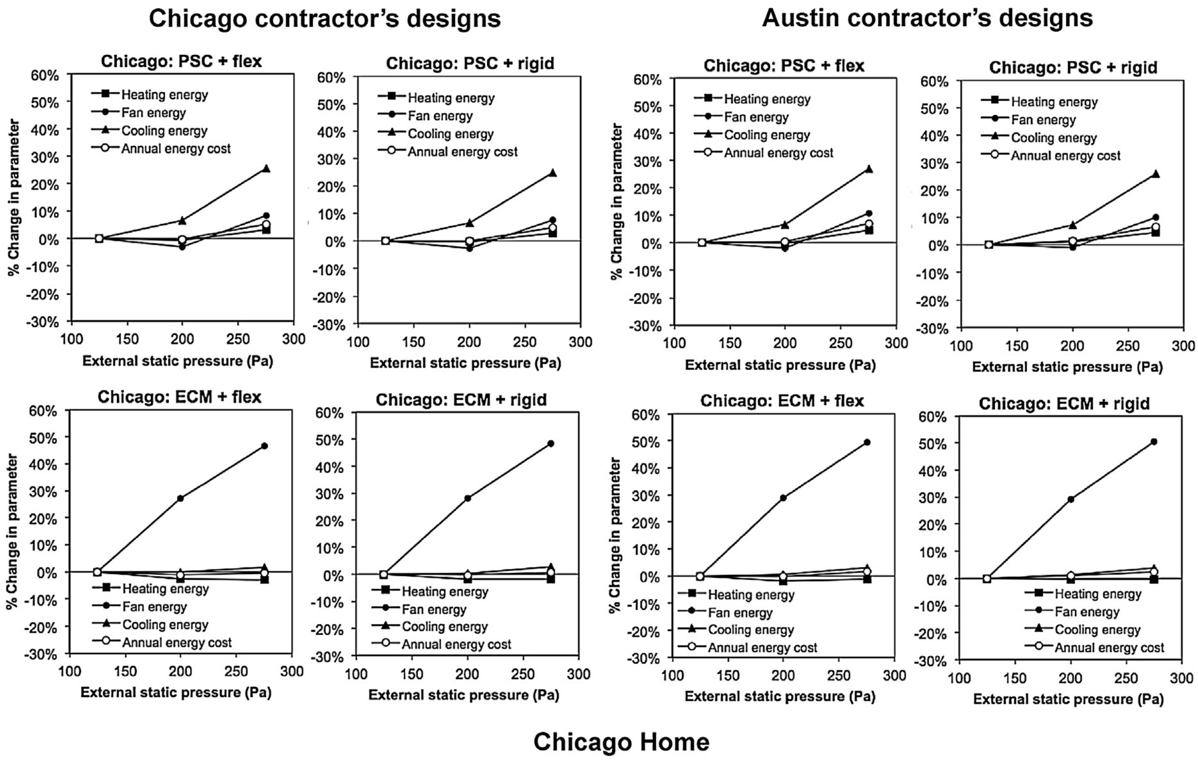


**Fig. 2.** Estimated relative change in annual fan, cooling, and heating energy usage and total annual combined heating and cooling energy costs for the Chicago home with both types of AHU blowers and both rigid and flex duct work at each duct design from both contractors.

*4.2.1.2. ECM blowers.* For the ECM + flex system, there were only small increases in cooling energy consumption of 0% and +2–3% at medium and high pressures relative to low pressures, respectively, which is generally appropriate for very small changes in airflow rates and cooling capacities (from Table 2). The slight increase in cooling energy at the highest pressure may be explained by an increase in heat rejected into the airstream by the ECM blowers using more power. There was a 27–29% and 47–50% increase in fan energy consumption for the two higher pressures, respectively, using both contractors' designs with ECM + flex combinations, due primarily to greater power draw of the ECM blowers at higher pressures. There was also a 1–3% reduction in heating energy at these higher pressures, likely due to the combination of increased reject heat from the fans as they drew more power at higher pressures, as well as a small reduction in conductive losses through lower UA ducts (particularly for the Chicago contractor's designs). Similarly for the ECM + rigid systems, cooling energy increased 0–1% and 3–4% at medium and high pressures relative to the low pressure designs; fan energy increased 28–29% and 48–50%, and heating energy decreased as much as 2% (Chicago contractor) or as little as 0% (Austin contractor) at each of the same pressures. This difference is likely due to the fact that for the Chicago home, the average total duct UA values across all scenarios was approximately 73% greater with the Chicago contractor's duct designs than the Austin contractor's designs (average of 120 W $K^{-1}$ vs. 70 W $K^{-1}$).

Differences in HVAC energy costs in the baseline year for the ECM scenarios were smaller than the PSC scenarios. Total HVAC energy costs were 0.2–1% lower for the medium pressure ECM + flex systems and between 0.2% lower and 1.2% higher for the medium pressure ECM + rigid systems, depending on contractor design. Total HVAC energy costs were between 0.3% lower and 1.6% higher for the high pressure ECM + flex combinations and 0.8–2.4% higher in the high pressure ECM + rigid combinations.

*4.2.2. Austin home energy simulations*

The relative comparison of annual (i) heating energy, (ii) fan energy, (iii) cooling energy, and (iv) total HVAC energy costs in the baseline year between each of the three static pressures for each duct system and fan type for the Austin home based on both the Chicago and Austin contractors duct designs is similarly shown in Fig. 3.

*4.2.2.1. PSC blowers.* In the Austin home with PSC blowers and flexible ductwork materials, cooling energy slightly decreased by 0.3% when moving from low pressure to medium pressure designs by the Chicago contractor but increased ~5% using the Austin contractor's designs. Again the difference stems from large differences in duct UA values in unconditioned space, which varied highly between the two contractors. When moving from low pressure to high pressure duct designs with PSC + flex systems, cooling energy increased by 14–18%, depending on contractor designs. The same impacts were greater in magnitude for the PSC + rigid combinations: cooling energy increased 3–4% at medium pressures and increased 17–20% at high pressures. Again, increases in cooling energy were due to a combination of longer system runtimes mitigated in part by a lower fan power draw (which rejects less heat into the airstream), lower compressor power draw, and reduced heat transfer across ductwork surfaces at the higher pressure designs.

