Thermoelectric Facades: Modeling Procedure and Comparative Analysis of Energy Performance in Various Climate Conditions

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ABSTRACT: This research study presents a methodology for simulating energy performance of thermoelectric (TE) facade systems. These novel facade systems can be used for localized heating and cooling in buildings. Simulations were performed to investigate impacts of TEs on buildings' energy performance by comparing them against a conventional HVAC system. The study was carried out by modeling a typical office space in IDA ICE software program, with an area of 3x3 m^2 (10x10 ft^2) and included one exterior wall (with an incorporated window), three adiabatic interior walls, a floor, and a ceiling. Simulations were performed for 15 different climates (climate zones 1A to 8). To simulate TE system's energy performance, an electric radiator, with characteristics that most closely matched that of the TE system, was used. This included assigning a certain area to the radiator and calculating its rated input power based on the climate condition. Based on the previously conducted research, 15% wall coverage was determined as the optimum area for heating and cooling production. Therefore, area of the electric radiator was assigned as 1.35 m^2 (15 ft^2). Given that the TE system's performance and output depend on the temperature difference between the building's internal and external environments, this was separately calculated for each climate zone and used for modeling energy performance of the TE system. Energy modeling results showed a reduction in energy consumption and improved performance of TE facade systems, compared to conventional HVAC systems. Energy Usage Intensity (EUI) comparison showed that the TE system exhibited improved performance in all climate zones. The results concluded that TE materials are promising intelligent components that can be used in facade assemblies for heating and cooling purposes.

KEYWORDS: Active facades, thermoelectric materials, energy performance, simulation, modeling
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INTRODUCTION

Thermoelectric (TE) materials are smart materials that can generate a voltage when exposed to a temperature gradient, utilizing the Seebeck effect and produce a temperature gradient when electricity is applied, exploiting the Peltier effect. They can be used for heating, cooling, and/or power generation, where heating and cooling modes can be switched by reversing current direction. It is possible to use TE modules as an alternative to conventional HVAC systems, when coupled with proper heat exchangers (Snyder et al. 2008). Thermoelectric heating and cooling have several advantages, compared to the conventional systems. The light-weight and compact size of TE modules, lack of mechanical parts, less maintenance requirements and cost, and elimination of chlorofluorocarbons (CFCs) and toxic refrigerants make TE systems environmentally friendly (Boukai et al. 2008; Upadhyaya et al. 2015). Research and development have focused on TE modules that convert heat energy into electricity (Montecucco et al. 2012; Snyder et al. 2008) and TE materials that offer higher energy efficiency through nanoscale engineering (Snyder et al. 2008).

Ibanez-Puy et al. (2015) investigated the design and construction process of a ventilated facade prototype that integrated TE materials. This research investigated the adaptability of heat transfer process within the prototype's air cavity by promoting it when heat dissipation is needed and reducing it when heat losses are not welcome (Ibanez-Puy et al. 2015). Aksamija et al. (2019) studied design and construction of two prototypes with incorporated TEs. One prototype was used to evaluate TE modules as stand-alone elements in the facade assembly, while the other was used to explore integration of TE modules and heatsinks in the assembly (Aksamija et al. 2019). In another study, Aksamija et al. (2020) investigated TE's heating and cooling potential by modeling facade-integrated TE systems and analyzing their thermal performance under varying external conditions. Results were promising and showed the applicability of this novel system for architectural and facade applications (Aksamija et al. 2020).

This study investigated heating and cooling potential and energy performance of TE facade systems, compared to a conventional VAV system. The following sections describe the background, research questions and methodology, and results.

1.0 BACKGROUND AND METHODOLOGY

1.1 Previous Work and Research Objectives

The research study presented in this paper is a part of larger research project, focusing on the integration of TE materials in facade assemblies. The research project started with experimental evaluation of built prototypes, thermal measurements, and simulations of heating and cooling potential. Figure 1 shows one of the prototypes that was used in the experimental study.

