

Modeling the energy and cost impacts of excess static pressure in central forced-air heating and air-conditioning systems in single-family residences in the U.S.



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ABSTRACT

Many central residential forced-air heating and air-conditioning systems contain high pressure drop elements such as high-efficiency or dust-loaded filters, dirty coils, or constricted or undersized ductwork, which are widely assumed to have substantial energy and economic impacts. However, the overall energy and cost consequences of excess static pressures have not been explored in depth across a wide range of climates, homes, or system characteristics. Therefore, we performed 780 annual building energy simulations using BEopt and EnergyPlus to predict the energy and cost impacts of realistic excess static pressures for typical new and existing single-family homes with both permanent split capacitor (PSC) blowers and electronically commutated motors (ECM) in 15 U.S. climate zones. Results demonstrate that excess static pressures can increase annual energy consumption and costs, but the magnitude varies by blower type and climate zone. Moderate increases in static pressures (i.e., from 50 to 150 Pa) were predicted to yield minimal increases in annual space conditioning energy costs (i.e., less than 3% across all homes, blowers, and climates), while more extreme increases in static pressure (i.e., from 50 to 350 Pa) were predicted to yield average increases in energy costs of ~9% with ECM blowers and ~18% with PSC blowers.

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1. Introduction

Residential buildings are responsible for over 20% of primary energy consumption in the U.S. and more than 45% of this amount is used for heating and air-conditioning [1]. Over 60% of existing residential buildings and approximately 90% of new residences in the U.S. use central forced-air distribution systems for space conditioning purposes [2]. Additionally, the vast majority of residential buildings in the U.S. are detached single-family dwellings (~70%) [3]. Therefore, central forced-air heating and air-conditioning systems in single-family residences play a crucial role in the energy use and costs attributable to the U.S. building stock. Many central residential heating and air-conditioning systems contain high pressure drop elements such as high-efficiency filters, dust-loaded filters, dirty coils, constricted or undersized ductwork, or closed registers or grilles [4–10]. These excess system pressures are widely

assumed to have substantial energy and economic impacts [11–14]. However, the overall energy and cost consequences of excess static pressures have not been explored in depth across a wide range of climates, homes, or system characteristics.

The energy impacts of high static pressures are highly dependent on both the type of blower motor used in the air handling unit and the magnitude of excess static pressure [9,12,13,15]. Two types of blower motors are most commonly used in residential forced-air systems: permanent split capacitor (PSC) motors and electronically commutated motors (ECM) [16]. These blower motors respond differently to increases in static pressures. In a system with a PSC blower, an increase in static pressure will typically lead to a decrease in the airflow rate, often a reduction in fan power draw (depending on the operating point on both the system and fan curves), a decrease in delivered sensible and latent capacity, and an increase in system runtime, which, if large enough, will also lead to an increase in total energy consumption [9].

Conversely, in a system with an ECM blower, which uses a combination of a brushless permanent magnet (BPM) motor and electronic converter to achieve variable speed operation [16], the fan speed will typically increase in order to maintain a relatively constant airflow rate and thus increase fan power draw while

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keeping sensible capacity, latent capacity, and system runtime relatively constant. The overall energy impacts depend largely on the increase in fan power and, to a lesser extent, the amount of excess heat rejected into the airstream. ECM blowers also tend to have higher efficiency and lower power draw than PSC blowers at most static pressures, and thus typically have lower power draw at most operating points [9]. As of 2002, approximately 90% of residential air handling units utilized PSC motors [17], although the share has decreased in recent years with the use of ECM blowers in newer equipment in both new construction and replacements in older homes [18–22].

Standard air-conditioning and heat pump test procedures assume that air handling units and fans are subject to relatively low external static pressures ranging from 25 to 50 Pa in the absence of coil pressure drop or between 75 and 125 Pa including the coil pressure drop, depending on the nominal capacity of the unit [5,23,24]. However, several field studies have demonstrated that most residential systems typically face much higher pressures. For example, in a study of 31 homes in Wisconsin, Pigg and Talerico (2004) measured total static pressures ranging from ~60 Pa to at least 250 Pa [25]. In a study of 60 new homes in California, Wilcox et al. (2006) measured total static pressures during periods of cooling operation ranging from ~75 Pa to as high as ~300 Pa [26]. Most recently, Proctor et al. (2011) measured total static pressures in 80 new homes in California ranging from approximately 130 Pa to over 300 Pa, with the average near ~215 Pa [10]. Similarly high static pressures have also been documented in other recent studies [5–8,27].

Although the magnitudes of excess static pressures in central residential forced-air heating and cooling systems have been well documented, the overall energy and cost consequences have not been explored in depth across a large number of climates, homes, or system characteristics. Therefore, in this work we performed whole building energy simulations using a combination of BEopt [28] and EnergyPlus [29] to predict the annual energy and cost impacts of a wide range of realistic static pressure conditions for two typical vintages of single-family homes (each with both ECM and PSC blowers) in 15 U.S. climate zones. Thirteen external static pressures were chosen to model in each location and home type, increasing from a low of 50 Pa as the baseline static pressure drop to as high as 350 Pa, corresponding to the range of realistic values observed in the literature. A total of 780 individual scenarios were modeled across the matrix of four home types, 15 climate zones, and 13 static pressure conditions.

2. Methodology

The next sections describe the characteristics of the case study model homes and geographic locations (Section 2.1); determinations of inputs for system static pressures, airflow rates, fan power draws, and heating and cooling capacities (Section 2.2); and the energy simulation procedures (Section 2.3).

2.1. Selection of model homes and geographic locations

Fifteen cities were selected to represent all major U.S. climate zones with a wide variety of heating degree days (HDD) and cooling degree days (CDD) [30], as shown in Table 1. Energy prices were assigned to each location based on state-level averages of annual retail electricity and natural gas prices for residential customers in 2013, which were gathered from the US EIA's Electricity Data Browser [31] and Natural Gas Summary [32], respectively.

Two types of homes were selected for modeling in each of the 15 cities: (1) a typical modern high-efficiency home, and (2) a

typical existing, slightly older, less efficient home. These home vintages were intentionally chosen to capture a range of envelope characteristics, air-conditioner and furnace capacities and efficiencies, and heating and air-conditioning system runtimes. In all climate zones, the same basic home geometry and heating and cooling system types were used, although assumptions for building envelope characteristics varied by location and vintage. The model home is a 188 m² single-family home with three bedrooms, two bathrooms, 2.4 m high ceilings, a natural gas furnace, and a central forced-air air-conditioning system. The selection of specific home characteristics is described in the next sections for each home type.

2.1.1. Modern high-efficiency home

The typical modern high-efficiency home was designed to meet or exceed 2009 International Energy Conservation Code (IECC) requirements in all 15 climate zones [30]. The modern high-efficiency homes were modeled with relatively high airtightness (3 ACH₅₀) in all locations. A detailed summary of all climate-specific characteristics for new homes is shown in Table 2. Walls were wood-framed with fiberglass batt insulation installed between studs 0.4 m on center in either 5 cm × 10 cm cavities (for RSI-2.29 m²K/W walls) or 5 cm × 15 cm cavities (for RSI-3.70 m²K/W walls), depending on location. Fiberglass batts were also modeled in the ceiling, with *R*-values dependent on climate zone. All windows were modeled as air-filled double-pane glazing with nonmetal frames, with low-gain (SHGC = 0.3) and low-e glazing. Window areas were set to 4, 8, 4, and 4 m² for front, back, left, and right facades, respectively (corresponding to window-to-wall ratios of approximately 12%, 24%, 12%, and 12%). Window *U*-values varied by location. Foundation types varied between crawlspace, basement, and concrete slab, depending on the most common prevalence in each location according to the US Census Bureau [33]. All homes faced north and had a vented attic.

