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Regional and national estimates of the potential energy use, energy cost and CO_2 emissions associated with radon mitigation by sub-slab depressurization

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Abstract

Active sub-slab depressurization (SSD) systems are an effective means of reducing indoor radon concentrations in residential buildings. However, energy is required to operate the system fan and to heat or cool the resulting increased building ventilation. We present regional and national estimates of the energy requirements, operating expenses and CO_2 emissions associated with using SSD systems at saturation (i.e. in all US homes with radon concentrations above the EPA remediation guideline and either basement or slab-on-grade construction). The primary source of uncertainty in these estimates is the impact of the SSD system on house ventilation rate. Overall, individual SSD system operating expenses are highest in the Northeast and Midwest at about \$99 y^{-1}, and lowest in the South and West at about \$66 y^{-1}. The fan consumes, on average, about 40% of the end-use energy used to operate the SSD system and accounts for about 60% of the annual expense. At saturation, regional impacts are largest in the Midwest because this area has a large number of mitigable houses and a relatively high heating load. We estimate that operating SSD systems in US houses, where it is both appropriate and possible (about 2.6 million houses), will annually consume 1.7×10^4 (6.4×10^3 to 3.9×10^4) TJ of end-use energy, cost \$230 (130 to 400) million (at current energy prices), and generate 2.0×10^9 (1.2×10^9 to 3.5×10^9) kg of CO_2. Passive or energy efficient radon mitigation systems currently being developed offer opportunities to substantially reduce these impacts.

Keywords: Sub-slab ventilation; Energy; Cost; CO_2 emissions; Active sub-slab depressurization; Residential buildings

1. Introduction

Exposure to indoor radon progeny is the single largest source of radiation exposure in the US general population [1]. Lubin and Boice [2] estimate that 10% of annual US lung cancer deaths are due to a lifetime of this exposure. Even in houses with average concentrations, the estimated risk of lung cancer attributable to radon exposure is 0.4% [3]. This risk is orders of magnitude larger than that associated with many man-made pollutants present in outdoor air and drinking water.

The largest source of radon in homes with elevated concentrations is the soil adjacent to the building [4]. In houses with basements, the common entry pathways are cracks in the slab, the crack between the slab and the basement walls, and unsealed penetrations in the basement walls. Entry can also occur through permeable walls, especially those made from concrete blocks. A relative depressurization of the basement with respect to outdoor air (typically on the order of one to ten Pa) is often sufficient to draw significant amounts of radon-laden soil gas into the house. Indoor–outdoor temperature differences, heating equipment, mechanical ventilation, and wind can all contribute to this depressurization.

Sub-slab depressurization (SSD) is the most commonly applied and thoroughly tested technique for reducing radon entry into houses. The system typically consists of a pit in the sub-slab gravel layer into which a pipe connected to outdoor air has been inserted (Fig. 1). A small fan in the pipe draws radon-bearing soil gas from the gravel layer and exhausts it to the outdoors. For the system to be effective, the pressure gradient between the basement and the gravel layer must be reversed throughout the gravel layer. This requirement drives the selection of fan power and placement of the system pit(s).

For many houses, SSD systems are effective at reducing indoor radon concentrations. However, the system's energy requirements can be considerable. In addition to removing soil gas and radon from below the slab, house air is drawn into the gravel layer and exhausted to the outdoors. The over-

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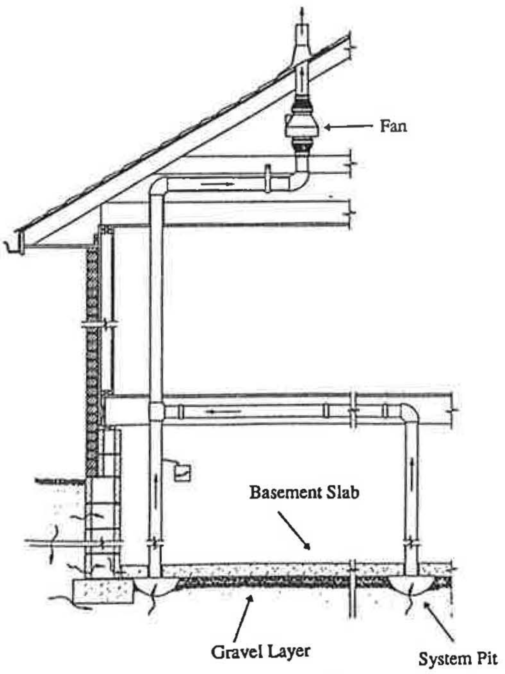

Fig. 1. Schematic of an SSD system [38]. The system fan draws radon-bearing soil gas from the pit and exhausts it to the outdoors.

all house ventilation rate therefore increases. Energy must be supplied to condition this increased air flow and power the system fan.