Annual fan energy decreased 15 and 11% with PSC + flex combinations when moving from low to medium pressure with the Chicago and Austin contractors' designs, respectively. Annual fan energy decreased 23–25% with the same combination when moving from the low to high pressure designs, depending on contractor design. Results were similar for the PSC + rigid systems (12–13% reductions for medium pressures and 22–23% for the lowest pressures). Annual heating energy consumption increased 5–9% and 11–12% for both PSC + flex and PSC + rigid systems at

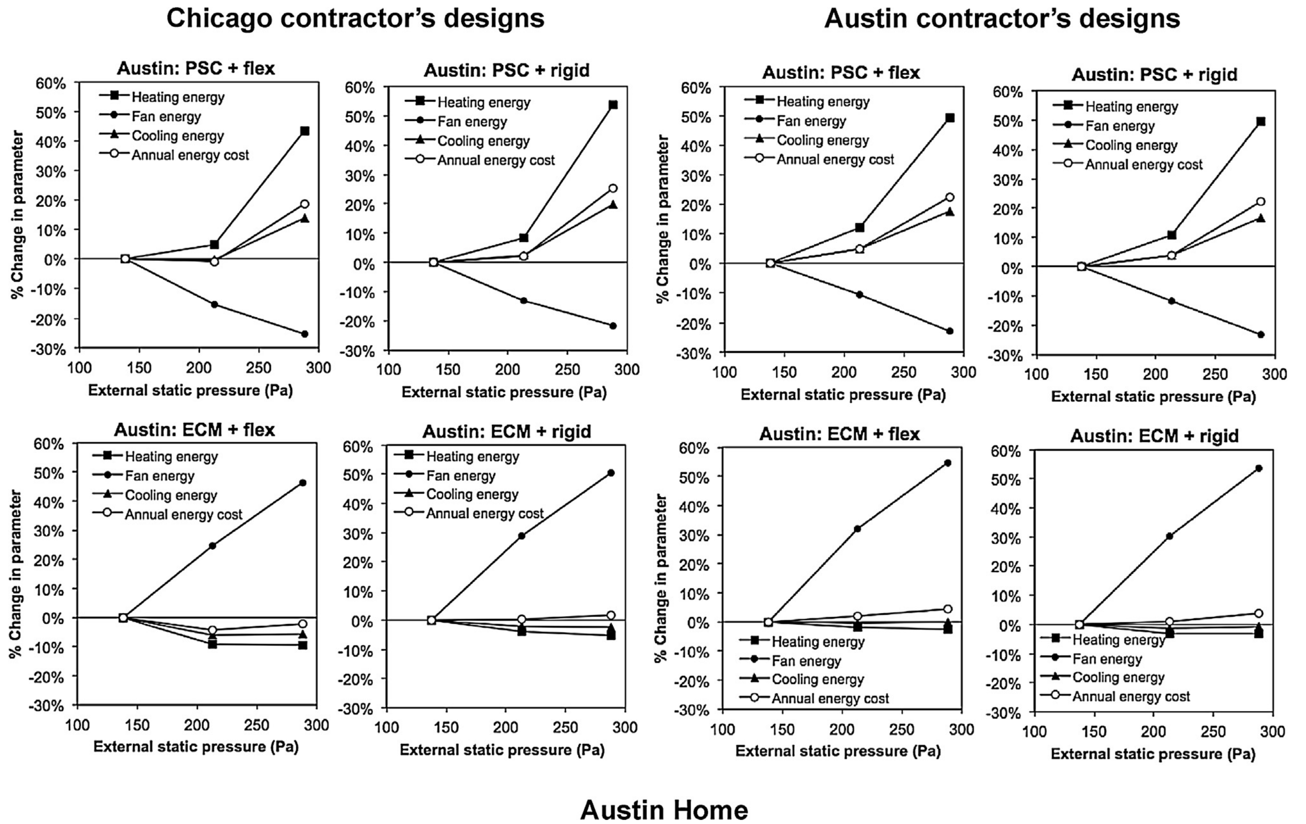


**Fig. 3.** Estimated relative change in annual fan, cooling, and heating energy usage and total annual combined heating and cooling energy costs for the Austin home with both types of AHU blowers and both rigid and flex duct work at each duct design from both contractors.

the medium pressures using the Chicago and Austin contractors' designs, respectively. More substantially, annual heating energy consumption increased 43–54% with the highest pressure Chicago contractor's PSC + flex and PSC + rigid designs and 49–50% with the highest pressure Austin contractor's PSC + flex and PSC + rigid designs.

Total HVAC energy costs in the baseline year were 1% lower and 19% higher for the medium and high pressure PSC + flex combinations compared to their low pressure counterparts, respectively, and 2% and 25% higher for the medium and high pressure PSC + rigid combinations, respectively, all with the Chicago contractor's designs. Similarly, total HVAC energy costs in the baseline year were 5% higher and 23% higher for the medium and high pressure PSC + flex combinations compared to low pressure designs, respectively, and 4% and 22% higher for the medium and high pressure PSC + rigid combinations, respectively, when using the Austin contractor's designs in the Austin home. Therefore, the lowest pressure duct designs in this home with a PSC blower could lead to substantial reductions in HVAC energy costs (as much as 22–25%) relative to those encountered using the highest pressure duct designs. Moderate pressure designs had a smaller impact, but still led to 2–5% higher heating and cooling energy consumption relative to the lowest pressures.