Supplemental mechanical ventilation systems were modeled in the new homes either as direct outdoor air supply systems (in mixed climates) or as energy recovery ventilators (ERVs) with 72% sensible recovery efficiency (in climates with extreme winters or summers). The new homes were also modeled with properly sized high-efficiency heating and air-conditioning systems for each climate zone. The efficiency of gas furnaces was modeled as 98% AFUE and the efficiency of 1-stage central DX air-conditioning units was modeled as 16 SEER (13 EER). Initial simulations in BEopt were used to properly size the central air-conditioner and gas furnace in each home, although adjustments were made to select more realistic air-conditioner and furnace sizes in common commercially available increments of nominal capacity (e.g., in increments of 1.77 or 3.53 kW). Insulated ductwork (RSI-1.4 m²K/W) with 7.5% duct leakage was installed in either the unfinished attic or basement, depending on location. Nominal airflow rates were assigned based on cooling capacity assuming a standard industry recommendation of 193 m³/h per kW of capacity.

2.1.2. Typical existing home

The typical existing homes were chosen to represent common existing, slightly older, and less efficient homes with moderate building envelope insulation, moderate airtightness (10 ACH₅₀), and larger and less efficient heating and air-conditioning systems for each climate zone based on typical existing home characteristics in each location. A detailed summary of all climate-specific characteristics for the existing model homes is shown in Table 3. Envelope characteristics such as *R*-values of walls, ceilings, and foundations, window *U*-values and SHGC, and window-to-wall areas were taken from two national surveys of existing homes built after 1979 [34,35]. Foundation types varied by location in the same manner as the modern high-efficiency homes. Window areas were set to

Table 1

Fifteen selected cities from all U.S. climate zones.

Climate zone	City	State	HDD	CDD	Electricity cost	Natural gas cost	
			K-days	K-days	\$/kWh	\$/GJ	\$/kWh
1A	Miami	FL	77	2342	0.114	19.1	0.069
2A	Houston	TX	812	1564	0.114	10.8	0.039
2B	Phoenix	AZ	734	2367	0.117	14.4	0.052
3A	Dallas	TX	1314	1472	0.114	10.8	0.039
3B	Los Angeles	CA	716	183	0.164	10.2	0.037
3C	San Francisco	CA	1662	17	0.164	10.2	0.037
4A	New York	NY	2700	603	0.188	12.9	0.046
4B	Albuquerque	NM	2369	681	0.117	9.2	0.033
4C	Seattle	WA	2441	86	0.087	11.7	0.042
5A	Chicago	IL	3505	471	0.103	8.5	0.030
5B	Denver	CO	3204	495	0.119	8.1	0.029
6A	Minneapolis	MN	4281	424	0.119	8.5	0.030
6B	Helena	MT	4242	177	0.104	8.5	0.030
7A	Fargo	ND	5042	282	0.091	7.7	0.028
7B	Aspen	CO	4646	34	0.119	8.1	0.029

Table 2

Climate-specific characteristics of the IECC 2009 compliant modern energy-efficiency homes in each location.

Location	Floor construction	Wall RSI (m ² K/W)	Attic RSI (m ² K/W)	Window U-value (W/m ² K)	Mech. Vent.	Cooling capacity (kW)	Heating capacity (kW)	Nominal airflow rate (m ³ /h)
1A – Miami	Slab, uninsulated	2.3	5.3	6.8	ERV	10.6	10.6	2040
2A – Houston	Slab, uninsulated	2.3	5.3	3.7	ERV	10.6	10.6	2040
2B – Phoenix	Slab, uninsulated	2.3	5.3	3.7	ERV	14.1	10.6	2720
3A – Dallas	Slab, uninsulated	2.3	5.3	2.8	Supply	12.3	10.6	2380
3B – Los Angeles	Slab, uninsulated	2.3	5.3	2.8	ERV	7.0	10.6	1360
3C – San Francisco	Slab, uninsulated	2.3	5.3	2.8	Supply	7.0	10.6	1360
4A – New York	Basement, RSI-1.76 walls	2.3	6.7	2.0	Supply	7.0	10.6	1360
4B – Albuquerque	Slab, RSI-1.76 exterior	2.3	6.7	2.0	Supply	8.8	10.6	1700
4C – Seattle	Slab, RSI-1.76 exterior	3.2	6.7	2.0	Supply	7.0	10.6	1360
5A – Chicago	Basement, RSI-1.76 walls	3.2	6.7	2.0	Supply	7.0	10.6	1360
5B – Denver	Slab, RSI-1.76 exterior	3.2	6.7	2.0	Supply	8.8	10.6	1700
6A – Minneapolis	Basement, RSI-2.64 walls	3.2	8.6	2.0	Supply	7.0	14.1	1360
6B – Helena	Slab, RSI-1.76 exterior	3.2	8.6	2.0	Supply	7.0	14.1	1360
7A – Fargo	Basement, RSI-2.64 walls	3.7	8.6	2.0	ERV	7.0	14.1	1360
7B – Aspen	Slab, RSI-1.76 exterior	3.7	8.6	2.0	ERV	7.0	10.6	1360

Table 3

Climate specific characteristics of the existing homes in each location.

Location	Floor construction	Wall RSI (m ² K/W)	Attic RSI (m ² K/W)	Window U-value (W/m ² K)	Cooling capacity (kW)	Heating capacity (kW)	Nominal airflow rate (m ³ /h)
1A – Miami	Basement, RSI-3.34 floor	1.94	4.76	2.78	14.1	10.6	2720
2A – Houston	Slab, RSI-0.88 exterior	1.94	4.76	2.78	17.6	14.1	3400
2B – Phoenix	Slab, RSI-0.88 exterior	2.29	5.11	2.78	17.6	10.6	3400
3A – Dallas	Slab, RSI-0.88 exterior	1.94	4.76	2.78	17.6	17.6	3400
3B – Los Angeles	Slab, uninsulated	1.94	4.40	2.78	10.6	10.6	2040
3C – San Francisco	Slab, uninsulated	1.94	4.40	2.78	10.6	14.1	2040
4A – New York	Basement, RSI-3.34 floor	2.29	4.76	2.78	14.1	17.6	2720
4B – Albuquerque	Slab, RSI-1.76 exterior	2.29	5.11	2.78	15.8	17.6	3060
4C – Seattle	Slab, RSI-1.76 exterior	1.94	5.64	2.78	7.0	14.1	1360
5A – Chicago	Basement, RSI-1.76 walls	2.29	5.64	2.78	15.8	24.6	3060
5B – Denver	Slab, RSI-1.76 exterior	2.29	5.11	2.78	14.1	21.1	2720
6A – Minneapolis	Basement, RSI-2.64 walls	3.35	5.64	2.78	15.8	28.1	3060
6B – Helena	Slab, RSI-1.76 exterior	2.29	5.11	2.78	14.1	28.1	2720
7A – Fargo	Basement, RSI-2.64 walls	3.35	5.64	2.78	14.1	31.7	2720
7B – Aspen	Slab, RSI-1.76 exterior	2.29	5.11	2.78	10.6	21.1	2040

20%, 40%, 20%, and 20% for front, back, left, and right, respectively. Windows were the same in all locations: air-filled double-pane with nonmetal frames, with higher *U*-values (2.78 W/m² K) and higher solar gain (SHGC=0.79) than modern high-efficiency homes.