Several investigators have studied the energy use and costs associated with SSD system operation in individual houses. Clarkin et al. [5] performed tracer-gas decay experiments in one Pennsylvania and two Virginia homes to determine the additional house ventilation generated by an SSD system. For these houses they estimated an increase in annual heating costs ranging from \$4 to \$32. Bohac et al. [6] studied a group of houses in the Twin Cities metropolitan area. They concluded that the SSD systems increased the annual energy expense by \$75. About half of this expense was due to increased heating requirements; the remainder was due to operation of the system fan. Henschel [7] examined SSD system operating costs for both a 50 and 90 W fan. He reports annual fan energy costs of \$35 and \$63 for the 50 and 90 W fan, respectively, and corresponding incremental conditioning costs of \$39 and \$79. Fisk et al. [8] estimate the annual increase in energy expense resulting from SSD system use in a Chicago climate is \$42 for homes with gas heat, and \$165 for electric resistance heat. Bonnefous et al. [9], using a numerical model to estimate the increase in house ventilation from an SSD system with two fans, predict an annual incremental heating expense of \$345 for a Chicago climate. The increased ventilation used in this study is large compared to the values from the previous four studies, and accounts for the relatively large annual expense. We have not incorporated these modeling results into our calculations. Groups in Canada [10] and Sweden [11,12] have also examined SSD system effectiveness and installation costs. Ericson et al. [11] report annual operating costs of \$12 (1984 \$). This amount does not include costs associated with the increased building ventilation associated with the SSD system operation.

These estimates are all for specific homes or for an average home in a specific climate. No effort has yet been made to determine the regional and national energy implications of SSD system operation at saturation. The purpose of this study is to make such estimates. We consider regional distributions of housing characteristics, types of heating fuels used, and heating and cooling loads. Estimates of SSD system operating expenses are computed using regional fuel prices. The CO_2 emissions associated with SSD system operation are computed by considering each region's mix of fuel use and the emission factor associated with each fuel. This parameter is presented as a metric of the potential environmental effects associated with SSD energy use.

2. Methods

2.1. Overview

To estimate the energy, cost and CO_2 emission implications of SSD operation, we have combined data from field tests and national surveys of housing characteristics and fuel use. For an average house in each region, we determine the heating, cooling and fan energy requirements of SSD system operation. We then calculate the number of houses in each region where an SSD system would be appropriate. In particular, these are the houses with a basement or slab-on-grade construction whose radon concentrations are above the EPA remediation guideline of 148 Bq m^{-3}.

The additional house ventilation generated by SSD system operation is estimated from the results of four field studies. This estimate is the largest source of uncertainty in our calculations, primarily because the available data are scarce. We therefore provide a range of values for our predictions based on this uncertainty.

Space conditioning costs are computed by means of a degree-day method [13] that accounts for heating and cooling equipment and air distribution system efficiencies. The significant regional variation in fuel costs, types of heating fuel used and CO_2 emission factors are included in our determination of cost and CO_2 emissions.

We have neglected the additional heating load imposed on the house by the SSD system drawing cool air through the soil and decreasing winter-time soil temperatures. A complex computer model would be required to accurately estimate the effect of soil cooling on the overall energy requirements of the SSD system. However, assuming that 50% of the air flow out of the SSD system originates from outdoors and 50% from indoors, conservation of energy dictates that this conduction heating load can be no greater than the increased heating load from additional infiltration. In reality, the additional load associated with soil cooling is likely to be substantially smaller than the loads calculated in this paper, and neglecting it makes our estimates of cost and energy use

Table 1
Placement of the states into the four census regions (Refs. [20] and [14])

Census region	States	EPA regions
Northeast	Connecticut, Maine, Massachusetts, New Hampshire, Vermont, Rhode Island, New Jersey, New York, Pennsylvania	1, 2
Midwest	Illinois, Indiana, Michigan, Ohio, Wisconsin, Iowa, Kansas, Minnesota, Missouri, Nebraska, North Dakota, South Dakota	5, 7
South	Delaware, the District of Columbia, Florida, Georgia, Maryland, North Carolina, South Carolina, Virginia, West Virginia, Alabama, Kentucky, Mississippi, Tennessee, Arkansas, Louisiana, Oklahoma, Texas	3, 4, 6
West	Arizona, Colorado, Idaho, Montana, Nevada, New Mexico, Utah, Wyoming, Alaska, California, Hawaii, Oregon, Washington	8, 9, 10

conservative (i.e. real cost and energy increases are likely to be somewhat higher than our estimates).

2.2. Census and EPA regions

We have estimated the impacts associated with the operation of SSD systems on both a census region and national basis. The indoor radon concentration data available to us are divided into EPA regions [14] which do not exactly match the census regions. Table 1 shows the division of states into the four census regions: Northeast (NE), Midwest (MW), South (S), and West (W). We group EPA regions 1 and 2 into the NE census region; EPA regions 5 and 7 into the MW census region; EPA regions 3, 4 and 6 into the S census region; and EPA regions 8, 9 and 10 into the W census region. There are four states which do not fit this categorization: Pennsylvania (EPA region 3, is placed in the NE census region), North and South Dakota (EPA region 8, are placed in the MW census region), and New Mexico (EPA region 6, is placed in the S census region). We assume that the error associated with grouping these four states as described is small.