*4.2.2.2. ECM blowers.* For the ECM + flex systems using the Chicago contractor's designs, there was a 6% increase in cooling energy consumption at both medium and high pressures, which captures the combined effects of excess heat rejected to the airstream by the AHU blowers drawing more power at greater pressures offset some by lower duct UA values. However, there was no observable change in cooling energy consumption at either pressure with the ECM + flex systems using the Austin contractor's designs, likely due to small changes in duct UA values with their designs. Annual fan energy increased by 25–32% and 46–55% for the medium and high pressure ECM + flex designs, respectively, depending on contractor designs. There was also a 9% and 2–3% reduction in heating energy at both of these higher pressures with the Chicago and Austin contractor designs, respectively, most likely due to the combined effects of reduced heat transfer across the lower UA ductwork designs in the unconditioned attic and the addition of excess reject heat from the fans drawing higher power at higher pressures. Similarly for the ECM + rigid systems, cooling energy decreased by 1–2% at both medium and high pressures relative to the lowest pressure; fan energy increased 29–30% and 50–54%; and heating energy decreased 3–5% at each of the same pressures, depending on contractor designs. Again, differences in total HVAC energy costs in the baseline year for the ECM scenarios were smaller than the PSC scenarios.

### 4.3. Life cycle cost analysis

Although the single-year annual simulation results above are helpful for interpreting energy usage and operational cost impacts of each duct design and blower combination, a life cycle analysis was also conducted to determine the true cost-benefit relationship between differences in initial costs among duct configurations and subsequent increases or decreases in HVAC energy costs. The NPV estimates are explored first by comparing both the medium and low system pressure conditions against the highest-pressure condition for each house and blower type and treating (1) flex duct systems and (2) rigid duct systems separately. Blower types and results from the Chicago and Austin contractors' duct designs and cost estimates are also treated separately. Flex and rigid duct systems are treated separately to limit the cost comparisons to the impacts of duct pressures alone (which is the main focus of this study). Additionally, comparisons across ductwork types are not always appropriate. For example, in the City of Chicago, flexible nonmetallic ductwork is not permitted in residential units per the building code, §18-28-603. In other settings, it may be standard industry practice for contractors to rely exclusively on flexible ductwork and thus rigid duct designs may seldom be used. However, one final comparison involved exploring the same data and the same division of blower types but also comparing the medium and low pressure systems with both flex duct and rigid sheet metal duct materials to the highest-pressure *flex* condition in each case. This procedure allows for a life cycle cost comparison *across* duct materials (i.e., of flex vs. rigid), although it is limited to several important assumptions and limitations outlined in the accompanying text in that section.

#### 4.3.1. NPV analysis assuming 15-year life cycle: flex duct only

In the NPV calculation procedure, we assumed that the entire cost of duct design and installation was incurred in the initial year (year 0). Subsequently, the total annual electricity and/or natural gas usage simulated for each home was assumed to remain constant each year for the following 15 years, which is generally appropriate considering that typical meteorological year (TMY) data drive the simulation inputs. Fig. 4 shows 15-year NPVs estimated for both the Chicago and Austin homes using both the Chicago (IL) and Austin (TX) contractors' flex duct designs.

For the PSC + flex combinations, lower pressure duct designs are predicted to have 15-year NPVs relative to the highest pressure designs ranging from approximately $430–$1670, depending somewhat on pressure but more so on contractor design (i.e., the combined effects of initial cost estimates and duct UA values based on individual designs). For the Chicago contractor's designs, the medium pressure PSC + flex combination yielded the highest NPV; for the Austin contractor's PSC + flex combinations, the lowest pressure PSC + flex combination yielded the highest NPV in the Austin home and was similar to the medium pressure results in the Chicago home.

For ECM + flex systems, 15-year NPVs of lower pressure scenarios ranged from a savings of $37 to an excess cost of $1435 with the Chicago contractor's designs. The Austin contractor's designs yielded savings in all lower pressure scenarios ranging from $109 to $419, again with the medium pressure duct system in the Chicago home having a higher NPV than the low pressure system and vice versa in the Austin home. These results suggest that within flexible duct systems only, both medium and low pressure duct systems can generally yield life cycle costs savings over a 15-year period, particularly for PSC systems and often for ECM systems, although the savings are not as large as with PSC blowers and may vary depending on actual duct designs and costs.

To provide a more concise summary of these results, Table 5 also summarizes these results using a simple nomenclature, whereby a positive NPV for a scenario (i.e., a scenario with life cycle cost savings) is marked with a positive sign (+) and scenarios with excess life cycle costs are marked with a negative sign (−).

According to Table 5, the lower pressure flex duct designs reflect life cycle cost savings over the high pressure flex designs in most of the modeled scenarios: six out of eight scenarios for the lowest pressure flex systems and seven out of eight scenarios for the medium pressure flex duct systems.

#### 4.3.2. NPV analysis assuming 15-year life cycle: rigid ducts only

Similar to the analysis for flex duct designs only above, Fig. 5 shows 15-year NPVs of lower pressure designs relative to the highest pressure designs estimated for the Chicago and Austin homes using both the Chicago (IL) and Austin (TX) contractors' rigid duct designs. Table 6 also summarizes these same data using the simplified "±" nomenclature used in the previous summaries.

Limiting life cycle cost comparisons to within rigid systems alone, the lower pressure rigid duct designs also reflect life cycle cost savings over the high pressure rigid designs in the majority of modeled scenarios: five out of eight scenarios for the lowest pressure rigid systems and six out of eight scenarios for the medium pressure rigid duct systems. This is particularly true for PSC blowers, but also for some ECM scenarios. However, the magnitude (and sometimes direction) of savings changed depending on blower type, level of pressure, and details of individual contractor duct designs and initial cost estimates. For example, all of the lower pressure duct designs from the Austin contractor yielded life cycle cost savings (ranging from $460 to $1510 for PSC + rigid combinations and from $64 to $244 for ECM + rigid combinations). The only scenarios that did not yield life cycle savings were those using the Chicago contractor's designs and estimates. ECM scenarios using the Chicago contractor's designs yielded excess life cycle costs in both homes and only one PSC scenario (low pressure in the Chicago home with the Chicago contractor's designs) is expected to yield excess life cycle costs. This was due to a combination of excess ductwork costs and higher duct UA values using only the Chicago contractor's designs; the Austin contractor's designs did not reflect such dramatic changes in upfront costs or duct UA. Details of individual contractor designs thus can have a very large impact on the economics of lower pressure duct systems in residences.

