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Evaluation of Ground-Source Variable Refrigerant Flow System for U.S. Office Buildings

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Abstract: This paper evaluates the energy performance of ground-source variable refrigerant flow (VRF) systems to condition office buildings located in various U.S. climates. Specifically, the performance of the ground-source VRF systems was determined and evaluated against that achieved by conventional space heating and cooling systems, including packaged terminal air-conditioners (PTACs), water-source heat pumps (WSHPs), ground-source heat pumps (GSHPs), and water-source VRF systems. A comparative analysis shows that ground-source VRF systems require significantly lower source energy uses than other heating and cooling systems in all U.S. climates, ranging from 21% to 50% for PTACs, from 36% to 52% for WSHPs, from 22% to 49% for GSHPs, and from 4% to 19% for water-source VRFs. These results indicate that ground-source VRFs can be suitable heating and cooling systems for all U.S. climates when designing high-energy-performance commercial buildings.

Keywords: cost analysis; office buildings; variable refrigerant flow (VRF) systems; ground-source heat pumps (GSHPs); ground-source VRF systems; water-source heat pumps

1. Introduction

According to the U.S. Energy Information Administration (EIA), the energy use and electricity consumption by the building sector accounted for 39% and 74% of, respectively, the total U.S. energy use and the total U.S. electricity consumption during 2016 [1]. In addition, historical EIA data indicate that the energy consumption attributed to heating, ventilating, and air-conditioning (HVAC) systems can be significant. Indeed, the average energy consumption for HVAC systems accounts for 44% of the total U.S. building energy use [2]. In particular, HVAC systems were responsible for, respectively, 18% and 31% of the total national energy and electricity consumption during 2016. Therefore, there is a need to utilize energy-efficient HVAC systems in order to reduce the energy consumption and the carbon footprint of the building sector not only in the United States, but also worldwide. Variable refrigerant flow (VRF) systems have been increasingly considered as energy-efficient alternatives to conventional HVAC systems [3–13]. A VRF system is a heat pump system that utilizes a refrigerant as a heat transfer medium between a single condensing unit and multiple air terminal units. Two categories of VRF systems are generally available depending on their condensing medium type: air-source VRFs or water-source VRFs. Indoor air terminal units connected to a single condensing unit can have different capacities and configurations, allowing individual zone control and simultaneous space heating and cooling [8]. The documented attractive benefits of VRF systems include the following:

- Higher seasonal energy efficiency as a result of the high part-load performance of single or multiple variable speed compressors.

- Reduced ductwork, as indoor units are installed near or inside thermal zones. The short ducts result in lower fan capacities and reduced fan energy use.
- Lower energy requirements as a result of using a refrigerant as the heat transfer fluid instead of water or air.
- Reduced operation and maintenance costs, as different indoor units can operate simultaneously in heating mode or cooling mode even when connected to a single condensing unit.

Figure 1 illustrates the main components of a typical water-source VRF system connected to a heating source (such as a boiler) and a cooling source (cooling tower) to serve various terminal units in order to heat and cool different thermal zones within a building. In order to improve the energy efficiency of the VRF system, a ground medium can be utilized to provide both heating and cooling sources similarly to ground-source heat pumps (GSHPs) [14]. Figure 2 presents the various elements of a ground-source VRF (GS-VRF) system. As noted in Figure 2, the use of boilers and cooling towers required for the conventional water-source VRF systems may not be needed for a GS-VRF system, possibly resulting in lower installation costs.

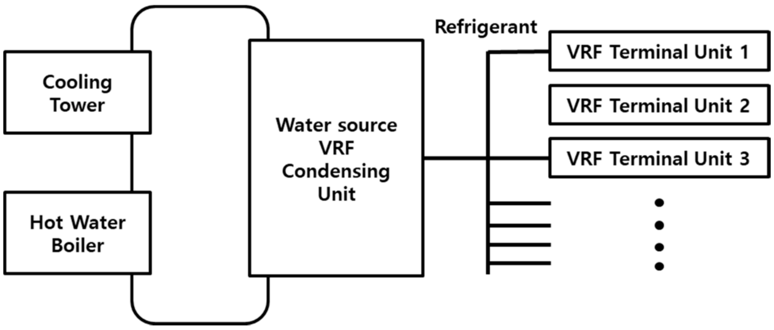

Figure 1. Typical components of a water-source variable refrigerant flow (VRF) system.