There were no mechanical ventilation systems modeled in the existing homes. BEopt was again used to properly size the central air-conditioner and gas furnace (which were typically larger than the new homes in each location), and again more realistic

air-conditioner and furnace nominal capacities were assigned based on commonly available incremental capacities of 1.77 or 3.53 kW. The efficiency of gas furnaces was modeled as 90% AFUE and the efficiency of 1-stage central DX air-conditioning units was modeled as 10 SEER (8.75 EER). Ductwork was placed in unconditioned attics or basements depending on location, with RSI-0.7 m²K/W insulation and 15% duct leakage. Nominal airflow rates were also assigned assuming a standard industry recommendation of 193 m³/h per kW of cooling capacity.

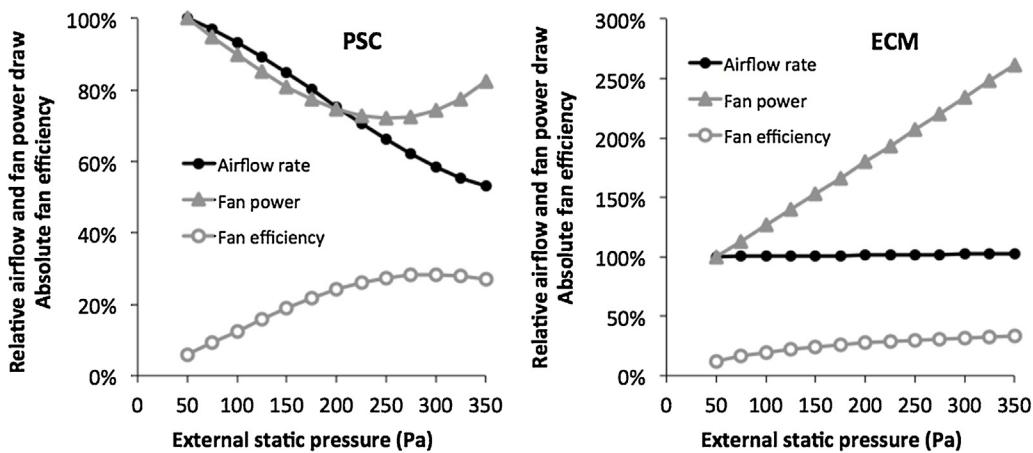


Fig. 1. Relative fan airflow rates, relative fan power draws, and absolute fan efficiencies for virtual models of generally representative PSC and ECM blowers [36].

2.2. Determining operating static pressures, airflow rates, and fan efficiencies

Thirteen external static pressures were chosen to model, increasing from a low of 50 Pa as the baseline static pressure drop to as high as 350 Pa, corresponding to the range of values measured in real homes as described in Section 1. These target external static pressures represent the total pressure that may be introduced by a combination of filters, supply, ductwork, coils, registers and return grilles. Both PSC and ECM blower motors were used in each home, creating four distinct home scenarios in each location: (1) new homes with ECM blowers, (2) new homes with PSC blowers, (3) existing homes with ECM blowers, and (4) existing homes with PSC blowers. A total of 780 individual scenarios were modeled herein, spanning a matrix of the four home types in 15 climates, each modeled at 13 static pressure conditions.

Polynomial fits of fan and efficiency curves for virtual model furnaces were selected from a review of residential air handling units by the U.S. Department of Energy [36] and were used to define inputs for each fan type. The relationships between fan airflow rate, fan efficiency, and fan power draw across the 13 external static pressures for these generally representative blower motors is shown in Fig. 1. These same curves have been used successfully in other recent modeling work [9]. Only relative changes in airflow rates and fan power draws are shown in Fig. 1 because nominal airflow rates and fan power draws (which were assumed to be achieved at the lowest static pressure of 50 Pa in each home) varied according to nominal heating and cooling capacities using the assumption of 193 m³/h per kW of cooling recommended by most manufacturers. For example, a 10.6 kW air-conditioning unit was assumed to have a nominal (maximum) airflow rate of ~2040 m³/h at 50 Pa, decreasing in response to increased static pressure for a PSC blower and remaining relatively constant for an ECM blower following the relationships in Fig. 1.

Fan power draw (W_{fan} , in units of W) was calculated for each static pressure condition in each home and location using Eq. (1), which is based on the airflow rate (Q_{fan} , m³/s), the total system pressure (ΔP_{system} , Pa), and the combined efficiency of the fan and motor ($\eta_{\text{fan+motor}}$, dimensionless). The relationship between fan efficiency and static pressure is also shown in Fig. 1 albeit in absolute terms. Nominal fan efficiencies started at 6% at the maximum flow rate (at 50 Pa) for PSC blowers and at 12% for ECM blowers. Airflow rates were assumed to be the same for both cooling and heating modes for simplicity; recent studies suggest that this is a reasonable assumption in many homes [9,13].

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

2.3. Annual energy simulation with BEopt and EnergyPlus

Annual energy simulations covering each home type, blower motor, climate zone, and static pressure condition were performed using a combination of BEopt Version 2.1.0.0 and EnergyPlus Version 8.1.0 following similar procedures used in Stephens (2014) [9]. BEopt was first used to generate EnergyPlus input files (IDF files) for each of the homes based on geometry and the basic inputs from Table 1. All inputs related to occupant activity and internal loads, such as window opening during mild weather and appliance, lighting, and miscellaneous load profiles were chosen as the default values in BEopt, which relies on a reference building defining by Building America House Simulation Protocols. IDF files were generated by first running initial simulations in BEopt with EnergyPlus as the engine, and then the EnergyPlus IDF files were copied and the initial BEopt simulation results were discarded. The IDF files were then edited to adjust the relevant input parameters for each of the 780 distinct scenarios across two home vintages, two fan types, 15 climate zones, and 13 static pressure conditions. Relevant inputs that varied for each scenario include the airflow rate, static pressure, fan efficiency, and nominal cooling and heating capacities. Nominal heating and cooling equipment capacities and airflow rates were changed from 'auto-size' as calculated by BEopt to proper sizes based on those listed in Table 1.

'Rated' airflow rates were kept at the maximum (i.e., nominal) value for each simulation case, but the 'design' and 'specified' airflow rates were adjusted for each model scenario. We also made changes to the fan static pressure, fan efficiency, cooling capacity, and heating capacity for each scenario by editing the IDF file directly. Airflow rates were changed in the following sections of the IDF: AirLoopHVAC:UnitaryHeatCool, Fan:OnOff, AirTerminal:SingleDuct:Uncontrolled, and Branch. Fan static pressure and fan efficiency, which along with airflow rates govern fan power draw (Eq. (1)), were adjusted in the Fan:OnOff section for each scenario. Nominal cooling and heating capacities were adjusted in the Coil:Cooling:DX:SingleSpeed and Coil:Heating:Gas sections, respectively. Finally, the time steps for each simulation case were changed to 6 under the Timestep and Sizing:Parameters sections. Built-in polynomial functions in EnergyPlus were then relied upon to calculate heating and cooling capacity, COP, and outdoor unit power draw as a function airflow rates using generic air-conditioning, heat pump, and furnace models. Thermostat set points were held constant in all locations at 21.1 °C in the

winter and 24.4 °C in the summer. Typical meteorological year (TMY3) weather files from the nearest site were used in each climate zone.

Annual HVAC energy related outputs from the EnergyPlus simulations were then used for cost estimates and subsequent analysis, including annual electricity use by the air handling unit fan ('fan energy'), electricity use by the condenser-compressor unit ('cooling energy'), and natural gas use by the furnace ('heating energy'). All units were converted to kWh for simplicity in comparisons, and the annual heating and cooling energy outputs were used to explore the impacts of increasing static pressures on both annual energy use and energy costs (assuming regional energy prices in Table 1) for all home types with each blower motor in each climate zone.