2.3. SSD-induced house ventilation

In addition to removing radon-bearing soil gas from below the slab, SSD systems increase the house ventilation rate. We use data collected during four studies of installed SSD systems to estimate this increase in air flow through the house. Two of the studies [15,16] directly measured the increase in house ventilation caused by the SSD system. Turk et al. [15] measured an average 5×10^{-3} m^3 s^{-1} increase in seven Pacific Northwest homes. In a study of five New Jersey homes, Turk et al. [16] report an average increase in ventilation rate of 2.5×10^{-2} m^3 s^{-1}.

The remaining two studies [17,5] measured flow rates through the SSD pipes and the proportion of the flow that originated in the house. To estimate the increase in house ventilation rate for these two studies we use an equation from the LBL infiltration model [18]

$$Q=\sqrt{Q_0{}^2+Q_{\mathrm{SSD}}{}^2} \tag{1}$$

where Q is the effective house ventilation rate with the SSD system operating (m^3 s^{-1}), Q_0 is an estimate of the unperturbed house ventilation rate (m^3 s^{-1}), and Q_{SSD} is the portion of the flow through the SSD pipes (m^3 s^{-1}) that originated in the house.

To utilize Eq. (1), an estimate of a typical house ventilation rate, Q_0, is required. Pandian et al. [19] summarized residential ventilation data based on 1836 perfluorocarbon tracer measurements across the US. They report an arithmetic mean and standard deviation of 0.60 and 2.2 ACH, respectively, for houses in the Northeast (this region is different from the NE region we have defined, but includes the areas of the Bohac [17] and Clarkin [5] studies). The national average heated floor area for single-family homes is 173 m^2 [20]. Therefore, assuming a ceiling height of 2.4 m (8 ft), Q_0 is 6.9×10^{-2} m^3 s^{-1}.

Eq. (1) is used to compute the house ventilation rate, Q, after installation of the SSD system. The difference between Q and Q_0 represents the effective increase in ventilation rate generated by the SSD system.

Table 2 summarizes the results from these four studies. The average increase in ventilation rate produced by the SSD systems is 9×10^{-3} m^3 s^{-1}. It is not possible, given our understanding of the system, for the house ventilation rate to decrease as a result of SSD system operation. We hypothesize that the two decreases observed in the Turk [15] Spokane study are a result of factors other than the SSD system (e.g. wind). The value of 6.9×10^{-2} m^3 s^{-1} (in the Turk [16] NJ study) is a significantly larger flow than the system fan is capable of generating. Again, we hypothesize that an external factor is responsible for this large increase. These three values

Table 2
Additional house ventilation rate generated by an SSD system, grouped by study

Study	Increase in ventilation (m^3 s^{-1})						
Turk: Spokane	−9.0E–03	1.3E–02	1.3E–02	−9.7E–03	1.7E–02	7.6E–03	4.2E–03
Turk: NJ	1.3E–02	1.5E–02	1.9E–02	6.9E–02	1.0E–02		
Clarken	1.8E–03	2.0E–04	1.5E–05				
Bohac	2.3E–04	3.9E–04	2.9E–03	5.8E–03	5.0E–03		

do not, however, significantly affect the mean. The increase in ventilation rate calculated from the entire data set (9×10^{-3} m^3 s^{-1}) is used as the estimate of additional air that must be conditioned throughout the year.

The approximation that this increase in ventilation rate is constant over time implies that varying weather conditions do not have a large effect on the SSD system's annual energy requirements. Given the large uncertainty in the average value of the increase in ventilation rate, our estimate would not be substantially improved by attempting to account for weather effects. We make the further approximation that the ventilation rate measurements of the four studies were made during weather conditions representative of the average. The scarcity of data, both geographically and temporally, prevents us from improving on this approximation.

For comparison, Henschel [7] assumed an SSD-induced increase in house ventilation of 1.8×10^{-2} m^3 s^{-1} for a 90 W fan. However, this estimate is not based on data from real SSD systems. Fisk et al. [8], report an increased ventilation rate of 2.0×10^{-2} m^3 s^{-1}. The current study improves on these estimates by including more data from installed SSD systems.

If the increase in ventilation rate data were statistically independent and normally distributed, the 95% confidence intervals for the increase across the housing stock would be 4.5×10^{-3} to 1.1×10^{-2} m^3 s^{-1}. However, the data are neither normal nor independent, nor is the data set large enough to formally correct for these circumstances. We therefore choose a range bounded by the minimum and maximum averages from each of the four studies mentioned above, or 6.8×10^{-4} to 2.5×10^{-2} m^3 s^{-1}. Sixteen of the twenty one datapoints fall within this range. The uncertainty in the increased house ventilation rate dominates the error in our predictions. SSD energy use, operating costs and CO_2 emissions that we report include a mean and an uncertainty range based on the above approximations.

2.4. Heating energy requirements

The mix of fuels used to heat homes varies with region. We define f_i to be the fraction of houses that use the 'ith' fuel type for heating in each region of the country (–). In the Northeast natural gas and fuel oil constitute the major heating energy sources. Natural gas and electricity are the major sources in the South, and natural gas is the largest source in the West and Midwest.

