Ventilation-based variable conductance approach for residential cooling energy reduction

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Introduction

There is ample evidence that addressing climate and energy research is a global challenge, which has an impact on our health.[1] It is critical to create practical and innovative solutions for sustainable development. Emphasizing this need, a recent article published in Nature Energy in 2020 [2] highlighted five thermal science related challenges that could potentially have a significant effect on our society. One of the challenges noted in the publication is about the use of variable conductance envelope in buildings.[2]

Climate control of buildings is associated with a remarkable energy consumption in the United States (US). In 2020, residential buildings emitted 561 MMT CO_2 from electricity consumption.[3] Out of the total 561 MMT CO_2, space heating and cooling accounted for 43% of energy consumption and CO_2 emissions in US homes.[3] Recent research showed that use of a variable conductance commercial building envelope can offer energy savings up to 40% across different cities in US, in turn, having an effect on Green House Gases (GHG) emissions.[4] This highlights the importance of studying technologies that can use variable conductance envelope method in our homes to decrease this energy consumption.

Variable conductance can be achieved using a variety of methods such as electrochromic windows,[5] breathing walls,[6] and use of dynamic insulation materials (DIM) methods.[7] All these techniques are associated with significant investment for the homeowner. In comparison, another strategy to achieve variable conductance envelope is an approach that relies on tracking outdoor temperature and humidity condition and notifying homeowners to open or shut their windows. In simple words, this strategy relies on opening/closing windows during the right time periods and this study will call this technique ‘selective window ventilation’ (SWV).[8] The SWV approach is promising because it requires no hardware and results can be obtained with software cuing. There is limited data on use of SWV method in residential buildings.[8]

Given this background, this study will focus on employing a SWV approach for residential homes to reduce cooling energy. Based on prior window ventilation research,[8] the hypothesis is that the SWV method could reduce associated carbon footprint of residential space cooling by 25%. This 25% reduction in cooling needs would lead to a potential benefit of 60 MMT CO_2 reduction, which is same as taking 4.5% of gasoline cars off the road in the US.[9, 10]

This study will assess the A/C cooling load and cost saving calculations using SWV for residential buildings. Estimating these savings may allow a community to consider variable conductance methods for residential buildings. This study may provide pilot findings that could serve as an important step towards generating ideas for sustainable living.

Research Questions, Hypothesis, Outcomes

1. The 1st purpose is to compare the SWV *vs.* the constant conductance methods for A/C cooling load of a typical sized (2000 ft^2) US home. This was estimated across four different cities in distinct climate zones over 12 months.

Hypothesis: The use of the SWV compared to constant conductance method will reduce A/C cooling load of a typical sized US home, when averaged across four different cities in distinct climate zones over 12 months.

2. The 2nd purpose is to demonstrate that the SWV compared to constant conductance approach can lead to significant annual savings on cooling cost of homeowner.

Hypothesis: The SWV approach compared to constant conductance approach will decrease the annual space cooling cost for a homeowner.

Expected Outcomes: SWV approach will offer a cooling load reduction and cost-effective method to cooling homes. These economic savings may motivate homeowners to consider variable conductance methods and in turn decrease energy emissions in the environment.

Materials and Methods

This simulation-based study combines data from literature with physics equations to estimate heat (thermal) load for a house, cooling load for A/C, and the annual cooling costs. These input data were entered into MS-Excel sheets and results were obtained by converting the equations to Excel formulas. The following steps were used to obtain the results needed to validate our hypotheses.

1. The four cities representing different USA regions and climates that were selected for the analysis are shown in Table 1.

Table 1. Selected cities and their climate zones

City name	Climate zone[11]
Sacramento, CA	Moist Subtropical Mid-Latitude Climate
Saratoga, NY	Moist Continental Mid-Latitude Climate
Miami, FL	Tropical Climate
Phoenix, AZ	Dry climate

For each of these cities, I obtained temperature and relative humidity monthly averages and standard deviation (using weather.com statistics and other data sources[12]). Using these data, I created input data tables of maximum temperature, minimum temperature, and humidity for four cities for 365 annual days using normal curve randomization function NORM.INV(RAND(), MEAN, STD. DEV.) (from the averages and standard deviations).