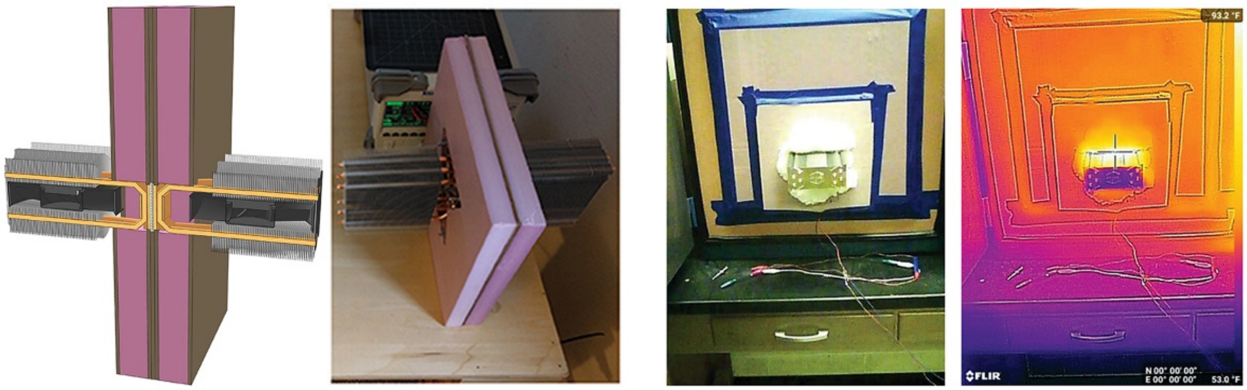

Figure 1: Experimental prototype and thermal imaging. Source: (Author 2018)

In the experimental study, prototype's heating and cooling outputs were evaluated using a thermal chamber to represent different external temperatures, while internal temperature was kept constant. Thermal chamber was set to 32°C, 16°C, -1°C, and -18°C (90°F, 60°F, 30°F, and 0°F), representing typical external temperatures found in most climates. The heating mode was tested under 16°C, -1°C, and -18°C (60°F, 30°F, and 0°F) temperatures, while the cooling mode was tested under 32°C and 16°C (90°F and 60°F). A thermal camera was used to measure the temperature of the exterior surface of the prototype. Results indicated that facade-integrated TE materials provide sufficient heating and cooling, as shown in Tables 1 and 2.

Table 1: Experimental results of thermal chamber testing, indicating temperature outputs in heating mode.

Chamber T °C (°F)	Voltage (v)	Current (A)	Power (W)	T output °C (°F)
-18 (0)	0	0	0	20 (68)
	1	0.17	0.17	19 (67)
	2	0.45	0.9	21 (70)
	3	0.74	2.22	23 (73)
	4	1.02	4.08	22 (72)
	5	1.12	5.6	24 (76)
	6	1.42	8.52	27 (80)
-1 (30)	0	0	0	12 (52)
	1	0.16	0.16	14 (56)
	2	0.45	0.9	21 (70)
	3	0.62	1.86	22 (72)
	4	0.87	3.48	21 (69)
	5	1.23	6.15	28 (82)
	6	1.4	8.4	24 (76)
16 (60)	0	0	0	23 (73)
	1	0.08	0.08	23 (74)
	2	0.73	1.46	23 (74)
	3	0.64	1.92	26 (79)
	4	0.9	3.6	27 (81)
	5	1.12	5.6	31 (88)
	6	1.41	8.46	36 (97)

Table 2: Experimental results of thermal chamber testing, indicating temperature outputs in cooling mode.