The energy required to heat the increased air flow through the house for the 'ith' fuel type, E_{hi} (GJ y^{-1} per house), is

$$E_{hi}=\frac{Q\rho c_p N_{\mathrm{HDD}}}{\eta}\left(\frac{8.64\times10^4\ \mathrm{s}}{\mathrm{day}}\right)\left(\frac{\mathrm{GJ}}{10^9\ \mathrm{J}}\right) \qquad (2)$$

where ρ is the air density (1.2 kg m^{-3}), c_p is the heat capacity of air (1000 J kg^{-1} K^{-1}), N_{HDD} is the annual number of heating degree-days (K d), and η is the efficiency of the heating and distribution system (–). The number of heating degree-days, for a single day, is the difference between the day's average temperature and 18 °C if this difference is a positive number, and 0 if it is a negative number. For this study, we use 'normal heating degree-days', which is the average number of heating degree-days per year between 1951 and 1980 [20]. N_{HHD} varies by fuel type because the geographic distribution of fuel-type use is not homogeneous within each region.

The overall efficiency, η, of each heating device is

$$\eta=\eta_e\eta_d \qquad (3)$$

where η_e is the equipment (e.g. furnace) efficiency for the particular fuel type (–), and η_d is the efficiency of the distribution system in delivering the conditioned air (–). A population-weighted national average efficiency for LPG, natural gas and fuel oil furnaces is 0.68 [21]. We take the efficiency of electric furnaces to be 1.0, of kerosene heaters to be 0.70, and wood stoves to be 0.30 [22].

In a study of houses with basements, Treidler and Modera [23] predict a duct distribution efficiency of 0.83. This efficiency is an average from three prototypical houses (one each in Georgia, Minnesota, and the District of Columbia), and considers both heating and cooling losses. In another paper, Modera [24] reports a 0.6–0.7 distribution efficiency for a house in a moderate California climate. For this study, we approximate the distribution system efficiency to be 0.75 for electric, LPG, natural gas, and fuel oil furnaces. A distribution efficiency of 1.0 is used for kerosene and wood heaters.

The energy required to heat the increased ventilation flow for an average house, E_h (GJ y^{-1} per house), in each region is

$$E_h=\sum_{\mathrm{fuels}} f_i E_{hi} \qquad (4)$$

2.5. Cooling energy requirements

We assume the increase in ventilation flow produced by the SSD system during the cooling season is the same as during the heating system ($Q=9\times10^{-3}$ m^3 s^{-1}). Ninety nine percent of the central air conditioners in the US are electric; the remaining are either LPG or natural gas ([20], Table 54). For simplicity, we assume that all the air conditioners in the country are electric.

The fraction of single-family homes with air conditioners, f_{AC} (–), is approximated by the ratio of the number of households with air conditioners to the total number of households in each region. In contrast to our assumption regarding the use of heating equipment, we assume that not all homes with air conditioners use them regularly. In the RECS [20] survey, households were asked how often they used their air conditioners. Four categories were available: 'not at all', 'only a few times' 'quite a bit' and 'all summer'. We take the fraction of houses with air conditioners who use them regularly, f_{use} (–), to be the fraction of households that declare a usage of 'quite a bit' or 'all summer'.

The annual number of cooling degree-days for each region, N_{CDD} (K d), is determined analogously to N_{HDD}. We use an average stock efficiency for the air conditioner of 8.09 Btu $\mathrm{W}^{-1}\,\mathrm{h}^{-1}$ [25] and a distribution system efficiency of 0.75. The coefficient of performance is therefore 2.4. The overall cooling system efficiency, η_c (–), is the product of the coefficient of performance and the distribution efficiency, or 1.78.

In addition to the sensible energy required to cool the air, there is a latent-heat energy, E_{lh} (GJ y^{-1} per house) associated with condensing a fraction of the water in the air stream. We use the technique of Byrne et al. [26] to estimate this energy demand

$$E_{\mathrm{th}} = \frac{Q\rho N_{\mathrm{LHD}}}{\eta_{\mathrm{c}}}\left(\frac{8.64\times10^4\ \mathrm{s}}{\mathrm{day}}\right)\left(\frac{\mathrm{GJ}}{10^9\ \mathrm{J}}\right) \tag{5}$$

where N_{LHD} is the number of latent enthalpy-days (J d kg^{-1}). Huang et al. [27] tabulate the number of latent enthalpy-days and the number of cooling degree-days for 45 cities in the US. The ratio of the latent-heat to sensible-cooling energy load, R (–), is

$$R = \frac{N_{\mathrm{LHD}}}{N_{\mathrm{CDD}}c_{\mathrm{p}}} \tag{6}$$

We calculate the average value of R for the cities in each region and assume that this average represents conditions throughout the region. For example, in the Northeast, the latent-heat energy adds an additional 13% energy requirement to the sensible-cooling load. The largest ratio is in the South, where, on average, the latent-heat load adds 25% to the cooling energy requirements.