2. I created a data table of electricity rates[13] (in $/KWh) for these four cities.
3. Considering the comfort for the people residing in a home, I gathered information from academic institutions[14] and the American Society of Heating, Refrigerating and Air-Conditioning Engineers[15] on human temperature and humidity comfort ranges to identify the temperature and humidity settings for the home. Based on data, I chose 21.1 C (70 F) and 60% as comfort settings for temperature and humidity, respectively.[15]
4. Since AC cooling load is addition of cooling and dehumidification loads, I created a lookup table of % latent heat on AC and outdoor relative humidity using literature.[16]
5. I obtained the heat emitted by normal human beings from literature as 100 W.[17] Based on the U.S. Census Bureau data (2021),[18] I assumed three people per family living in the house with them being in the house for 2/3 of daily time.
6. To calculate the heat load from appliances, the appliance powers[19] were obtained and their usage time/day was assumed as in Table 2.

Table 2. Appliance Power and Use Data

Appliance	Power (W)	Time use per day (h)
Cooking range (one burner)	500	0.25
Microwave	1000	0.16
Refrigerator	200	6

7. The insulation values (commonly called R-value) for house[20] in the four cities were found from literature and converted to SI units from default imperial values. The house was assumed to have two floors, square plan shape, 20 ft height, and 2000ft^2 total area. Using these values and geometric rules, the exposed side and roof area of the house were calculated. The house was assumed to have sixteen windows, each 3 x 5'.

8. For the cases with SWV, the air ventilation velocity was assumed 1 mph, which is the average wind speed on a still air day.
9. The heat load and electrical load for the constant conductance was calculated using the following equations

   Average appliance heat load = [Summation of (Appliance Power x Time use per day)]/24, where 24 is the hours per day.

   Human heat load = Number of people in the house x Average daily time in the house x Heat emitted per human.

   Heat into the house from insulation = (1/R-value) x House exposed area x (Outdoor temperature – human comfort temperature), where the human comfort temperature, as mentioned before, is 21.1 C.

   Total heat load = (Average appliance heat load + Human heat load + Heat into the house from insulation)/(1.0 - % latent heat)

   Total A/C Cooling load = Total heat load/Coefficient of Performance (COP), where the COP is assumed 3 for A/C with 10.3 SEER.

10. The load calculation for SWV is identical to constant conductance except that the window cooling effect is subtracted from the total heat load (from above step) prior to estimating A/C electrical load. Using the daily maximum and minimum temperatures from the data table, I created hourly variation of temperature by assuming the minimum temperature point is always at 6 AM and maximum at 4 PM. I linearly graded the temperature between 6 AM and 4 PM. I used the following physics equation to calculate the SWV cooling effect.

If outdoor temperature < 21.1 C and humidity < 60% then

SWV cooling = Air density x Air Specific Heat x Window area x Total number of windows x Air velocity of 1 mph x (Outdoor temperature – indoor comfort temperature).

Else

SWV cooling = 0

11. The A/C cooling loads for constant conductance and SWV were then summed across all days of each month to get monthly variation.
12. Finally, the monthly A/C electrical load was multiplied by electricity rate to find cooling monthly bill for both the insulation cases.

Data analysis: For the first research question, to compare data between the SWV and constant conductance method, an unpaired t test (two-tailed) was used with statistical significance set at $P < 0.05$. All statistical analyses were performed using MS-Excel ToolPak.