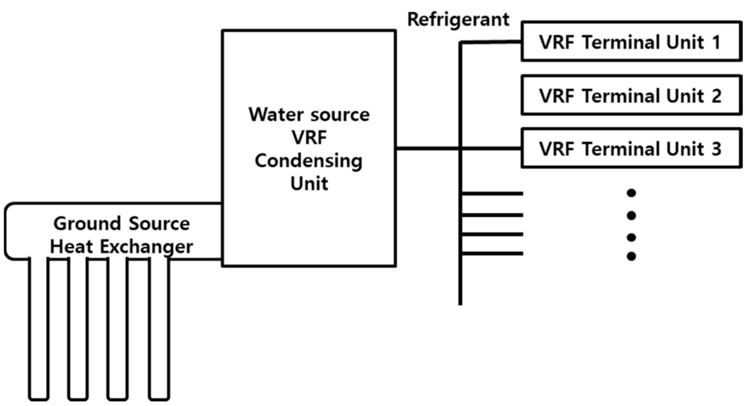

Figure 2. Typical components of ground-source variable refrigerant flow (VRF) system.

The analysis of the performance of air- and water-source VRF systems has been reported widely in the literature [3–13]. For instance, Goetzler discussed through case studies some of the benefits of VRF systems, including ease of installation, low maintenance costs, improved thermal comfort with individual set-point control, and increased energy efficiency [3]. Specifically, Goetzler indicated that VRF systems could reduce HVAC energy consumption by 30% to 40% compared to rooftop variable-air-volume (VAV) systems. Similarly, Thornton et al. found that VRF systems could achieve HVAC energy savings ranging from 30% to 60% compared to other conventional HVAC systems [7]. In particular, VRF systems have (i) lower cooling energy by a range of 30% to 50% compared to air-cooled chiller and unitary air-conditioning systems; (ii) lower heating energy by up to

75% compared to gas furnaces, boilers, and VAV systems with electric reheats; and (iii) lower fan energy ranging from 25% to 75% compared to conventional constant-air-volume systems. Koh et al. compared the cooling energy consumption and electrical peak demand of VRF systems to those obtained for conventional chiller-based VAV systems and packaged VAV (PVAV) systems for a typical light commercial building [8]. Koh et al. concluded that VRF systems can have lower peak electrical demand than VAV and PVAV systems by respectively 40% and 30% and can save operating energy use by 47% compared to VAV systems and by 40% compared to PVAV systems. Kim et al. also compared VRF systems to VAV systems for a prototypical medium-office-building model developed by the U.S. Department of Energy (DOE) for various U.S. climate conditions [9]. Kim et al. found that VRF systems saved between 15% and 42% in terms of site energy and between 18% and 33% in terms of source energy associated with HVAC equipment, compared to those achieved for VAV systems for all climate conditions. Zhou et al. performed energy analysis of VRF systems for office buildings using a whole-building energy simulation program and compared the energy consumption of VRF systems to VAV systems and fan-coil plus fresh air systems (FPFAs) [10]. On the basis of their analysis results, Zhou et al. found that VRF systems saved 22.2% and 11.7% in building energy consumption relative to, respectively, VAV and FPFA systems. Using an experimental testing approach, Im et al. evaluated the energy performance of a VRF system and a rooftop VAV unit for a multi-zone building with emulated office occupancy [11]. The testing analysis showed that the VRF system could reduce cooling energy consumption compared to the rooftop VAV unit by 29%, 36%, and 46% under 100%, 75%, and 50% thermal load conditions, respectively. Liu et al. assessed the energy-efficiency levels of both air-source VRF systems and GSHPs to heat and cool small office buildings located in Chicago and Miami [12]. Unlike other reviewed studies, Liu et al. found that GSHPs were more energy efficient than air-source VRF systems for both U.S. climates (Miami and Chicago). Finally, Aynur et al. used experimental data as well as simulation analyses to compare the energy performance of VRF systems to VAV systems to air condition an existing office building [13]. The analysis results indicated that the VRF systems provide energy-use savings ranging from 27.1% to 57.9% compared to the VAV systems.