Chamber T °C (°F)	Voltage (v)	Current (A)	Power (W)	T output °C (°F)
16 (60)	0	0	0	24 (76)
	1	0.36	0.36	22 (72)
	2	0.65	1.3	21 (70)
	3	0.77	2.31	17 (63)
	4	1.08	4.32	8 (46)
	5	1.41	7.05	12 (54)
	6	1.82	10.92	10 (50)
32 (90)	0	0	0	23 (73)
	1	0.19	0.19	17 (63)
	2	0.43	0.86	19 (67)
	3	0.65	1.95	14 (57)
	4	0.92	3.68	19 (67)
	5	1.27	6.35	19 (67)
	6	1.6	9.6	16 (61)

The study was further extended by developing methods for integrating TE materials in various facade assemblies, as shown in Figure 2. For example, aluminium panels would act both as cladding and exterior heat sinks and would be connected to the TE materials with a copper conducting system. An interior heat sink would be installed, acting as a radiant panel to provide heating and cooling. Facade-integrated TE system could be installed as a modular piece and would be insulated from the rest of the exterior wall. The modular nature of this system makes it suitable for all building types and retrofits of the existing buildings.

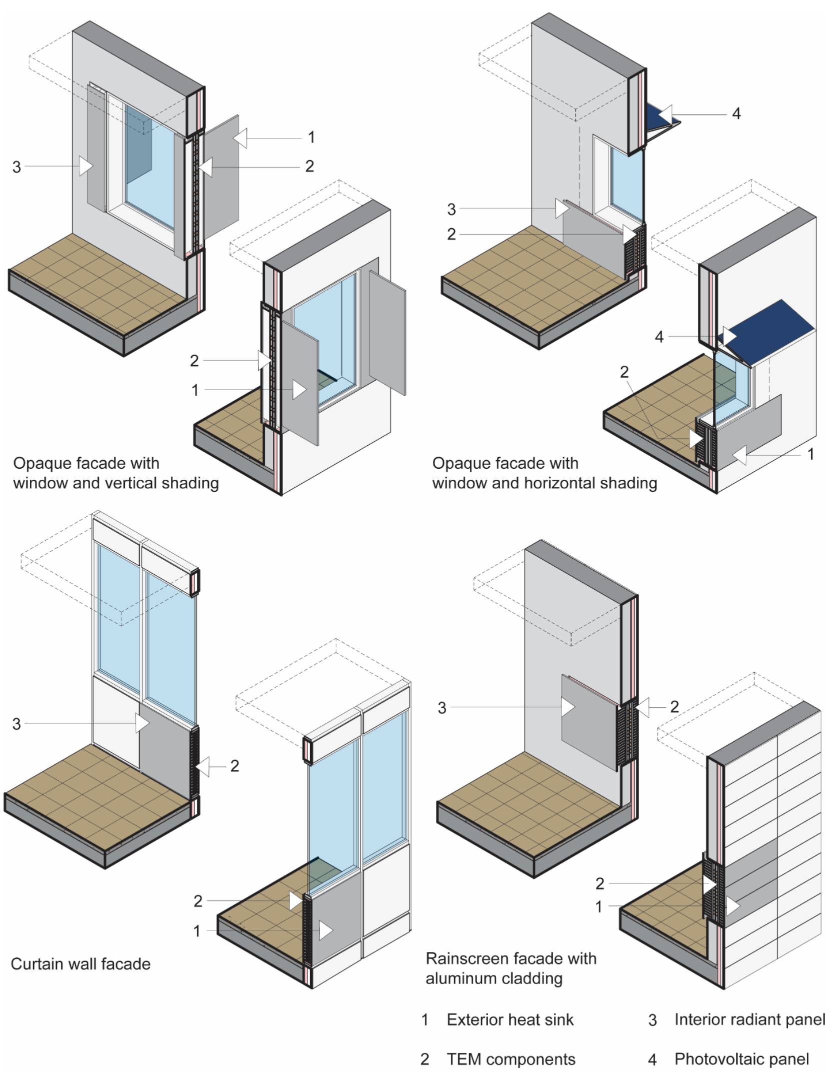

Figure 2: Different types of active facade systems with integrated TE materials. Source: (Author 2020)

In this research study, the objectives were:

- To evaluate energy performance of TE facade systems in various climatic conditions and
- To compare their energy consumption against a conventional HVAC system.