3. Results

3.1. Baseline annual space conditioning energy consumption and costs

Results for estimates of annual site energy consumption from the 60 baseline simulations spanning the four home and blower combinations operating at 50 Pa in each of the 15 climate zones are shown in Fig. 2. Annual HVAC site energy consumption was predicted to be higher in the existing homes than in the new homes, as expected, and higher in homes in colder climates with more heating degree-days. Values of annual HVAC site energy use ranged from a low of only ~1620 kWh in the new home in Los Angeles, CA (with only 716 HDD and 183 CDD) to as high as ~36,850 kWh in the existing home in Fargo, ND (with 5042 HDD and 282 CDD). The average total HVAC site energy use was ~12,810 kWh across all baseline simulations, just below the national average residential usage for space conditioning of ~13,650 kWh in 2005 [37].

The maximum annual electricity consumption (for cooling and fan energy combined) occurred in the existing home with a PSC blower in Phoenix, AZ (~8870 kWh), while the minimum space conditioning electricity consumption occurred in the new

home with an ECM blower in San Francisco, CA (only ~100 kWh). Conversely, the maximum annual natural gas consumption for heating purposes occurred in the existing home with a PSC blower in Fargo, ND (~35,240 kWh), while the minimum natural gas consumption occurred in the new home with a PSC blower in Miami, FL (~11 kWh). Comparing across fan types, the lower power draw of ECM fans relative to PSC fans at the baseline static pressure conditions were predicted to yield annual fan energy savings; however, fan energy use is only a small portion of the overall HVAC energy consumption in most homes, particularly in heating-dominated climates.

Similarly, results for estimates of annual site energy costs for space conditioning purposes from the 60 baseline static pressure simulations are shown in Fig. 3. Estimates of total heating, cooling, and fan energy costs (i.e., 'HVAC energy' costs) at nominal static pressures, airflow rates, and fan power draws ranged from as little as \$83 in the new home with an ECM blower in Los Angeles, CA to as high as \$1132 in the existing home with a PSC blower in New York, NY. The average annual total HVAC energy cost was predicted to be just under \$600 across all homes and climates, which is about 30% less than the national average household in 2005 [38]. Overall, these baseline results demonstrate a reasonable range of space conditioning energy costs across a wide range of climate zones and housing types the U.S.

3.2. Influence of static pressure on annual space conditioning energy use

Results for changes in annual natural gas and electricity use for space conditioning purposes for all 13 static pressures were compared to baseline estimates at 50 Pa in the following sections, first for new homes and then for existing homes.

3.2.1. New homes

Fig. 4 shows estimates of changes in annual natural gas and electricity use for space conditioning purposes in the new high-efficiency homes with both ECM and PSC blower motors at all static

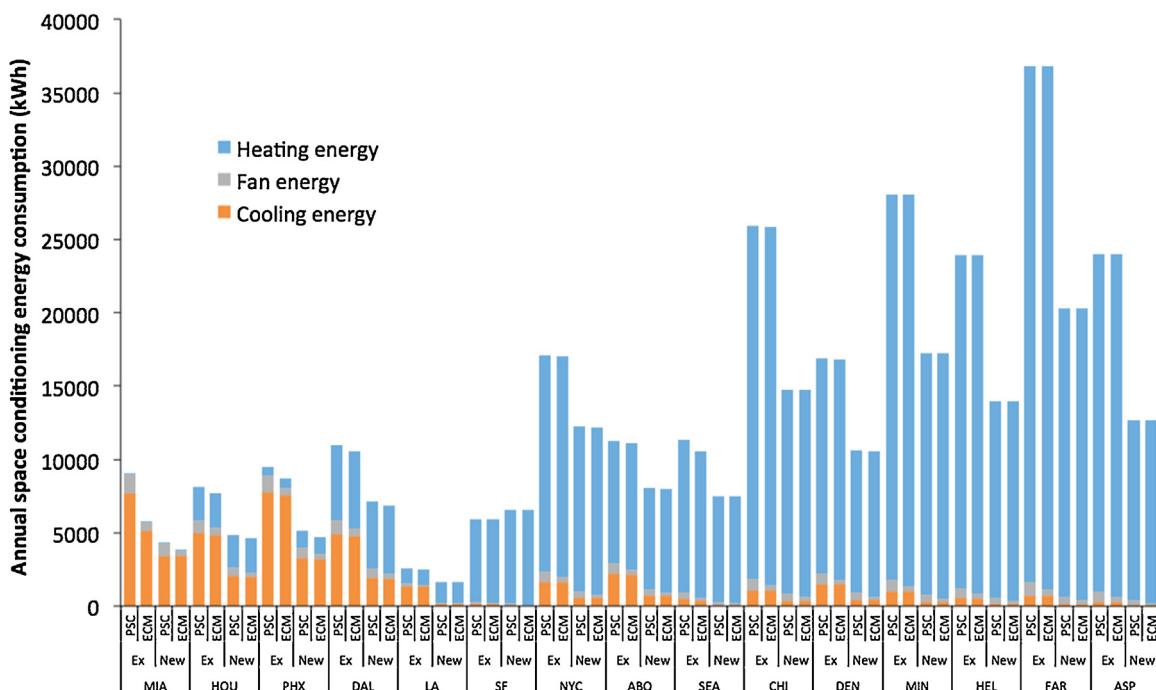


Fig. 2. Baseline estimates of annual space conditioning energy consumption (including heating, cooling, and fan energy) in both new and existing homes with both PSC and ECM blowers operating at a static pressure of 50 Pa in each of the 15 model locations. Natural gas and electricity are both shown in units of kWh.

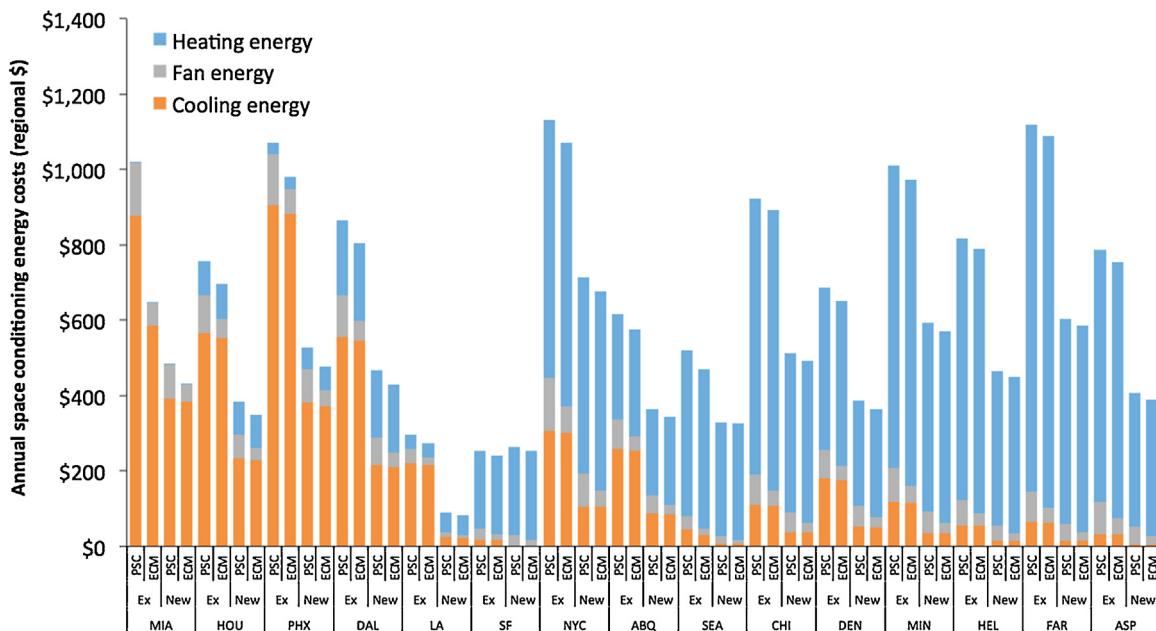


Fig. 3. Baseline estimates of annual space conditioning energy costs (including heating, cooling, and fan energy) in both new and existing homes with both PSC and ECM blowers operating at a static pressure of 50 Pa in each of the 15 model locations. Energy cost estimates assume regional residential energy prices for natural gas and electricity.