Overall, these results suggest that within the constraints of using rigid duct materials, low pressure duct systems can generally yield life cycle cost savings in systems with PSC blowers (i.e., up to ~$1500), depending on contractor design characteristics and upfront costs. In systems with ECM blowers, lower pressure duct systems can either yield slight life cycle cost savings or as much as ~$1500 in excess life cycle costs in these two homes,

**Table 5**
Summary of 15-year NPV analysis for flex ducts only.

| Home | Contractor | Blower | 15-year NPV relative to high pressure flex[a] | |
|---|---|---|---|---|
| | | | Flex low | Flex medium |
| Chicago | IL | PSC | + | + |
| | | ECM | − | + |
| | TX | PSC | + | + |
| | | ECM | + | + |
| Austin | IL | PSC | + | + |
| | | ECM | − | − |
| | TX | PSC | + | + |
| | | ECM | + | + |
| Number of scenarios w/savings | | | 6/8 | 7/8 |

[a] Positive signs (+) reflect life cycle cost savings. Negative signs (−) reflect excess life cycle costs.

**Table 6**
Summary of 15-year NPV analysis for rigid ducts only.

| Home | Contractor | Blower | 15-year NPV relative to high pressure rigid[a] | |
|---|---|---|---|---|
| | | | Rigid low | Rigid medium |
| Chicago | IL | PSC | − | + |
| | | ECM | − | − |
| | TX | PSC | + | + |
| | | ECM | + | + |
| Austin | IL | PSC | + | + |
| | | ECM | − | − |
| | TX | PSC | + | + |
| | | ECM | + | + |
| Number of scenarios w/savings | | | 5/8 | 6/8 |

[a] Positive signs (+) reflect life cycle cost savings. Negative signs (−) reflect excess life cycle costs.

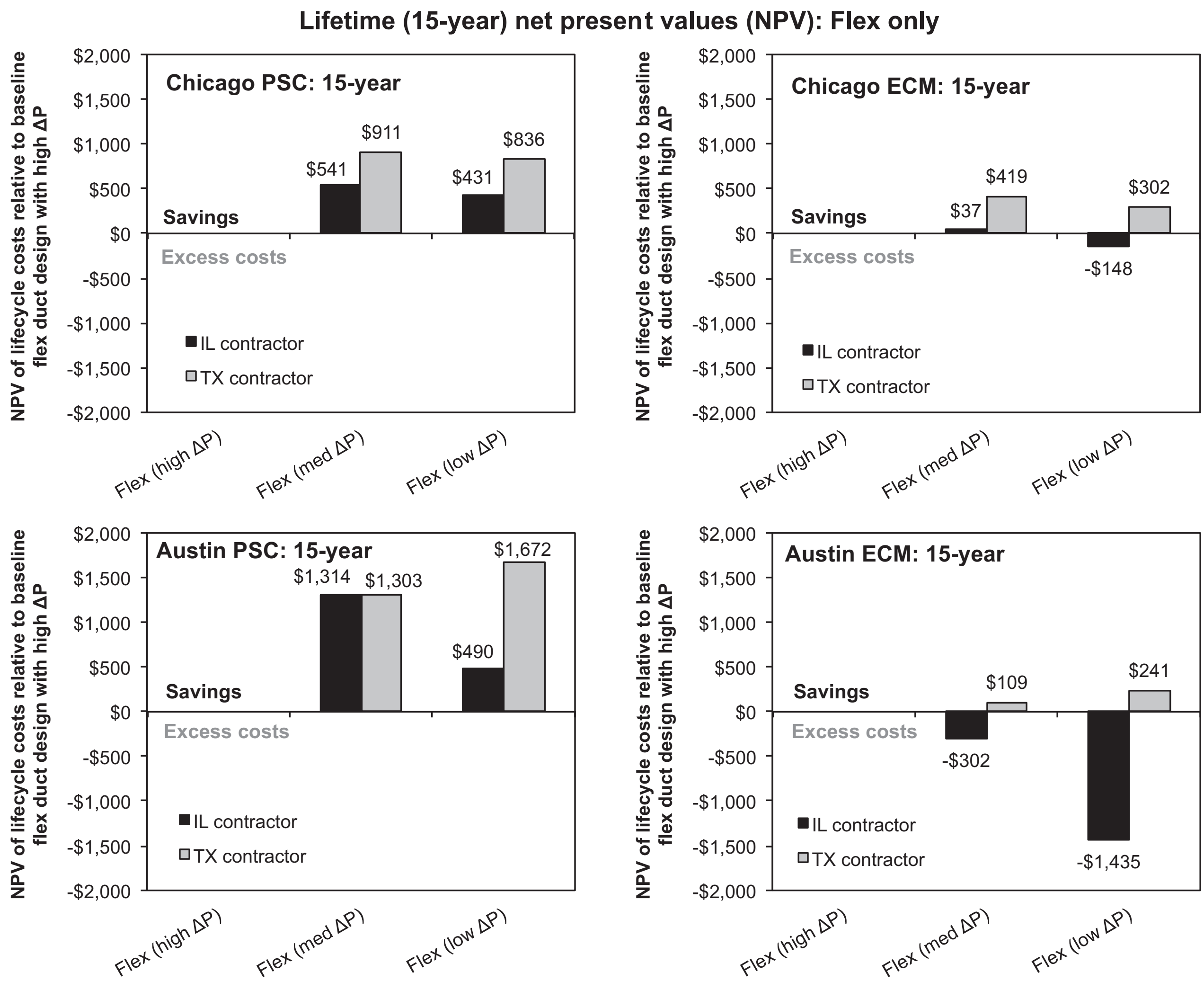


**Fig. 4.** Net present value (NPV) of the life cycle costs of *flex* duct designs over 15-year life relative to a high pressure *flex* duct design in each location and with each type of blower installed and duct designs from both contractors. The high pressure case refers to 275 Pa of total pressure for the Chicago home and 288 Pa of total pressure for the Austin home. Positive values represent scenarios with lifetime savings.

depending primarily on contractor cost estimates and design characteristics.