The energy required to cool the increased flow of air generated by the SSD system, E_{c} (GJ y^{-1} per house), is calculated analogously to E_{h} (see Eq. (2)). However, E_{c} also depends on the latent-heat load and the fraction of homes that use their air conditioner on a regular basis:

$$E_{\mathrm{c}} = \frac{Q\rho c_{\mathrm{p}} N_{\mathrm{CDD}}}{\eta}(1+R) f_{\mathrm{AC}} f_{\mathrm{use}}\left(\frac{8.64\times10^4\ \mathrm{s}}{\mathrm{day}}\right)\left(\frac{\mathrm{GJ}}{10^9\ \mathrm{J}}\right) \tag{7}$$

2.6. *Fan energy requirements*

The majority of fans used in SSD systems are either 50 or 90 W. Typically, the 90 W fan is used in existing homes, and a 50 W fan is used in new construction where a sufficient sub-slab gravel layer has been installed. From conversations with several mitigators and researchers (e.g. Refs. [28] and [29]), we estimate that 85% of the fans currently being installed are 90 W, and 15% are 50 W; thus the average rated fan power is 84 W. Fans under load draw about 80% of their rated power [6]. Therefore, assuming continuous operation, the fan energy required for the average house, E_{f} (GJ y^{-1} per house), is 2.1 GJ y^{-1} per house.

2.7. *Fuel costs*

Column 7 of Table 3 shows the regional cost of each type of fuel, C_{fuel} (\$ GJ^{-1}) [30]. The energy cost of wood is approximated by assuming a price of \$100 t^{-1} and an energy content of 15 GJ t^{-1}. Because the fraction of homes that use wood for heat is small, the error introduced by the uncertainty in this price has a negligible effect on the overall energy cost.

2.8. *Heating costs*

The cost to heat the additional ventilation flow for a particular fuel, C_{hi} (\$ y^{-1} per house), is $E_{\mathrm{h}i}C_{\mathrm{fuel}}$. The cost to heat this flow, C_{h} (\$ y^{-1} per house), for an average house in each region is

$$C_{\mathrm{h}} = \sum_{\mathrm{fuels}} f_i C_{\mathrm{h}i} \tag{8}$$

2.9. *Cooling and fan costs*

The cost to cool the additional air flow for an average house, C_{c} (\$ y^{-1} per house), is the product of E_{c} and the cost of electricity. The cost to run the SSD system fan, C_{f} (\$ y^{-1} per house), is the product of E_{f} and the cost of electricity.

2.10. *CO_2 emissions*

Regional CO_2 emission factors for electricity production are a function of the area's mix of electrical power generating fuels. To account for this, we weight the national average of 186 $\mathrm{kgCO_2\ GJ^{-1}}$ [31] by each region's CO_2 emissions, $m_{\mathrm{CO_2}}$ (10^3 $\mathrm{tCO_2}$), per electric utility sales, S (GWh) [32]. The regional CO_2 emission factor, $e_{\mathrm{CO_2}}$ ($\mathrm{kgCO_2\ GJ^{-1}}$), is then approximated as

$$e_{\mathrm{CO_2}} = (186\ \mathrm{kgCO_2\ GJ^{-1}})\frac{[m_{\mathrm{CO_2}}/S]_{\mathrm{region}}}{[m_{\mathrm{CO_2}}/S]_{\mathrm{national}}} \tag{9}$$

where the subscripts region and national refer to the geographical area over which the ratio is taken. The CO_2 emission factors for natural gas, fuel oil, LPG and kerosene are independent of region [33]. Wood has a net emission factor of 0 if it is harvested sustainably; this is the value we use here.

The mass of CO_2 emitted for a particular heating fuel, $M_{\mathrm{h}i}$ ($\mathrm{kgCO_2\ y^{-1}}$ per house), is $E_{\mathrm{h}i}e_{\mathrm{CO_2}}$. The mass of CO_2 emitted from producing the heating energy, M_h ($\mathrm{kgCO_2\ y^{-1}}$ per house), is

$$M_{\mathrm{h}} = \sum_{\mathrm{fuels}} f_i M_{\mathrm{h}i} \tag{10}$$

The CO_2 emissions generated as a result of producing the cooling energy, M_{c} ($\mathrm{kgCO_2\ y^{-1}}$ per house), and system fan energy, M_{f} ($\mathrm{kgCO_2\ y^{-1}}$ per house), are $E_{\mathrm{c}}e_{\mathrm{CO_2}}$ and $E_{\mathrm{f}}e_{\mathrm{CO_2}}$, respectively. In these two expressions, $e_{\mathrm{CO_2}}$ is the emission factor for electricity.