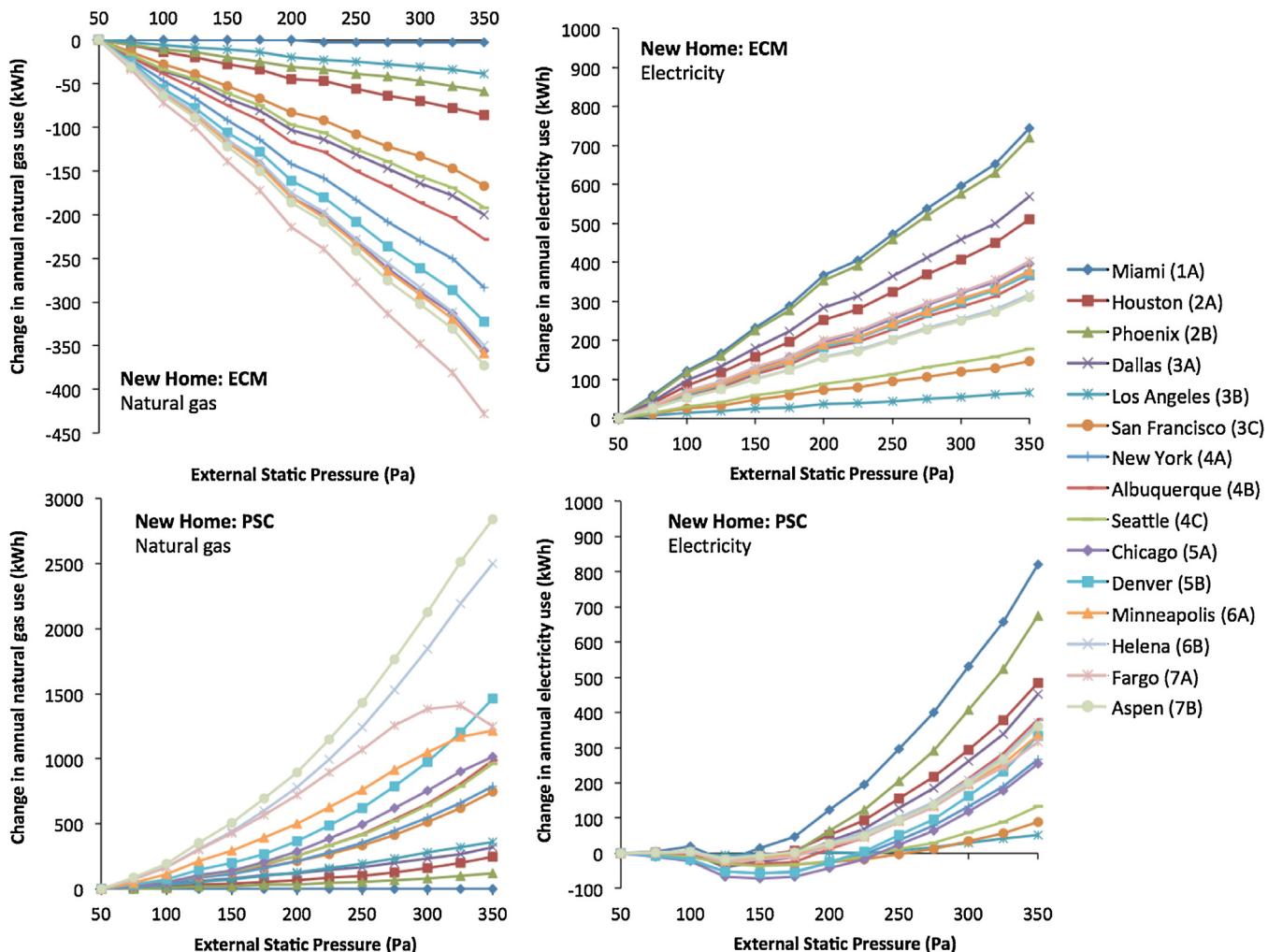


Fig. 4. Changes in annual natural gas and electricity use for space conditioning purposes for new high-efficiency homes with both ECM and PSC blower motors at various static pressures (compared to 50 Pa).

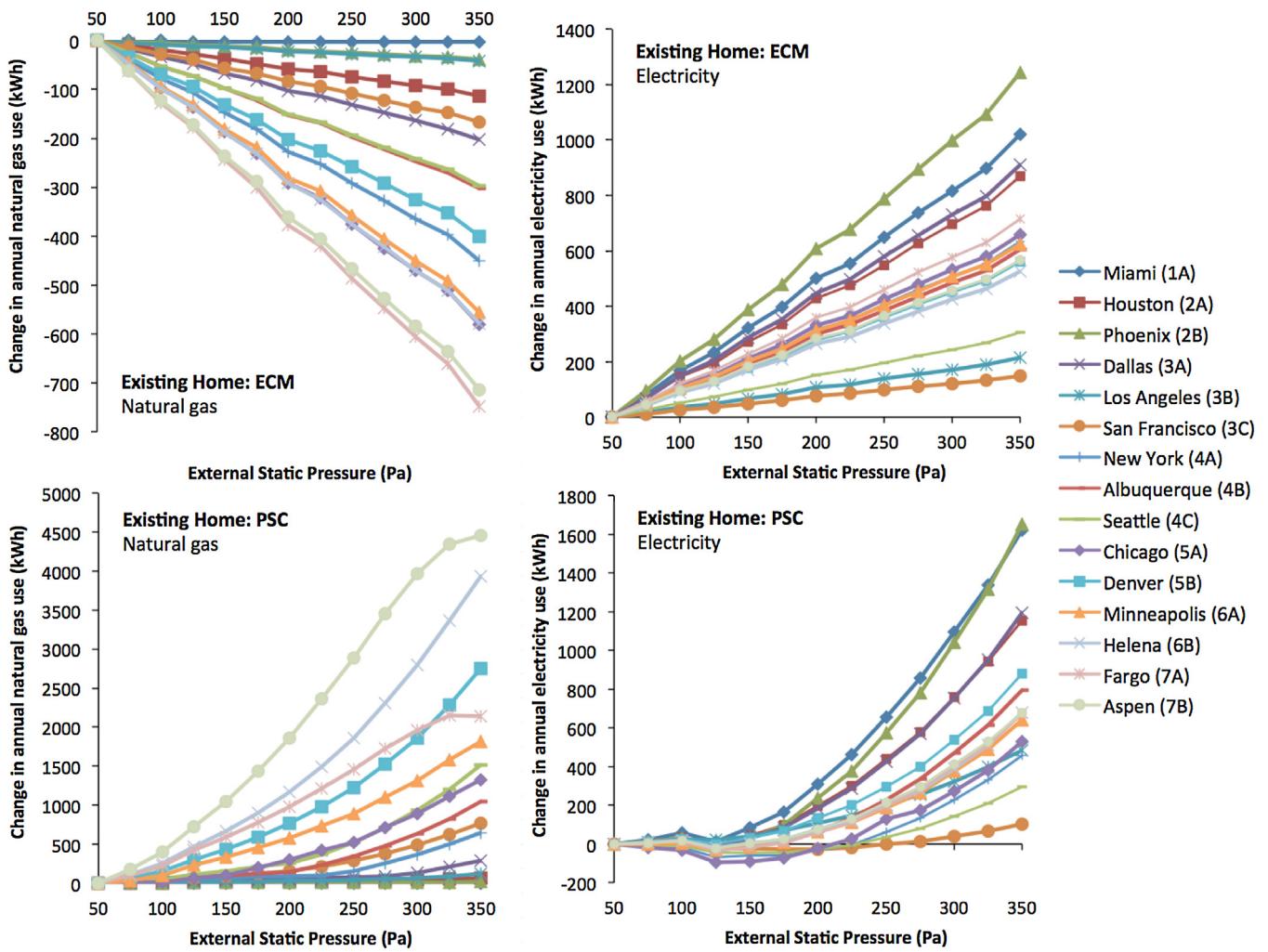


Fig. 5. Changes in annual natural gas and electricity use for space conditioning purposes for older, existing homes with both ECM and PSC blower motors at various static pressures (compared to 50 Pa).