### *4.3.3. 15-year NPV analysis: comparing both flex and rigid duct scenarios*

There are also cases where one may have the option to select either flexible or rigid metal duct materials. Therefore, we have provided an additional life cycle cost comparison of each of the modeled scenarios comparing across both flex and rigid duct materials, all referenced to what was originally expected to be the least expensive initial cost scenario: the highest pressure flex condition. Figs. 6 and 7 show 15-year NPVs calculated for each of the Chicago and Austin contractors' duct designs and cost estimates, respectively. Both the medium and low pressure flex designs, as well as the low, medium, and high pressure rigid designs, are compared to the highest pressure flex duct design in this analysis. Positive values again indicate scenarios that yield net savings over an assumed 15-year lifetime. Importantly, this analysis assumes that each duct type is equally capable of achieving the target pressures specified. In reality, flexible ductwork materials are much more likely to be constricted during construction due to installation with excessive compression, excessive sag, or being pinched by wires and cables. Therefore these results should be interpreted with some caution.

Table 7 summarizes these results comparing both ductwork materials for both homes with designs from both contractors using the same simple nomenclature as in previous sections. Again, most of the medium and low pressure flex duct designs are predicted to yield life cycle cost savings relative to the high pressure flex designs across both homes and both contractor designs. Six out of eight low pressure flex duct scenarios are expected to yield life cycle cost savings while seven out of eight medium pressure flex duct scenarios are expected to yield savings. These results are the same as the flex only section above. However, in this analysis none of the rigid duct scenarios are expected to yield life cycle savings; their initial cost estimates from both contractors are too high relative to any expected annual HVAC energy cost savings. These results suggest that for this particular home in this particular climate and under the assumptions described herein, lower pressure duct designs yield 15-year life cycle savings only for flexible ductwork. Switching to rigid ductwork and assuming that the target pressures can be met does not yield life cycle cost savings because of very high upfront costs. However, as mentioned, this analysis is limited to the assumption that both ductwork materials are equally likely to achieve the desired pressures.

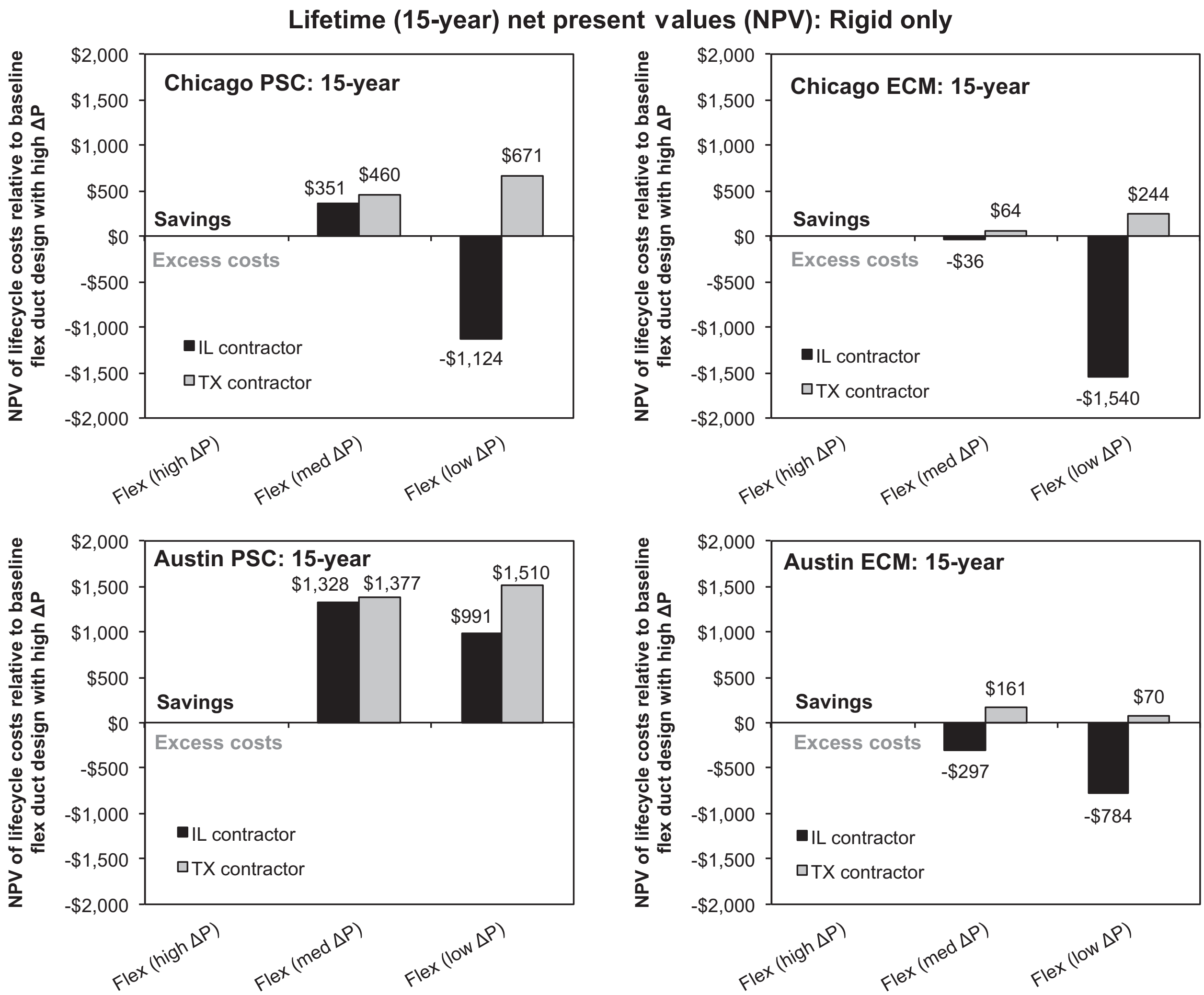


**Fig. 5.** Net present value (NPV) of the life cycle costs of *rigid* duct designs over 15-year life relative to a high pressure *rigid* duct design in each location and with each type of blower installed and duct designs from both contractors. The high pressure case refers to 275 Pa of total pressure for the Chicago home and 288 Pa of total pressure for the Austin home. Positive values represent scenarios with lifetime savings.