Compared to air-source VRF systems, limited studies have been published to evaluate the performance of GS-VRF systems. Thornton et al. [7] mentioned that a ground source connected to a water-source VRF system would provide large energy savings, although it would require additional costs for ground-source borehole wells without detailed analysis. Karr [15] evaluated the energy performance of GS-VRF systems as well as other HVAV systems to maintain thermal comfort in a single-story assisted living building under various climatic conditions [15]. Specifically, Karr found that GS-VRF systems could achieve energy savings that ranged from 32% to 41% relative to air-source heat pumps. In addition to the fact that the selected structure is not representative of commercial buildings, the modeling details for GS-VRF systems and other HVAC systems are not provided in Karr’s analysis, including energy-efficiency indicators and performance curves. A more recent study by Im et al. used measured data and simulation analysis to evaluate the performance of a GS-VRF system to heat and cool a university building located in Rochester, MI [16]. The field-testing data indicated that pumps and indoor units accounted for, respectively, 16% and 33% of the total energy consumed by the GS-VRF system. The simulation analysis compared the energy performance of the GS-VRF system to that achieved by two configurations of VAV system with hot water reheat: (i) the first configuration consisted of an air-cooled chiller and a gas-fired boiler that were rated on the basis of the minimum energy-efficiency levels of the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 90.1-2010; (ii) the second configuration had a chiller and a boiler that had the highest efficiency then available on the market. The analysis results showed that the GS-VRF system achieved source energy savings of 33% and 29% compared to VAV system configurations (i) and (ii), respectively. However, the study of Im et al. was limited to one U.S. climate and lacked modeling details for GS-VRF systems.

The study presented in this paper fills the need for a comprehensive evaluation of the energy performance of GS-VRF systems compared to other types of VRF systems, GSHPs, and VAV systems for a wide range of climates to assess its suitability as an energy-efficient HVAC system for U.S. office buildings. First, the analysis methodology is described, including the details for the office-building model, the performance curves, and energy-efficiency parameters for the VRF systems and GSHPs. Then, the analysis results are summarized in terms of both total energy consumption and electrical peak demand for all HVAC systems and two office-building design configurations. Finally, general guidelines are provided to assess the suitability of GS-VRF systems to heat and cool U.S. office buildings.

2. Analysis Methodology

2.1. General Analysis Approach

The analysis carried out in this study utilized a whole-building energy simulation tool to model and evaluate the energy performance of various HVAC systems, including GS-VRF systems, to maintain thermal comfort within a medium-size office building. Specifically, and in order to account for the dynamic impact of various building systems on heating and cooling thermal loads, an hourly whole-building energy modeling (BEM) tool, the DOE-2 energy simulation engine, was utilized to assess the performance of the various HVAC systems considered in the study [17]. Energy consumption data obtained from a U.S. office building were first used to calibrate the energy model considered in the simulation analysis. Then, the calibrated energy model was utilized to develop office-building models for various U.S. climates in order to assess the performance of GS-VRF compared to other HVAC systems. Figure 3 illustrates the various data, simulation tools, and analysis techniques used in the study.

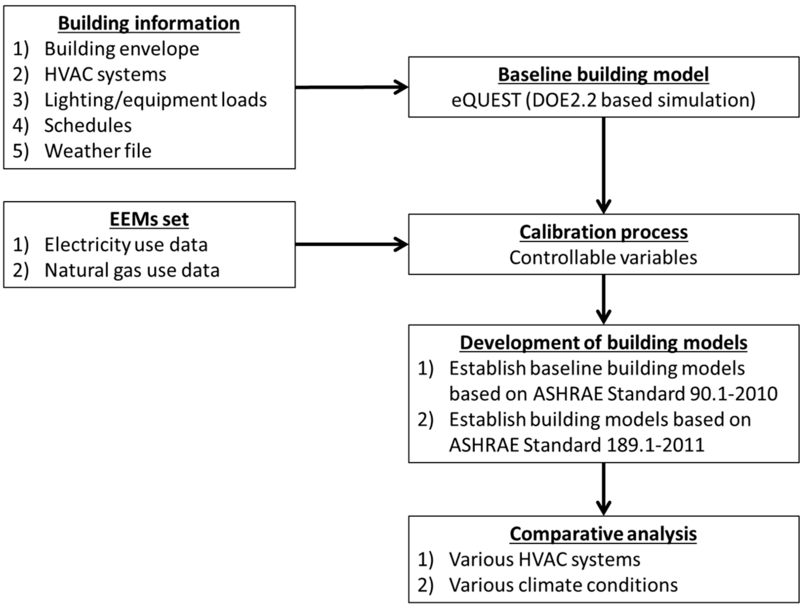

Figure 3. Flowchart for the simulation environment for the ground-source variable refrigerant flow (GS-VRF) evaluation analysis.