Table 3
Energy requirements, expense and CO_2 emissions associated with heating the additional ventilation air

Fuel type	Region	Fractional use [a], f_i (–)	No. of heating degree-days [b], N_{HDD} (°C d)	Total efficiency [c], η	Energy, E_{hi} and E_h $(\mathrm{GJ\ y^{-1}}$ per house)	Fuel cost [d], C_{fuel} $(\$\ \mathrm{GJ}^{-1})$	Cost, C_{hi} and C_h $(\$\ \mathrm{y}^{-1}$ per house)	Emission factor [e,f,g], e_{CO_2} $(\mathrm{kgCO_2\ GJ^{-1}})$	CO_2 production, M_{hi} and M_h $(\mathrm{kgCO_2\ y^{-1}}$ per house)
Natural gas	NE	0.46	2747	0.51	5.0	6.80	34	50.5	250
Electricity	NE	0.10	2885	0.75	3.6	26.10	93	157	560
Fuel oil	NE	0.39	2860	0.51	5.2	7.30	38	69.4	360
Wood	NE	0.03	3728	0.30	11.5	6.70	77	0.0	0
LPG	NE	0.01	3225	0.51	5.9	12.90	76	60.0	350
Kerosene	NE	0.02	3706	0.70	4.9	8.30	41	67.7	330
Total	NE				5.1		43		320
Natural gas	S	0.44	1407	0.51	2.6	5.50	14	50.5	130
Electricity	S	0.38	1003	0.75	1.2	18.30	23	178	220
Fuel oil	S	0.05	1750	0.51	3.2	6.70	21	69.4	220
Wood	S	0.04	1600	0.30	4.9	6.70	33	0.0	0
LPG	S	0.07	1224	0.51	2.2	9.20	20	60.0	130
Kerosene	S	0.02	1369	0.70	1.8	7.70	14	67.7	120
Total	S				2.1		19		160
Natural gas	MW	0.72	3175	0.51	5.8	5.80	33	50.5	290
Electricity	MW	0.11	3012	0.75	3.7	24.10	90	259	960
Fuel oil	MW	0.05	3558	0.51	6.5	7.00	45	69.4	450
Wood	MW	0.04	3429	0.30	10.6	6.70	71	0.0	0
LPG	MW	0.07	3311	0.51	6.0	12.10	73	60.0	360
Kerosene	MW	0.00	0	0.70	0.0	7.90	0	67.7	0
Total	MW				5.8		45		370
Natural gas	W	0.64	1652	0.51	3.0	5.50	16	50.5	150
Electricity	W	0.24	2085	0.75	2.6	18.30	47	141	360
Fuel oil	W	0.00	2601	0.51	4.7	6.50	31	69.4	330
Wood	W	0.06	2911	0.30	9.0	6.70	60	0.0	0
LPG	W	0.02	2341	0.51	4.2	9.60	41	60.0	250
Kerosene	W	0.00	0	0.70	0.0	7.70	0	67.7	0
Total	W				3.2		26		190

[a] Ref. [20], Table 20, p. 62.
[b] Ref. [20], Table 55, p. 185.
[c] See Eq. (3) of text.
[d] Ref. [30], pp. 19–174.
[e] Ref. [33], Table 11, p. 15.
[f] Ref. [31], Table A.4, p. 21.
[g] Ref. [32], Tables 43 and 45.

2.11. Number of houses where an SSD system is applicable

The number of houses in each region with annual-average, living-area indoor radon concentrations greater than 4 pCi l^{-1} was estimated by Marcinowski et al. [14] (here we assume that the EPA and census regions match). We take the fraction of houses in each region where an SSD system is appropriate as the fraction of single-family houses with a basement or slab-on-grade construction. The number of houses in which an SSD system is appropriate, N_H (–), is calculated as the product of the number of houses with indoor concentrations greater than 4 pCi l^{-1} and the fraction of houses with a basement or slab-on-grade construction.

The annual energy required to run all the SSD systems in each region is $N_H(E_h+E_c+E_f)$. The annual cost for this energy is $N_H(C_h+C_c+C_f)$, and the resulting annual CO_2 emissions are $N_H(M_h+M_c+M_f)$. Finally, the energy, cost and CO_2 emissions for the entire US are calculated by combining the values from the four regions.

In these computations, we have made the approximation that the type of heating fuel used, radon levels and substructure type are uncorrelated. To decide whether a more complex analysis was necessary, we examined the radon levels in the National Residential Radon Survey (NRRS) [34] by both house substructure type and type of heating fuel used. We found that the substantive results of performing the analysis with the NRRS data are only slightly different from the results presented here. Most of the discrepancies in estimated energy cost and energy usage are due to the fact that the NRRS suggests a somewhat higher proportion of mitigable homes with high radon concentrations would be electrically heated (and fewer would be gas or oil heated). In no region were

Table 4
Energy requirements, expense and CO_2 emissions associated with cooling the additional ventilation air

Region	Fraction of single family homes with air conditioning [a], f_{AC}	Fraction of households with air conditioning that use it [b], f_{use}	No. of cooling degree-days [c], N_{CDD} (°C d)	Efficiency of air conditioner and distribution system, η	Latent enthalpy ratio, R (–)	Energy, E_c (GJ y^{-1} per house)	Cost, C_c (\$ y^{-1} per house)	CO_2 production, M_c (kgCO_2 y^{-1} per house)
NE	0.56	0.36	421	1.78	0.13	0.05	1	7.7
S	0.87	0.77	1159	1.78	0.25	0.51	9	90
MW	0.73	0.42	481	1.78	0.15	0.09	2	23
W	0.40	0.50	767	1.78	0.01	0.08	1	11

[a] Ref. [20], Table 11, p. 38; Table 54, p. 180.
[b] Ref. [20], Table 54, p. 180.
[c] Ref. [20], Table 56, p. 186.