## 5. Discussion

There were a total of 48 scenarios modeled herein, which complete a simulation matrix comprising two contractors' duct designs, two model homes, two types of blowers, two types of duct materials, and three levels of duct pressures. If flexible and rigid duct materials are treated separately, sixteen of these simulations represent baseline highest pressure duct designs, leaving a total of 32 lower pressure comparison scenarios. In the Chicago home with flexible ductwork, the lower pressure scenario that provided the greatest life cycle cost savings (highest NPV) relative to the highest pressure scenario was that with a PSC blower operating at medium pressure using the Austin contractor's designs ($911). The lowest pressure PSC scenario with the Austin contractor's designs yielded the next largest cost savings ($836). In the same home with rigid ductwork, the lowest pressure PSC scenario with the Austin contractor's designs yielded the greatest life cycle cost savings (highest NPV) ($671). Three of the four lower pressure PSC scenarios using

**Table 7**
Summary of 15-year NPV analysis for both flex and rigid ductwork.

| Home | Contractor | Blower | 15-year NPV relative to high pressure flex[a] | | | | |
|---|---|---|---|---|---|---|---|
| | | | Flex low | Flex medium | Rigid low | Rigid medium | Rigid high |
| Chicago | Chicago | PSC | + | + | – | – | – |
| | | ECM | – | + | – | – | – |
| | Austin | PSC | + | + | – | – | – |
| | | ECM | + | + | – | – | – |
| Austin | Chicago | PSC | + | + | – | – | – |
| | | ECM | – | – | – | – | – |
| | Austin | PSC | + | + | – | – | – |
| | | ECM | + | + | – | – | – |
| Number of scenarios w/savings | | | 6/8 | 7/8 | 0/8 | 0/8 | 0/8 |

[a] Positive signs (+) reflect positive NPVs (i.e., life cycle cost savings). Negative signs (–) reflect excess life cycle costs.

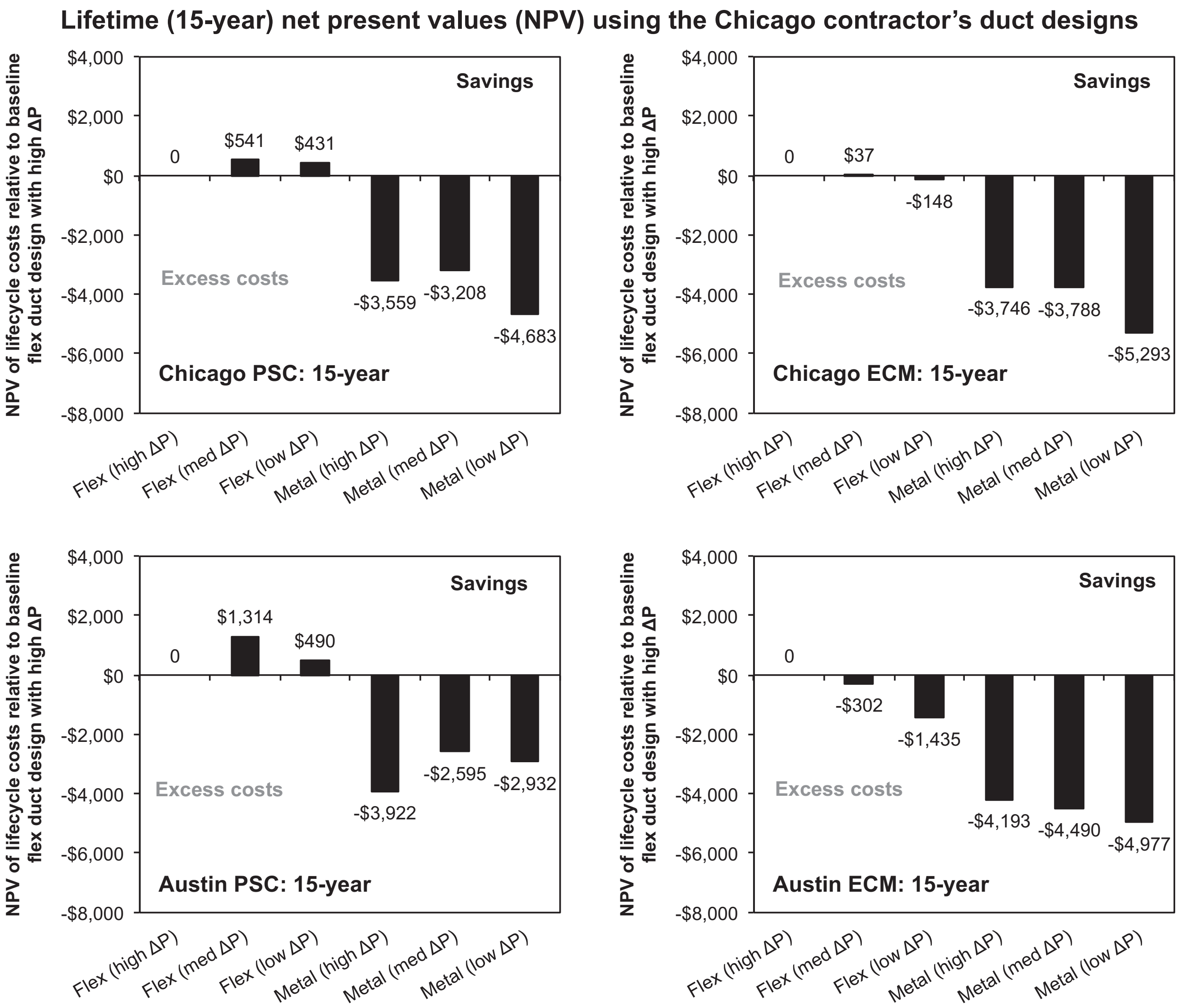


**Fig. 6.** Net present value (NPV) of the life cycle costs of both flex and rigid duct designs over 15-year life relative to the *high pressure flex* duct condition in each location and with each type of blower installed. Duct designs are limited only to the Chicago contractor's for clarity. The high pressure case refers to 275 Pa of total pressure for the Chicago home and 288 Pa of total pressure for the Austin home. Positive values represent scenarios with life cycle cost savings.

the Chicago contractor's designs actually yielded excess life cycle costs (as much as $1540 more), suggesting again that design details and cost estimates play an important role in the life cycle cost impacts of lower pressure duct designs.