The study was conducted by modeling a typical office in IDA ICE software program, where a single office space was considered. Variables included HVAC system (TE facade as a novel and a VAV as a conventional system), and climate conditions. Fifteen different climate zones were considered, as shown in Table 3.

Table 3: Selected climate zones/regions and representative cities used for the energy modelling.

Climate zone	City	Zone	Region
1A	Miami, FL	Very hot	Moist
2A	Houston, TX	Hot	Moist
2B	Phoenix, AZ	Hot	Dry
3A	Memphis, TN	Warm	Moist
3B	El Paso, TX	Warm	Dry
3C	San Francisco, CA	Warm	Marine
4A	Baltimore, MD	Mixed	Moist
4B	Albuquerque, NM	Mixed	Dry
4C	Salem, OR	Mixed	Marine
5A	Chicago, IL	Cool	Moist
5B	Boise, ID	Cool	Dry
6A	Burlington, VT	Cold	Moist
6B	Helena, MT	Cold	Dry
7	Duluth, MN	Very cold	N/A
8	Fairbanks, AK	Subarctic	N/A

The office space had an area of 3x3 m^2 (10x10 ft^2) and included one exterior wall (with an incorporated window), three adiabatic interior walls, a floor, and a ceiling. The internal loads included one occupant, constant equipment and lighting loads, which were identical in all the developed models.

1.2. Thermoelectric modeling

To model the TE system in IDA ICE software program, 15% wall coverage with TE modules was treated as an electric radiator, covering 1.35 m^2 (15 ft^2) of the building envelope. Due to inability of the existing energy modelling software programs to model and simulate TE systems, the radiant system was used as a representative system. To model the TE system and simulate its impacts on energy performance, characteristics that most closely matched that of the TE system were assigned to the electric radiator, including a certain area (in respect to the building envelope's total area) and a calculated input power. Since TEs' performance and output depend on the temperature difference between the building external and internal environments, the input powers were calculated separately based on each climate zone. Here, the indoor temperature was constantly kept at 21°C (70°F) and the maximum and minimum outdoor temperatures were extracted from the historical weather data, specific to each location. In Table 4, power rating calculations for various climate zones are shown. This information was used to develop 30 different energy models, two for each climate zone, where the only differences between the models considered different HVAC type. Results of energy modelling are presented in the following section and implications of these results are discussed.

Table 3: External and internal temperature difference and the associated power rating values for TE system.

Climate zone	Mean delta T °C (°F)	Power rating per TE module (W)	Total power rating (W)
1A	15 (59)	80	2,160
2A	18 (64)	78	2,106
2B	21 (70)	75	2,025
3A	25 (77)	70	1,890
3B	22 (72)	75	2,025
3C	15 (59)	80	2,160
4A	25 (77)	70	1,890
4B	24 (75)	70	1,890
4C	25 (77)	70	1,890
5A	29 (84)	63	1,701
5B	27 (81)	65	1,755
6A	33 (91)	55	1,485
6B	30 (86)	60	1,620
7	32 (90)	57	1,539
8	34 (93)	55	1,485

2.0 RESULTS

Results of the thirty simulations in IDA ICE program included monthly and annual energy performance, as well as Energy Usage Intensity (EUI) for each analyzed climate zone. Monthly energy data included lighting, equipment, HVAC auxiliary, electric cooling, electric heating, and fuel heating. Additionally, given that lighting and equipment types and schedules were identical in all simulation models, energy consumption data associated with them were eliminated from the comparisons. Therefore, in the comparative analysis of the energy performance results, HVAC auxiliary, electric cooling, and fuel heating energy performance were the only data taken into consideration.

Trend of the monthly energy use of TE system vs. that of VAV system was summarized by merging the fifteen climate zones into three categories: very hot to warm (1A to 3C), mixed (4A to 4C), and cool to subarctic (5A to 8). From each category, two zones/locations were selected to represent energy performance differences, as shown in Figures 3 and 4.