Results

Comparison of the SWV vs. the constant conductance methods for A/C cooling load

Tables 3 and 4 provide the input datasets for the four cities in terms of temperatures, electricity rates, and house insulation values.[12, 13, 20]

Table 3. R-value, Electricity Rates, Temperature, and Humidity Input Data for Sacramento and Saratoga

Month	Max Temp (ºF)	Min Temp (ºF)	Humidity (%)	Max Temp (ºF)	Min Temp (ºF)	Humidity (%)
Jan	56.5	41.1	70%	32	14.3	63%
Feb	62.2	43.7	59%	35.4	16	59%
Mar	67.8	46.7	52%	45.3	24.8	54%
Apr	73.5	49.3	44%	60.3	35.9	48%
May	81.3	54	37%	72.5	47	51%
Jun	89.0	58.7	32%	79.9	56.2	54%
Jul	94.4	61.4	30%	83.8	60.9	54%
Aug	93.5	61	30%	82.1	59.4	56%
Sep	89.3	58.8	39%	74.9	51.8	57%
Oct	78.9	52.9	57%	62.1	40.5	57%
Nov	65.3	45.3	69%	48.7	30.8	57%
Dec	56.4	40.7	69%	37	21.6	57%
	Sacramento (R – 38), 0.26 $/KWh			Saratoga (R – 47); 0.23 $/KWh		

Table 4. R-value, Temperature and Humidity Input Data for Miami and Phoenix

Month	Max Temp (ºF)	Min Temp (ºF)	Humidity (%)	Max Temp (ºF)	Min Temp (ºF)	Humidity (%)
Jan	73.6	61.2	60%	70.6	38.5	33%
Feb	74.8	63.3	57%	73.7	40.9	28%
Mar	76.5	65.2	55%	80.4	45.9	23%
Apr	79.6	69.8	55%	86.9	50.9	16%
May	82.7	73.6	58%	95	59.1	13%
Jun	86	76.5	65%	103.7	67	12%
Jul	87.8	78	63%	105.9	75.8	21%
Aug	88.1	78.1	64%	104.8	75.1	23%
Sep	87	77.2	66%	100.8	68.9	23%
Oct	83.7	74.4	63%	91	56.3	23%
Nov	78.9	68.6	60%	79	45.1	34%
Dec	76.1	64.6	60%	69.3	37.7	23%
	Miami (R – 25); 0.14 $/KWh			Phoenix (R – 33); 0.13 $/KWh		

Figure 1. KW A/C cooling load for four cities across calendar months for constant conductance and SWV; top-left Sacramento, top-right Saratoga, bottom-left Miami, bottom-right Phoenix. Note that SWV calculation assumes that 25% of the house windows are open for 25% of the time with 25% opening.