pressures (compared to 50 Pa). Results vary highly by climate zone and fan type.

ECM blowers. For new homes with ECM blowers, annual natural gas consumption was predicted to remain essentially constant at all pressures in climates without meaningful heating requirements (e.g., Miami, FL), while decreasing nearly linearly with static pressure in all other climates. Reductions in annual natural gas consumption were particularly large for the coldest climates with the highest heating requirements (e.g., as high as a 400 kWh/year reduction at the highest static pressure in Fargo, ND). Any reductions in heating energy use likely stem from increased reject heat added to the air stream during heating periods as ECM blowers use more power to overcome the larger static pressure drops. Although fan efficiency increases with static pressure in Fig. 1 it never reaches 50% and thus still rejects a substantial portion into the air stream. Conversely, annual electricity use is predicted to increase nearly linearly with increased static pressure in all climate zones due to a combination of higher fan power draws by ECM blowers and slightly increased system runtimes due to additional reject heat added to the air stream during cooling periods. Predicted increases in annual electricity use at the highest static pressure (350 Pa) ranged from less than 100 kWh in the mild climate of Los Angeles, CA, to nearly 800 kWh in the cooling-dominated climates of Miami, FL and Phoenix, AZ.

PSC blowers. For new homes with PSC blowers, annual natural gas consumption was predicted to increase at higher static pressures in all climates other than Miami, FL (which has essentially no heating requirements). The relationship between heating energy use and static pressure was typically super-linear, following exponential or polynomial increases at higher static pressures with rates of increases based on climate zone. The steepest increases occurred in the coldest climates, reaching as high as an additional 2500 kWh or more at 350 Pa in Fargo, ND and Helena, MT. Increases in annual natural gas use stem from a combination of reduced airflow rates and heating capacities at higher static pressures, which lead to longer system runtimes during heating periods as well as a reduction in the amount of heat rejection to the air stream at lower fan power draws. In two cases (Fargo, ND and Minneapolis, MN), the curve actually bends downward at the highest static pressures (beyond 300 Pa); however, in these cases we observed that at these extremely low airflow rates at the highest static pressures, the systems were not able to meet space conditioning loads and thus any energy savings are due to an inability to maintain thermal comfort in the space.

Estimates of changes in annual electricity use (combined fan and cooling energy) at higher static pressures for the new homes with PSC blowers followed similar patterns, although there were periods of small reductions in annual electricity use at static pressures between ~100 and ~200 Pa for many climate zones. The reason

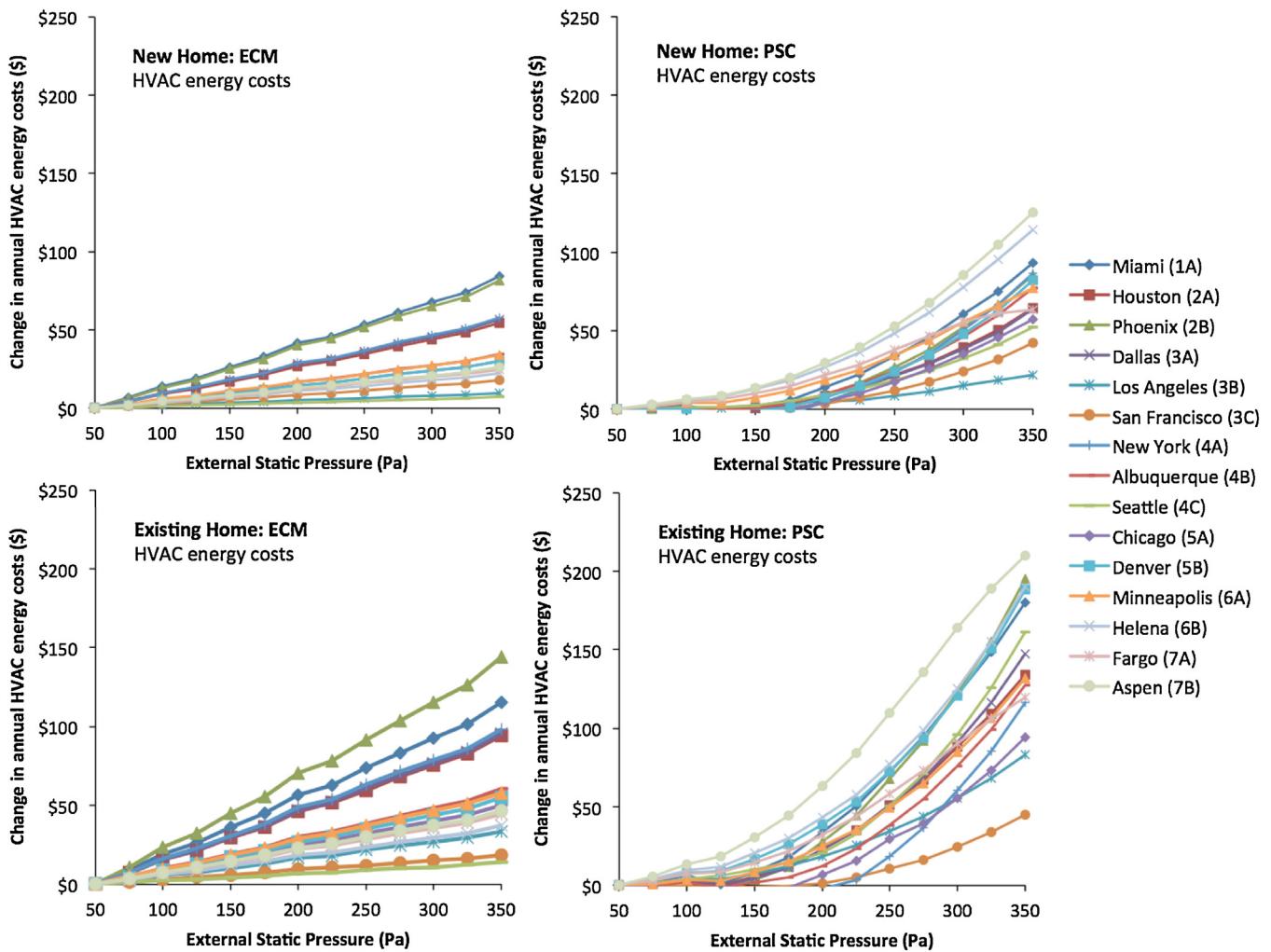


Fig. 6. Changes in HVAC energy costs (i.e., natural gas for heating and electricity for cooling and fan energy) at various static pressures across all home types, fan types, and locations.

for reductions in electricity use at moderate static pressures is likely attributed to a combination of only modestly reduced cooling capacities at the moderately reduced airflow rates in conjunction with reduced fan power draws. Because reductions in cooling capacity are not linear with reductions in airflow for typical residential systems [7,9,12], there remains a narrow region of static pressure conditions where although systems may have slightly higher runtimes, reduced fan power draws and reductions in heat rejection into the air stream at lower airflow rates can actually lead to very small reductions in electricity use (predicted to be less than 100 kWh in this new modeled home). This has been observed experimentally in previous studies as well [6]. However, at the most extreme static pressures (i.e., 300–350 Pa), electricity consumption was predicted to increase in all climates as increases in system runtimes eventually result in larger energy increases than any savings from fan power draw and heat rejection into air streams may provide.