Table 5
Energy requirements, expense and CO_2 emissions associated with running the system fan

Region	Energy, E_f (GJ y^{-1} per house)	Cost, C_f (\$ y^{-1} per house)	CO_2 production, M_f (kg CO_2 y^{-1} per house)
NE	2.1	55	330
S	2.1	39	370
MW	2.1	51	540
W	2.1	38	300

Table 6
Regional per-house energy use, expense and CO_2 emissions associated with SSD system use

Region	Energy (GJ y^{-1} per house)	Cost (\$ y^{-1} per house)	CO_2 production (kgCO_2 y^{-1} per house)
NE	7.2	99	660
S	4.7	67	620
MW	7.9	97	930
W	5.3	66	500

the differences between the results presented here and those using the NRRS data greater than 15%. Since use of the NRRS entails its own problems of correcting for small sample sizes (the survey sampled only 125 of about 3100 counties in the US), a simple analysis based on it would not necessarily be more accurate than the present work.

3. Results and discussion

3.1. Regional, per-house impacts of SSD system use

Calculated heating energy impacts and expenditures are summarized in Table 3. The energy, E_h (Table 3, column 6), required to heat the additional ventilation air ranges from 2.1 GJ y^{-1} per house in the South to 5.8 GJ y^{-1} per house in the Midwest. The cost of supplying this energy, C_h (Table 3, column 8), varies from \$19 y^{-1} per house in the South to \$45 y^{-1} per house in the Midwest. The CO_2 emissions associated with this energy generation, M_h (Table 3, column 10), range from 160 kgCO_2 y^{-1} per house in the South to 370 kgCO_2 y^{-1} per house in the Midwest. The per-house heating energy, cost, and associated CO_2 emissions are largest (and comparable) in the Northeast and Midwest.

Calculated cooling energy impacts and expenditures are summarized in Table 4. The cooling energy requirements, E_c (Table 4, column 7), are much lower than the heating energy requirements. Our estimates range from 0.05 GJ y^{-1} per house in the Northeast to 0.51 GJ y^{-1} per house in the South. The cooling energy requirements are highest in the South where more homes have air conditioners, more of the homes with air conditioners use them, and the number of cooling degree-days is relatively large. Cooling fuel costs attributable to the SSD system, C_c (Table 4, column 8), are relatively small, ranging from \$1 to \$9 y^{-1} per house. CO_2 emissions, M_c (Table 4, column 9), are largest in the South, at 90 kgCO_2 y^{-1} per house.

The required fan power per house is independent of region. Therefore, the variations in fan operating expense and CO_2 emissions are a function only of regional electricity costs and CO_2 emission factors. Table 5 summarizes our calculations. Among regions, the average cost to run the fan, C_f (Table 5, column 3), varies from \$38 to \$55 y^{-1} per house, while CO_2 emissions, M_f (Table 5, column 4), range from 300 to 540 kgCO_2 y^{-1} per house. The emissions generated from producing power for the fan are the largest contributor to CO_2 emissions associated with SSD system operation.

Table 6 gives the per-house energy use, expense and CO_2 emissions associated with SSD system operation. Overall energy requirements range from 4.7 to 7.9 GJ y^{-1} per house. Costs vary from \$66 to \$99 y^{-1} per house. CO_2 emissions range from 500 to 930 kgCO_2 y^{-1} per house. The fan consumes, on average, about 40% of the end-use energy used to operate the SSD system. However, because electricity is the most expensive fuel, the fan accounts for about 60% of the annual expense in all four regions.

For comparison, a new, energy efficient refrigerator of moderate size (18 ft^3) consumes about 2.3 GJ y^{-1}. We predict that an SSD system will use about two to three times this

Table 7
Total regional and national energy requirements, expense and CO_2 emissions associated with SSD system use

Region	No. houses [a] with indoor concentrations >4 pCi l^{-1}	% of houses with a basement or slab-on-grade [b]	No. houses that are subject to SSV mitigation, N_H	Total energy (fan + ventilation) (TJ y^{-1})	Total cost (fan + ventilation) (M\$ y^{-1})	Total CO_2 (fan + ventilation) (kgCO^2 y^{-1}
NE	5.94E+05	54	3.19E+05	2.3E+03	32	2.1E+08
S	1.92E+06	37	7.03E+05	3.3E+05	47	4.4E+08
MW	2.46E+06	52	1.29E+06	1.0E+04	130	1.2E+09
W	7.46E+05	39	2.92E+05	1.6E+03	19	1.5E+08
US	5.72E+06		2.60E+06	1.7E+04	230	2.0E+09

[a] Ref. [4], Table 8, p. 705.
[b] Ref. [20].

amount of energy; the lower value corresponding to a house in the South or West, and the higher value corresponding to a house in the Midwest or Northeast.

3.2. Regional and national implications

Table 7 summarizes our calculations of the regional and national energy demand, cost and CO_2 emissions associated with SSD system operation at saturation. Here we assume that all houses with a basement or slab-on-grade construction that also have indoor radon concentrations above 4 pCi l^{-1} are mitigated with an SSD system (about 2.6 million houses nationwide). The impacts are largest in the Midwest, where the heating load and the number of mitigable houses are large.