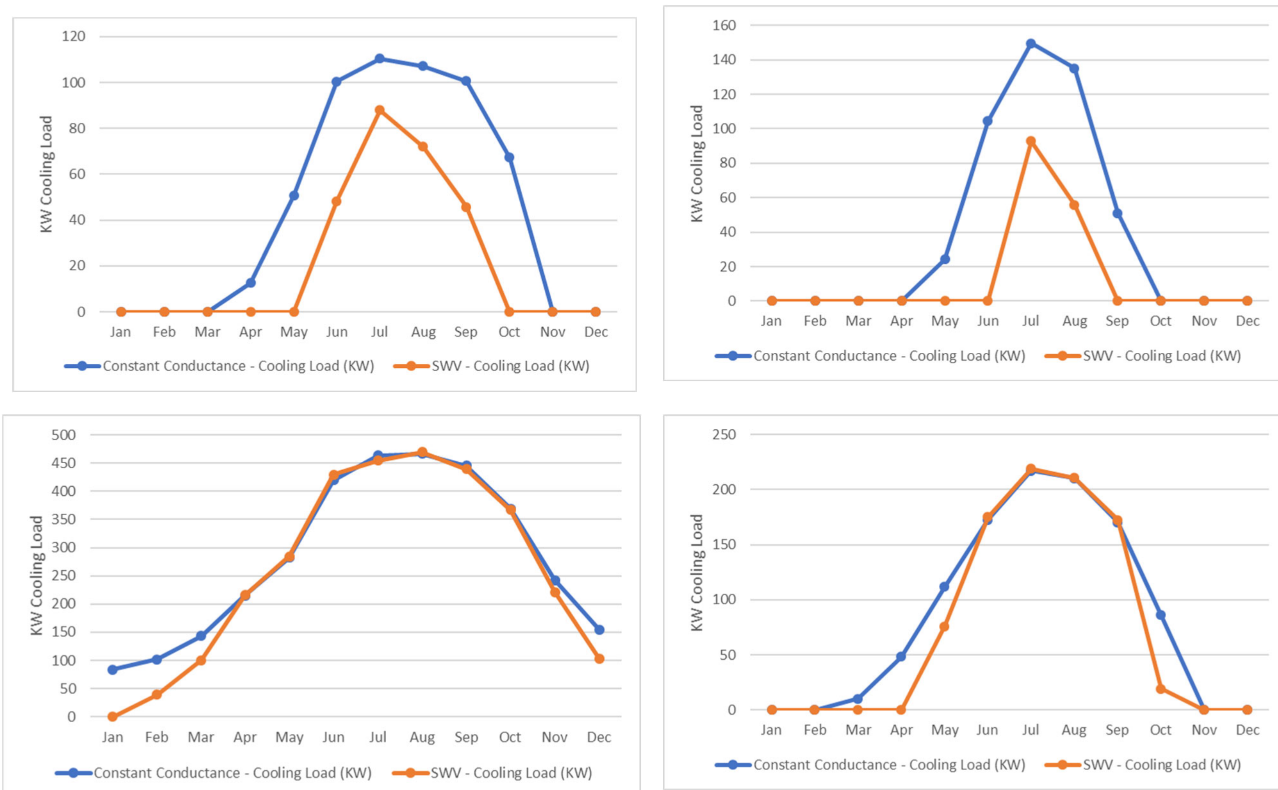

Figure 1 highlights the A/C cooling load for four cities across a year between the constant conductance case and SWV. For Sacramento and Saratoga, the cooling loads initiate in spring (Mar and Apr) and end in fall (Oct and Nov). Across all these months, the SWV provides a significant reduction (p-value < 0.05; refer to Table 5) to the cooling load as compared to constant conductance. Most notably, the months of April, May, and September are most impactful months for SWV vs. constant conductance for Sacramento and Saratoga. On the contrary, for Miami and Phoenix, the SWV method provides cooling reduction at the starting and ending months of the cooling season. However, in peak summer months, the SWV does not create any impact on these cities.

Table 5. t-test results for monthly A/C cooling load data between constant conductance and SWV.

City	Constant Conductance Mean (SD), KKW	SWV Mean (SD), KW	t statistic	P-value
Sacramento	78.4 (36.1)	36.3 (36.8)	5.72	0.0006
Saratoga	92.9 (53)	29.7 (42)	4.66	0.0005
Miami	282.35 (145.0)	260.46 (171.8)	2.46	0.015
Phoenix	128.4 (76.3)	109.1 (95.44)	1.99	0.04

SWV compared to a constant conductance approach can lead to significant annual savings

Figure 2. Reduction in annual A/C cooling load between constant conductance and SWV for the four cities.