3.2.2. Existing homes

Fig. 5 shows estimates of changes in annual natural gas and electricity use for space conditioning purposes in the older, existing, and less efficient homes with both ECM and PSC blower motors at all static pressures compared to 50 Pa.

ECM blowers. Results for the existing homes with ECM blowers were similar in shape to those from new homes, although the magnitude of decreases in natural gas use and increases in electricity

use were larger. Annual natural gas consumption again decreased approximately linearly with increases in static pressure, decreasing by over 700 kWh in Fargo, ND and Aspen, CO at the highest static pressures (350 Pa). Increases in electricity use for cooling and fan energy purposes at the highest pressures were as small as 200 kWh in San Francisco and as large as nearly 1300 kWh in Phoenix, AZ.

PSC blowers. Results for changes in annual natural gas and electricity consumption in the existing homes with PSC blowers were also similar in shape to those predicted in new homes, albeit with greater absolute increases in energy consumption. Predicted increases in annual natural gas consumption ranged from approximately zero in hot climates such as Phoenix, AZ and Houston, TX to as much as ~4500 kWh in Aspen, CO at the highest static pressure. Again, slight reductions in electricity use were predicted at moderate static pressures of ~100–200 Pa, eventually leading to increases in all climates at static pressures over 300 Pa. The smallest increases in electricity use for cooling and fan energy at the highest static pressure (350 Pa) was around 100 kWh in San Francisco, CA, while the greatest increases were over 1600 kWh in Phoenix, AZ and Miami, FL.

3.3. Influence of static pressure on annual space conditioning energy costs

The predicted changes in annual natural gas and electricity consumption for space conditioning purposes at the various static

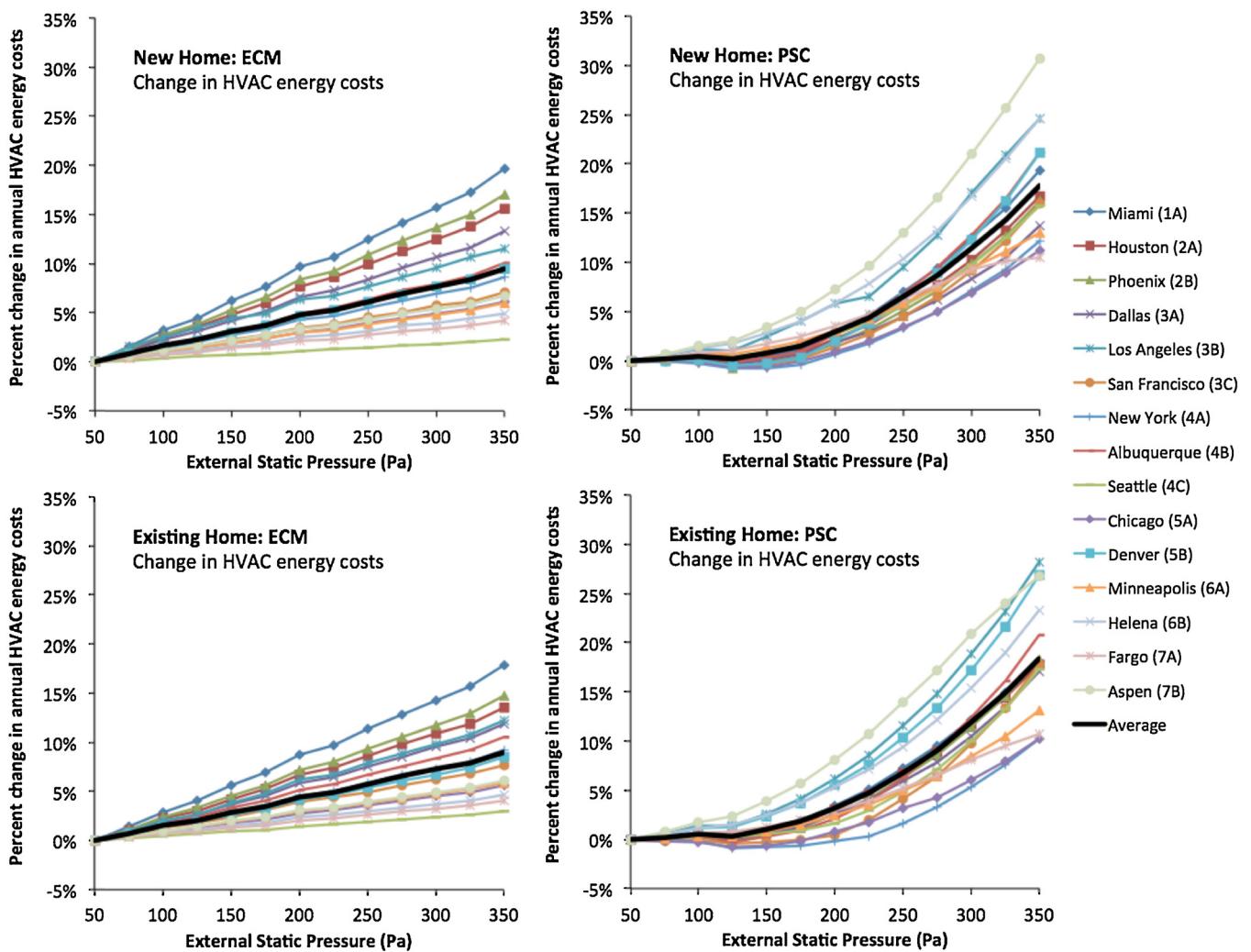


Fig. 7. Relative changes in HVAC energy costs (i.e., natural gas for heating and electricity for cooling and fan energy) at various static pressures across all home types, fan types, and locations.

pressures from Figs. 4 and 5 were then used to estimate changes in annual HVAC energy costs for both home vintages and fan types using regional energy price estimates from Table 1 as shown in Fig. 6.

In all climates, increased external static pressures were predicted to lead to increases in annual HVAC energy costs for almost all static pressure conditions when taking into account changes in annual natural gas and electricity consumption and regional energy prices. Interestingly, increases in annual HVAC energy costs at moderate pressures (e.g., 100–150 Pa) were predicted to be very small (i.e., less than \$10–20 per year) in both new and existing homes with PSC blowers in most climates but as much as \$50 in existing homes with ECM blowers in some climates (e.g., Phoenix, AZ). However, at higher pressures (e.g., 300–350 Pa), annual HVAC energy costs were predicted to increase by as much as \$100 or more in new homes with PSC blowers in the coldest climates and as much as \$150–200 in existing homes with PSC blowers in both hot and cold climates. Conversely, increases in annual HVAC energy costs at the highest pressures were not as extreme in homes with ECM blowers: less than \$90 in new homes with ECM blowers and less than \$150 in existing homes with ECM blowers in all climates. Overall, these results suggest that excess static pressures can indeed increase HVAC energy costs across a wide range of home types, fan types, and climates, particularly at extreme pressures beyond 300 Pa; however, for more moderate increases in static pressure,

the impacts on annual HVAC energy costs were typically less than \$25–50.