Over the entire US, we estimate that, annually, 1.7×10^4 (6.4×10^3 to 3.9×10^4) TJ of end-use energy would be consumed by the SSD systems at a cost of about \$230 (130 to 400) million. In addition, about 2.0×10^9 (1.2×10^9 to 3.5×10^9) kgCO_2 per year would be emitted as a result of producing this energy. The ranges presented here are based on our uncertainty in the increased house ventilation rate caused by the SSD system.

For perspective, the energy consumed nationally by the SSD systems at saturation is approximately equal to the energy consumed by 230 000 cars. The national CO_2 emissions associated with SSD system operation are about equal to the CO_2 emissions of 350 000 cars [35].

4. Conclusions

The implications of operating SSD systems in homes with radon concentrations above the EPA remediation guideline are considerable. Individual SSD system operating costs vary, by region, between \$66 and \$99 per year. The higher cost corresponds to a house in the Northeast or Midwest, and the lower cost to a house in the South or West. By combining data of the distribution of indoor radon concentrations and house substructure types, we estimate a national annual cost of \$230 (130 to 400) million at saturation. This cost is associated with an annual national energy demand of 1.7×10^4 (6.4×10^3 to 3.9×10^4) TJ, and 2.0×10^9 (1.2×10^9 to 3.5×10^9) kg of CO_2 emissions. Because of its relatively high heating load and large number of mitigable houses, the impacts of SSD use are largest in the Midwest. Improving our estimate of the SSD-induced house ventilation could substantially decrease the uncertainty in these predictions.

Very little research has been conducted to optimize the energy efficiency of SSD systems. Saum [36] and Fisk et al. [8] have reported satisfactory performance with a 10 W system fan for some new houses. Passive or energy-efficient systems [37,8] offer opportunities to drastically reduce the fan energy required by SSD systems. We expect these techniques will also have a much smaller impact on house ventilation, thereby largely avoiding the heating and cooling expenses associated with SSD system use. Further research should be aimed at defining the possible energy savings, relative effectiveness of reducing indoor concentrations, and applicability of these low-energy mitigation techniques.

5. Nomenclature

C_c	cost to cool the additional air flow for an average house (\$ y^{-1} per house)
C_f	cost to run the SSD system fan (\$ y^{-1} per house)
C_{fuel}	fuel cost (\$ GJ^{-1})
C_h	cost to heat the additional air flow for an average house (\$ y^{-1} per house)
C_{hi}	cost to heat the additional air flow for a particular fuel (\$ y^{-1} per house)
c_p	heat capacity of air (1000 J kg^{-1} K^{-1})
E_c	energy required to cool the additional air flow for an average house (GJ y^{-1} per house)
e_{CO_2}'	regional CO_2 emission factor (kgCO_2 GJ^{-1})
E_f	energy required to run the SSD system fan for an average house (GJ y^{-1} per house)
E_h	energy required to heat the increased air flow for an average house (GJ y^{-1} per house)
E_{hi}	energy required to heat the increased air flow for the 'ith' fuel type (GJ y^{-1} per house)
E_{lh}	latent-heat energy demand for an average house (GJ y^{-1} per house)
f_{AC}	fraction of single-family homes with air conditioners (–)

f_i	fraction of houses that use the '*i*th' fuel type (–)
f_{use}	fraction of homes with air conditioners who use them regularly (–)
M_c	mass of CO_2 emitted from producing the cooling energy ($\text{kgCO}_2\ \text{y}^{-1}$ per house)
m_{CO_2}	regional CO_2 emissions ($10^3\ \text{tCO}_2$)
M_f	mass of CO_2 emitted from producing the fan energy ($\text{kgCO}_2\ \text{y}^{-1}$ per house)
M_h	mass of CO_2 emitted from producing the heating energy ($\text{kgCO}_2\ \text{y}^{-1}$ per house)
M_{hi}	mass of CO_2 emitted for a particular heating fuel ($\text{kgCO}_2\ \text{y}^{-1}$ per house)
N_{CDD}	annual number of cooling degree days for each region (K d)
N_{H}	number of houses in which an SSD system is appropriate (–)
N_{HDD}	annual number of heating degree days (K d)
N_{LHD}	annual number of latent enthalpy-days (J d kg^{-1})
Q	effective house ventilation rate with the SSD system operating ($\text{m}^3\ \text{s}^{-1}$)
Q_0	unperturbed house ventilation rate ($\text{m}^3\ \text{s}^{-1}$)
Q_{SSD}	flow through the SSD pipes ($\text{m}^3\ \text{s}^{-1}$)
R	ratio of the latent heat to sensible cooling energy load (–)
S	regional electric utility sales (GWh)

Greek letters

η	efficiency of the heating and distribution system (–)
η_e	efficiency of the cooling and distribution system (–)
η_d	efficiency of the distribution system (–)
η_e	heating equipment efficiency (–)
ρ	air density ($1.2\ \text{kg m}^{-3}$)

Note: (–) indicates a variable is non-dimensional.

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