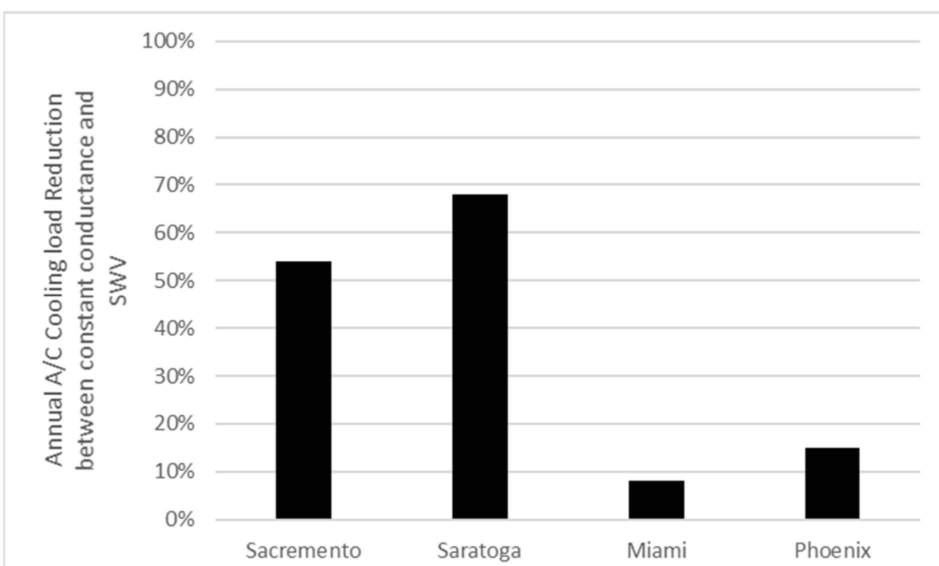

Figure 3. Annual A/C cost difference between constant conductance and SWV for the four cities.

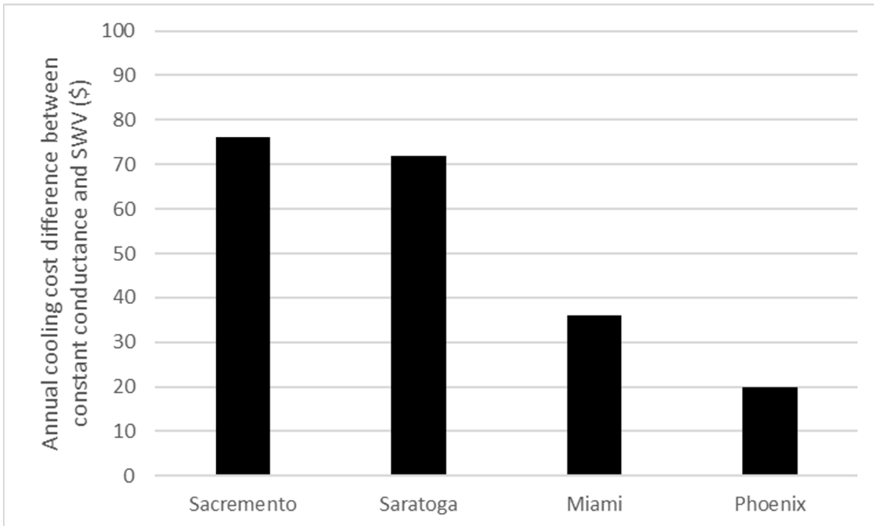

Figure 2 shows the % reduction in A/C cooling load and annual savings caused by SWV. Mid-latitude cities with temperate climates such as Sacramento and Saratoga can benefit greater than 50% from SWV vs. constant conductance. In comparison, in Miami and Phoenix, due to persistent hot and humid weather, the SWV produces cooling load reduction of less than 40%, as compared to constant conductance. Figure 3 translates the A/C cooling load reduction to annual cooling cost difference for homeowners using the electricity prices. The annual cooling cost savings for Sacramento and Saratoga are higher than those in Miami and Phoenix (by a margin of $35).

Discussion

Heating and cooling costs make up 20-40% of total consumption in buildings.[21] This study is focused on studying the benefits of using SWV over constant conductance in terms of A/C cooling load and annual cooling costs. This method offers a simple and cost-effective solution to allow homeowners to reduce cooling cost and lower GHG.