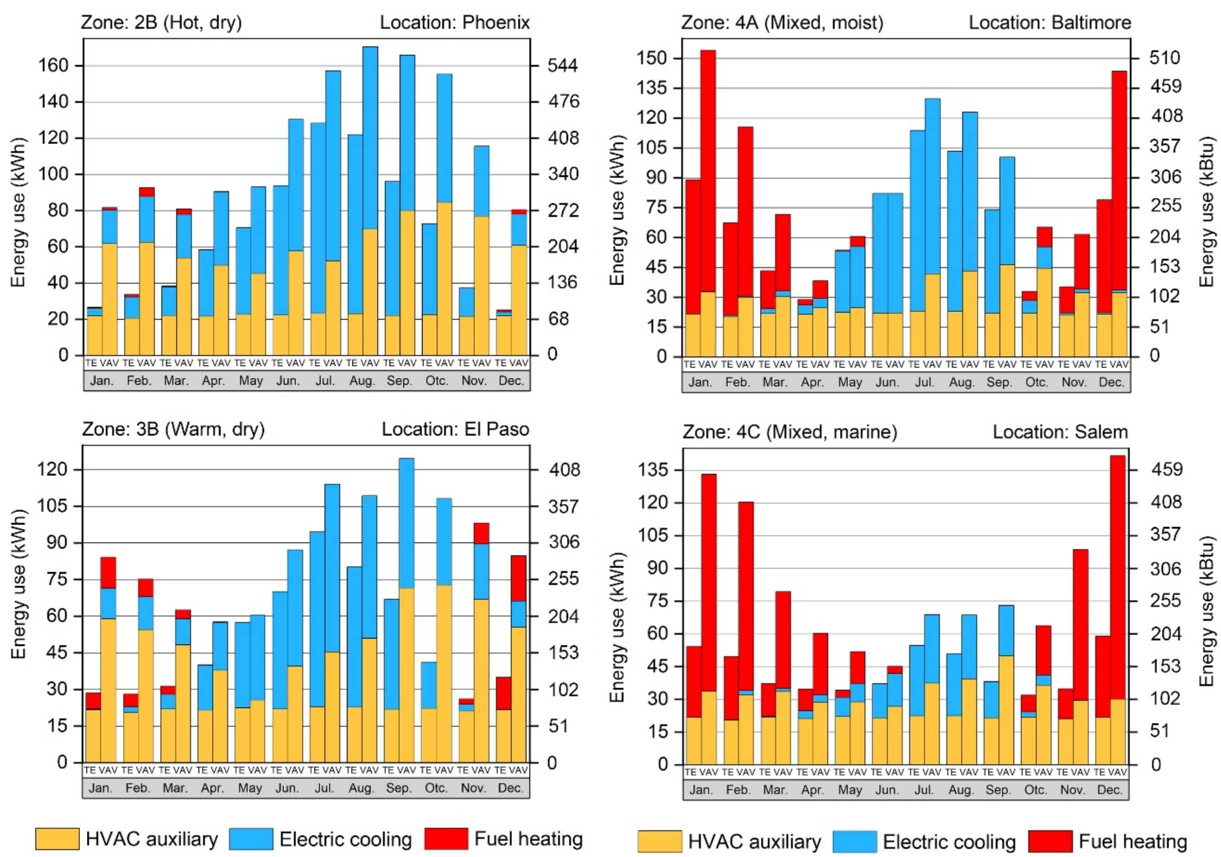

Figure 3: TE vs. VAV monthly energy use in climate zones 2B (Phoenix), 3B (El Paso), 4A (Baltimore) and 4C (Salem). Source: (Author 2021)

Results indicate that monthly energy consumption with the VAV system was always higher than for the TE facade system. Here, considering climate conditions (very hot to warm), higher amount of energy was needed for cooling purposes, compared to heating loads. Heating was only used during the coldest months of the year (January, February, March, November, and December), while electric cooling was predominant during the summer and fall months. Monthly energy usage of the two systems in mixed climates (zones 4A and 4C) was higher than for very hot to warm zones (zones 2B and 3B) due to higher heating loads. TE system showed a significant performance improvement compared to the conventional HVAC system, especially in heating modes.