Fig. 7 displays the same predicted changes in HVAC energy costs from Fig. 6 on a relative (i.e., percentage) basis, along with the average across all 15 cities (in black).

Relative increases in annual HVAC energy costs were similar across both new and existing home types and varied more by both fan motor type and climate. For example, in both new and existing homes with ECM blowers, HVAC energy costs increased approximately linearly at ~1.5–1.6% per 50 Pa increase in static pressure, on average across all climate zones. This increase ranged from as little as ~0.4–0.5% per 50 Pa for new and existing homes in Seattle, WA to as much as ~3.0–3.3% per 50 Pa for new and existing homes in Miami, FL. At the highest static pressure (350 Pa), the average increase in HVAC energy costs was predicted to be ~9% with ECM blowers in both home vintages.

Conversely, the average increase in annual HVAC energy costs for both new and existing homes with PSC blowers ranged from less than 2% per 50 Pa across all climates from static pressures ranging from 50 to 150 Pa (with a mean of only ~0.4–0.5% per 50 Pa). However, the average increase in HVAC energy costs then increased exponentially beyond 150 Pa to a minimum of ~10% at 350 Pa in Chicago, IL and New York, NY and a maximum of ~31% at 350 Pa in Aspen, CO. The overall mean increase in HVAC energy costs with a PSC blower at 350 Pa was ~18% across all climates.

Overall, these results clearly demonstrate that in all climates excess static pressures are expected to yield increases in annual HVAC energy costs, but the magnitude varies highly by both fan type and climate zone.

4. Discussion

In order to demonstrate the utility of the results herein, it is instructive to consider some typical increases in external static pressures that systems commonly face and explore the likely impact on energy consumption and costs. As an example, in Stephens et al. (2010) the external static pressure of a residential air handling unit increased by ~43 Pa from 145 Pa to 188 Pa after replacing a MERV <5 filter with a higher efficiency MERV 11 filter [7]. In the test system containing a PSC blower, airflow rates were reduced by ~11% at this increase in static pressure. In Fig. 1 of this work, an increase in static pressure from 145 to 188 Pa in a system with a PSC blower would be expected to reduce airflow rates by ~8%, which is reasonably similar to the measurements in Stephens et al. (2010). Similar increases in filter pressure drop and decreases in airflow rates have also been observed with higher efficiency filters in other recent studies [13,24].

According to Fig. 6, a 43 Pa increase in static pressure from 145 to 188 Pa would be expected to increase total HVAC energy costs by under a few dollars per year in a new home with an ECM or PSC blower in a mild climate such as Seattle, WA, to as much as \$15/yr in a new home with an ECM blower or \$35/yr in an existing home with an ECM blower in Miami, FL or Phoenix, AZ. Changes in annual HVAC energy costs at this increase in static pressure would be negligible for PSC blowers in either home type in several climates, sometimes even yielding slight energy savings. In other climates, this same increase in pressure drop would be expected to yield increases in HVAC energy costs of around \$10–15/yr in new homes with PSC blowers and as much as \$30–40/yr in old homes with PSC blowers, particularly in cold climates such as Aspen, CO. On a percentage basis, the same 43 Pa increase in pressure drop from 145 to 188 Pa is expected to increase annual HVAC energy costs by ~2–3% in the average home with either an ECM or PSC blower (Fig. 7). These estimates are all generally in line with findings from other similar simulation studies of excess pressure drop introduced by higher efficiency filters [13] or dirty coils [14]. If this same initial pressure drop of 145 Pa is increased beyond 188 Pa to 250 Pa or higher by any other means, additional HVAC energy costs will continue to increase linearly for ECM blowers but will increase exponentially for PSC blowers, leading to even greater energy and cost impacts.

Interestingly, the initial operating pressure also influences the HVAC energy impacts of increased static pressures, particularly for PSC blowers. To illustrate this, Fig. 8 shows how the 43 Pa increase in static pressure from 145 Pa to 188 Pa due to the replacement of a MERV <5 filter to a MERV 11 filter in an existing home with a PSC blower compares to the same 43 Pa increase in static pressure in a system in which the starting operating pressure was 215 Pa (this is the average value measured in homes in Proctor et al., 2011 [10]). On average across all climate zones, an increase in static pressure from 215 Pa to 258 Pa in this home and blower combination would be expected to increase annual HVAC energy costs by approximately 4% compared to only 2% when starting at 145 Pa. Thus, the initial static pressure can meaningfully influence the magnitude of changes in annual HVAC energy costs due to the introduction of additional pressure drop.

There are a few limitations to this work worth noting. First, the results are unique to the ranges of home characteristics, fan curves, equipment capacity and efficiency curves, and climate zones used herein, although we attempted to span a wide range of these inputs to establish reasonably generalizable results. Second, this

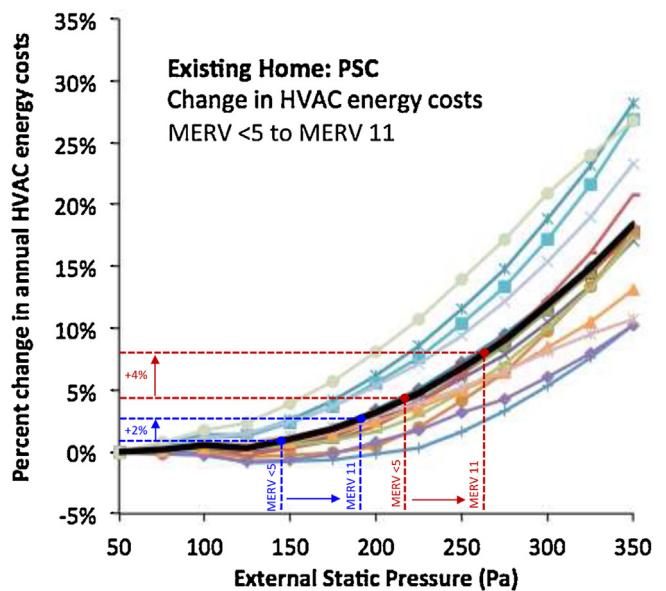


Fig. 8. Illustration of percentage changes in annual HVAC energy costs in the existing home with a PSC blower with the introduction of increased pressure drop filters under two initial static pressure conditions.

work assumes that static pressures are constant throughout the annual simulations. This assumption may be reasonable for systems with minimal fouling of filters and coils over time (i.e., environments with low indoor particle concentrations or frequent filter replacements [6,39]), but may not be appropriate for systems with pressure drops that do vary in time (i.e., with infrequent filter changes where filter or coil pressure drops increase with loading [13]). Finally, this work did not explore other factors such as changes in equipment reliability or maintenance issues that may arise at extreme static pressures.

5. Conclusions

Results from the 780 annual building energy simulations herein demonstrate that excess static pressures can increase energy consumption and costs in central residential forced-air heating and air-conditioning systems, but the magnitude varies highly by both fan type and climate zone. Moderate increases in static pressures (i.e., from 50 to 150 Pa) were predicted to yield relatively minimal energy impacts: less than ~3% increases in annual HVAC energy costs for ECM blowers and less than 1% for PSC blowers on average across all climate zones. However, more extreme increases in static pressure (e.g., moving from 50 to 350 Pa) were predicted to yield larger energy and cost impacts: average increases in annual HVAC energy costs at the highest static pressures across all modeled homes were ~9% with ECM blowers and ~18% with PSC blowers. These results provide valuable insight into the energy and cost impacts of excess static pressures in residential heating and air-conditioning systems across a wide range of climate conditions.

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