In agreement with our first hypothesis, we found that SWV produces statistically significant reduction in A/C cooling load across all cities with Sacramento and Saratoga showing more marked impact due to their cooler mid-latitude climates. This is because there are more time periods in a year for Sacramento and Saratoga, where the outdoor temperature and humidity are within comfort range. Aside from relative comparison, it is also important to note that absolute A/C cooling load for Miami is greater than Phoenix. Though the summer temperatures in Phoenix are scorching hot, it may be the higher humidity in Miami that causes a higher cooling load (due to higher % latent heat load). It is also important to point out that the cooling loads do not just depend on outdoor weather conditions but also on the R-value of houses that vary across the USA. The lower the R value the greater the heat entering the house through insulation. Houses in Miami have the lowest average R-value (25), whereas houses in Saratoga have the highest average R-value (47) (unit for R-value is hr-ft^2-R/Btu). During summer, SWV has an insignificant impact in Miami and Phoenix. This is because unlike Saratoga and Sacramento, the summer months in Phoenix and Miami are extremely hot (consistently > 21.1 C). Furthermore, in summer months, Miami is also very humid, which causes further reduction in the impact of SWV over constant conductance. That said, we obtained an 8 – 62% reduction in A/C cooling load across the cities. A similar technology, electrochromic windows,[22] can allow higher energy savings (up to 39 – 59%). However, the benefits are influenced by orientation, the control strategy adopted, climatic condition and location. Furthermore, electrochemical windows will add large upfront costs to the homeowner (unlike SWV). Similarly, DIM showed 15 – 39% reduction in A/C cooling load across the three cities picked in the study.[23] DIM will also require the homeowner to make significant investments (upfront costs).

Cost is an important factor for homeowners to adopt energy saving products/solutions. In agreement with our second hypothesis, the SWV produces significant annual savings for the homeowner. To the best of my knowledge, the only studies[7, 24] that have estimated cooling load reduction using variable conductance were conducted on commercial buildings and not residential. These studies[7, 24] showed variable conductance approaches can save commercial buildings between 7-42% in heating and cooling costs depending on the location. The current study only focuses on cooling costs. As a result, our cooling load reductions are higher than those reported for commercial buildings for places such as Saratoga that have a cooler mid-latitude weather pattern. Furthermore, the cost savings using SWV over constant conductance for Sacramento and Saratoga range between $70 - 80. This shows if a homeowner wanted to invest in an innovative technology such as SWV with three-year payback, the technology will have to be below $250. This seems reasonable and encouraging given the price of similar energy efficient products such as Nest falls in the same range.[25] Finally, note that the A/C cooling load reduction is a comparative measure while the annual savings is an absolute measure relying on total A/C cooling load and the electricity pricing. Hence, even though Sacramento cooling load reduction is lower than Saratoga, the savings are higher for Sacramento because of higher electricity pricing and higher annual A/C cooling load. A similar fact is true between Miami and Phoenix.

The current study has several limitations, which needs further research in the area: consideration for cooling and not for winter heating, assumption that windows only let visible light in and filter out 100% of the infrared waves, averaging appliance and human heat loads across a single day vs. hour-by-hour, and size of home and human comfort parameters. Any change to them might impact the results.

Conclusion

This study objectively focuses on employing a SWV approach vs constant conductance for residential homes to reduce A/C cooling energy. Preliminary findings from this study showed that the cooling load reductions with the SWV approach ranged between 8 – 68% depending on the location. For cities such as Miami with hot tropical climate, the impact of SWV is less, while the impact is more for mid-latitude cooler cities like Saratoga. Our findings also show that the cooling cost savings can range from $20 – 76 annually. Given the simplicity of the approach, which is based on the principle of opening windows, the study shows that savings of up to $70-$80 may be obtained by homeowners in mid latitude climates. With these savings and potential software for cuing homeowners to open windows, the SWV is easy to install in our current homes. Given that residential heating and cooling is highlighted as an important challenge in addressing climate change, preliminary findings from this study suggest that approaches such as SWV for cooling residential buildings may need further investigation.

Risk and Safety

Since the proposed study is purely analytical (computer simulations) involving no use of live matter or personal data, I do not anticipate any risk associated with this study.

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