In the Austin home with flexible ductwork, the lower pressure scenario that provided the greatest life cycle cost savings relative to the highest pressure scenario was that with a PSC blower operating at the lowest pressure using the Austin contractor's designs ($1672). The medium pressure PSC scenarios with either contractor's designs provided the next largest savings (around $1300). Again, results of lower pressure scenarios with the Chicago contractor's designs and cost estimates were more variable, sometimes providing savings (as much as $1300) and sometimes yielding excess life cycle costs (as much as $1400). In the same home with rigid sheet metal ductwork, the lowest pressure PSC scenario with the Austin contractor's designs again yielded the greatest life cycle cost savings ($1510), with the medium pressure scenario and the Austin contractor's designs not far behind ($1377). Results with the Chicago contractor's estimates were again more variable, with savings as large as $1328 and excess life cycle costs as high as $784.

Taken together, these results suggest that either medium or low pressure flex duct systems are generally preferred from a life cycle cost perspective in these two homes with either contractor's designs, particularly if a PSC blower is installed, and that the magnitude (and sometimes direction) of savings will depend mostly on individual contractor duct designs and cost estimates. These savings are predicted primarily because the lower pressure designs allow for the HVAC systems to maintain adequate airflow rates and operate for shorter periods of time over the course of a year.

### 5.1. Sensitivity

Changes in a number of assumptions in this work may have led to very different results and conclusions. For example, changes in assumptions for future energy costs, duct leakage fractions, ductwork insulation values, thermostat set points, envelope thermal performance, HVAC equipment efficiency (i.e., SEER for both air-conditioning units, AFUE for the furnace, and HSPF for the heat pump), HVAC equipment and ductwork lifespans, and the location of the ductwork (i.e., moving inside to conditioned space), can all have a large impact on the simulation results. However, it was beyond the scope of this project to systematically vary each parameter individually as would be appropriate for a large suite of Monte Carlo simulations, so we rely primarily on a qualitative discussion of the sensitivity to these important parameters with some quantitative approximations of one particular influence.

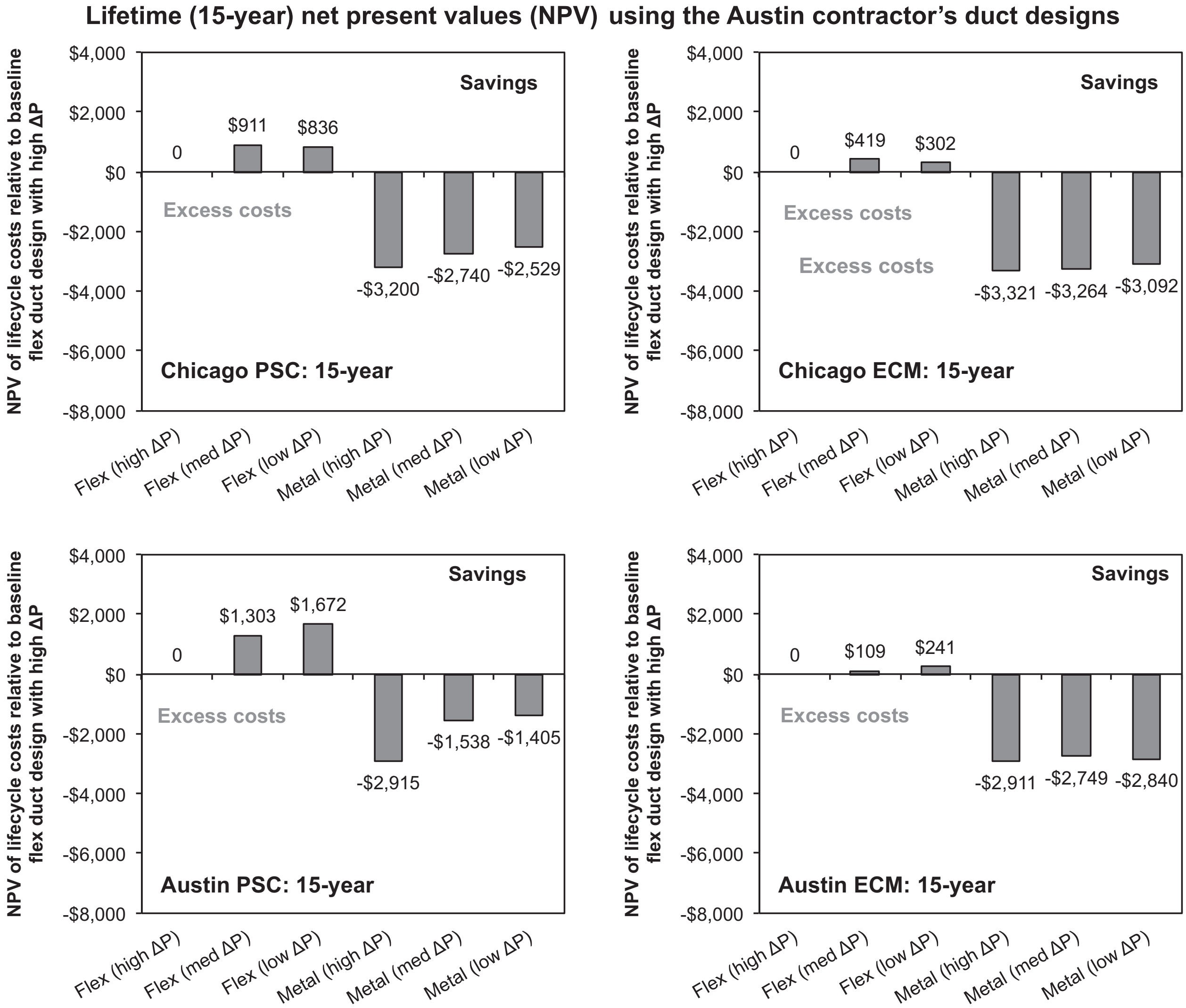


**Fig. 7.** Net present value (NPV) of the life cycle costs of both flex and rigid duct designs over 15-year life relative to the *high pressure flex* duct condition in each location and with each type of blower installed. Duct designs are limited only to the Austin contractor's for clarity. The high pressure case refers to 275 Pa of total pressure for the Chicago home and 288 Pa of total pressure for the Austin home. Positive values represent scenarios with life cycle cost savings.