Figure 4 shows results for monthly energy consumption in climate zones 6A and 8. Here, TE system showed a much higher energy efficiency, specifically during coldest months. In this category (cold to subarctic), there was a significant reduction in monthly electricity use since most of the cooling loads were eliminated except during the hottest months of the year. Moreover, fuel usage for heating purposes was higher than that of the other two climate categories (very hot to warm and mixed), due to the much colder weather conditions.

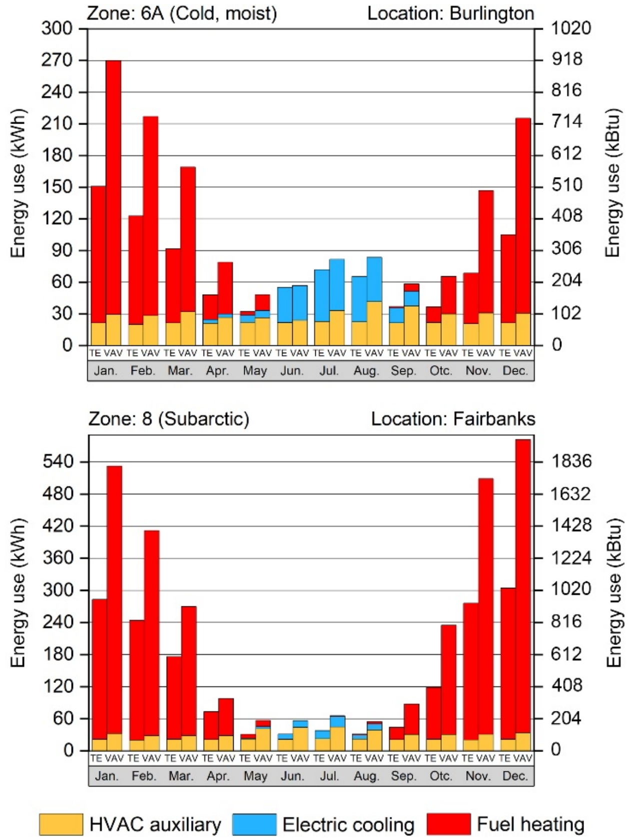

Figure 4: TE vs. VAV monthly energy use in use in climate zones 6A (Burlington) and 8 (Fairbanks). Source: (Author 2021)

Annual energy consumption comparisons of the TE facade vs. VAV systems are illustrated in Figure 5. Here, changes in energy usage (i.e., HVAC auxiliary, electricity, fuel consumption) between the two systems are shown. Considering the variation in weather conditions, moving from climate zone 1A to 8, electricity use for cooling significantly decreased, while consumed fuel for heating purposes remarkably increased. Unsurprisingly, total energy use in climate zone 8 (subarctic), due to the significant increase in heating loads, and consequently, fuel consumption, was significantly higher than other climate zones. In Figure 6, deviations in Energy Usage Intensities (EUIs) between the two systems in the selected climate zones are shown. For this purpose, VAV's EUI was selected as the baseline, with the objective to compare energy performance of the innovative TE system against that of the conventional HVAC system. Results of the EUI comparison showed that, regardless of climate zones, EUI deviations were always negative, indicating improved energy performance when TE system was used.

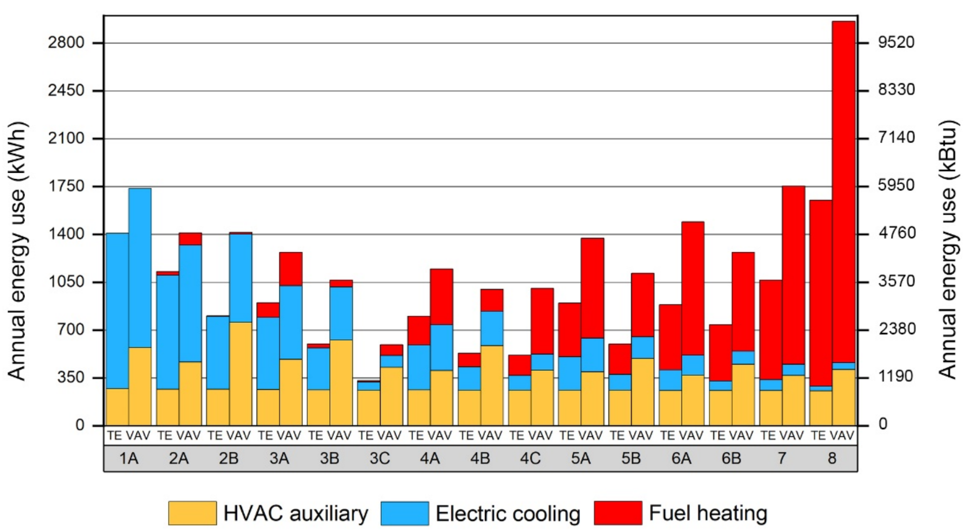

Figure 5: Annual energy use comparison of TE vs. VAV system, in various climate zones. Source: (Author 2021)

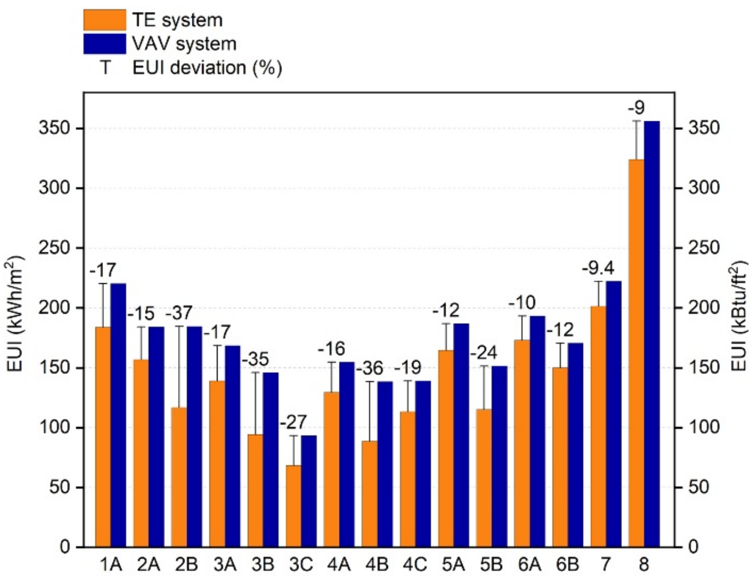

Figure 6: EUI comparison between the two systems in various climate zones. Source: (Author 2021)

CONCLUSION

The results of the current and previous research indicated that TE materials are promising active components that can be used in facade assemblies for localized heating and cooling purposes. TE system is an independent system that solely operates based on the temperature differences between the internal and external environments, containing no moving parts or harmful substances. Utilizing the temperature differences, TEs can warm up in heating mode and absorb heat in cooling mode. Compared to the conventional HVAC systems, maintenance of TE systems is easier due to the modularity of their components. Moreover, occupants of each room within the same building can use the system based on their personal preferences.

Energy modeling results, performed for various climate zones, showed reduction in energy use and improved performance of TE systems, compared to conventional VAV system. It was concluded that TE system was more energy efficient in all climate zones and conditions, compared to the VAV system. Regardless of the climate zones, monthly and annual energy usage (i.e., electricity, fuel, and HVAC auxiliary) of the TE facade system was lower than that of VAV system.

The developed TE system shows a promising direction for intelligent, active facades that react to environmental conditions and can be used for localized heating and cooling. Future studies will investigate and test full-scale facade mock-ups that integrate TE modules, with the objective to evaluate their thermal performances.

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