For one, if future energy costs for either natural gas or electricity were to increase at a greater rate than what is modeled herein, the predicted annual savings in energy costs for each of the lower pressure duct scenarios would be larger and would thus yield larger life cycle savings relative to the baseline high pressure flex conditions. Depending on the increase in energy costs this could potentially increase the number of scenarios with life cycle cost savings. Similar impacts would be seen if other inputs that affect the absolute amount of energy used for space conditioning were also varied, including higher thermostat settings in the winter, lower thermostat settings in the summer, decreased envelope performance, and decreased HVAC equipment efficiency. Conversely, lower thermostat settings in the winter, higher thermostat settings in the summer, improved envelope performance, increased HVAC equipment efficiency, and moving ducts into conditioned space would all work to decrease annual energy demands and thus make differences between scenarios even smaller, which could potentially decrease the number of scenarios in which positive NPVs are observed.

As an example of the potential of these effects, we explored how the results may vary with one particularly important set of input parameters: HVAC equipment efficiency. The modeled homes relied on SEER 15 air-conditioning units (both homes), a heat pump with 8.5 HSPF (Austin), and a gas furnace with 92.5 AFUE (Chicago). If the efficiency of the air-conditioning units was decreased to SEER 13, the HSPF was decreased to 7.7, and the furnace was decreased to AFUE 80, which are each more in line with code minimums in most locations, then the modeled homes would be expected to use approximately 15% more energy for cooling in both homes and 10 and 16% more energy for heating in the Austin and Chicago homes, respectively, using a simple comparison of nominal COP values. Systems would not run longer because the loads would not change; only the amount of energy required to meet the same loads would change at each time step. This simple linear approximation was verified using only one altered simulation case. Using these simple differences, although the magnitude of savings changed by as much as about $250 in terms of 15-year NPV, the number of simulation cases resulting in life cycle cost savings did not change, suggesting that the summary of results herein is not impacted significantly by these assumptions for input parameters. Other variations in input parameters may have different impacts but are not explored in this work.

A final important assumption to explore is the use of a 15-year life cycle in our NPV calculations. A 15-year timeline was used because although duct systems are expected to last much longer, these simulations rely on accurate assumptions for HVAC equipment efficiency. Typical HVAC equipment lifespans are in the range of 15 years, so it is very likely that in the lifespan of a duct system, some or all HVAC equipment components would be replaced. However, there is no way of knowing what efficiency equipment will be available on the market 15 years from now, let alone what their upfront costs may be. Therefore, we simply explored the sensitivity of our results to the assumption of life cycle length by repeating our analyses with a 30-year life cycle. Importantly, adjusting to a 30-year lifespan did not drastically change the direction of most results herein. In fact, only one scenario (the PSC + rigid medium pressure design in the Chicago home using the Chicago contractor's designs) moved from a net excess cost to a slight net savings. The magnitude of savings did however increase over time for most scenarios. These results suggest that the assumed timeframe does not have a large impact on this analysis in these homes and under all of the underlying assumptions used herein.

### *5.2. Limitations*

There are a number of important limitations to this work that should be mentioned. For one, this work was limited to the particular homes, climates, duct designs, cost estimates, and choices of input parameters used herein. Results may not be extrapolated directly to other environments. Second, this work did not capture any changes in system pressures over time; pressures were assumed constant throughout the year. Third, this work assumed that both flexible and rigid sheet metal ductwork have the same likelihood of being installed according to industry quality standards and therefore can meet the specified design pressures. In reality, flexible ductwork materials are more likely to be constricted during construction due to installation with excessive compression, excessive sag, or being pinched by wires and cables. However, these impacts were not captured herein. Fourth, this work focused only on energy consumption impacts and did not explore other factors such as air distribution effectiveness, occupant comfort, indoor air quality, or noise. Finally, this work did not explore differences in equipment reliability and maintenance that may differ across the ductwork materials used or between the two blower types. For example, blower motors may need to be replaced more often when subjected to excessive static pressures, but we are not aware of accurate ways to estimate replacement times under different operational conditions and thus these impacts remain beyond the scope of this study. Future work should systematically explore the sensitivity of these results and conclusions to deviations from a number of important input parameters and assumptions used herein.

## 6. Conclusions

It is commonly assumed that lower pressure duct systems are preferred for use in central residential heating and air-conditioning systems because they will result in greater airflow rates and cooling and heating capacities with PSC blowers and lower fan power draws with ECM blowers. Results from the 48 annual building energy simulations and life cycle cost analyses using a number of blower types, ductwork materials, and duct designs meeting a range of specified external static pressures in the two model homes described herein suggest the following:

1. Lower airflow rates and heating and cooling capacities caused by excessive system pressures (e.g., total external static pressures of 275–288 Pa) introduced by duct designs with high static pressures in the model homes with PSC blowers yielded substantial increases in HVAC energy use compared to the same systems operating with lower pressure duct designs (e.g., total external static pressures of 125–138 Pa).
2. HVAC energy impacts of the same systems using ECM blowers were not as large as those using PSC blowers because although ECM blowers draw more power to maintain nearly constant airflow rates and heating and cooling capacities at higher pressure drops, fan power was a small portion of the overall HVAC energy use.
3. When the initial costs of lower pressure duct designs were taken into account over a 15-year or 30-year life cycle, lower pressure duct designs generally yielded life cycle cost savings relative to the highest pressure duct systems, particularly in homes with PSC blowers and particularly when making comparisons with constant ductwork materials (i.e., comparing flex only or rigid only).
4. Lower pressure duct designs combined with ECM blowers can also yield life cycle cost savings over the highest pressure duct designs, although the magnitude of savings was typically lower than with PSC blowers and varied depending on specific duct design details and contractor cost estimates.
5. Specific details in contractor duct designs and cost estimates intended to meet specific external static pressures can have a large influence on the impacts that ductwork designs can have on HVAC energy consumption and total life cycle costs in residences.

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