For the whole-building energy analysis, the DOE-2 simulation engine was utilized because it can model various HVAC systems, including VAV systems, GSHPs, water-source VRFs, and GS-VRF systems. In particular, DOE-2 utilizes the G-function technique to model the thermal response of the ground medium associated with GSHPs and GS-VRF systems depending on the design characteristics and thermal properties of boreholes [18]. For this study, Table 1 summarizes the data used to model the ground-source heat exchangers and boreholes for both GSHPs and GS-VRF systems.

Table 1. Characteristics of ground heat exchangers used for ground-source heat pumps (GSHPs) and ground-source variable refrigerant flow (GS-VRF) systems.

Borehole depth	76 m
Borehole diameter	0.152 m
Grout conductivity	1.47 W/m·K
Ground thermal conductivity	2.91 W/m·K
Ground thermal diffusivity	1.11×10^{-6} m^2/s
Fluid	Ethylene glycol
Pipe diameter (outside)	0.0267 m
Pipe diameter (inside)	0.0218 m
Pipe conductivity	0.398 W/m·K

2.2. Building Energy Models

The building energy models considered in the study are specific to medium-size office buildings. As an initial step in the development of the energy models, an existing office building located in Barberton, Ohio was selected to establish a calibrated building energy model using the DOE-2 simulation analysis tool. The existing office building was initially built as an education building in 1956 and later in 2015 was renovated and converted to an office building. Table 2 presents a summary of the main features of the baseline office-building model considered in this study. Figure 4 illustrates a three-dimensional (3D) rendering of the building energy model. As a baseline system, the office building uses packaged terminal air-conditioners (PTACs) for space cooling and unit ventilators served by hot-water boilers for space heating. Figures 5–7 illustrate the hourly occupancy schedules, lighting schedules, and equipment schedules used for the office-building modeling analysis.

Table 2. Characteristics of the baseline office building.

Location	**Barberton, OH**
ASHRAE climate zone	5A
Design temperature (ASHRAE Standard 90.1-2010)	Cooling, 29 °C, dry-bulb Heating, −18 °C, dry-bulb
Number of floors	1 stories
Total conditioned floor area	2746 m^2
Floor-to-floor height	3 m
Window–wall ratio (WWR)	30%
Roofs	U-value: 0.273 W/m^2·°C
Exterior walls	U-value: 0.511 W/m^2·°C
Window glazing	U-value: 2.27 W/m^2·°C (solar heat gain coefficient: 0.4)
Lighting power density (LPD)	10.23 W/m^2
Equipment power density (EPD)	9.58 W/m^2
Total cooling capacity	2047 kW
Heating, Ventilation & Air-Conditioning (HVAC) system (system efficiency including fan power)	Cooling: PTAC (COP*: 2.73) Heating: unit ventilator with hot-water boilers (efficiency: 80%) (*COP = Coefficient of Performance)
Fan type (power)	Constant volume (0.6383 kW/m^3/s)
Operation schedule	Monday–Friday: 8 a.m. to 5 p.m. Saturday, Sunday, and holidays: closed
Thermostat set-point	Occupied hours: (cooling) 24.0 °C/(heating) 21.1 °C Unoccupied hours: (cooling) 26.6 °C/(heating) 15.5 °C
Supply air temperature	Cooling, 12.8 °C, dry-bulb Heating, 40.6 °C, dry-bulb

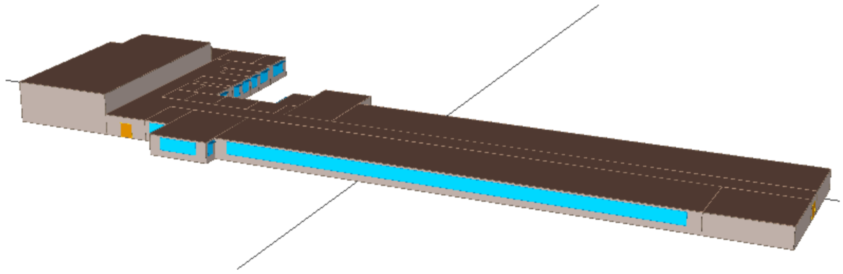

Figure 4. Three-dimensional (3D) rendering of the office-building energy model.

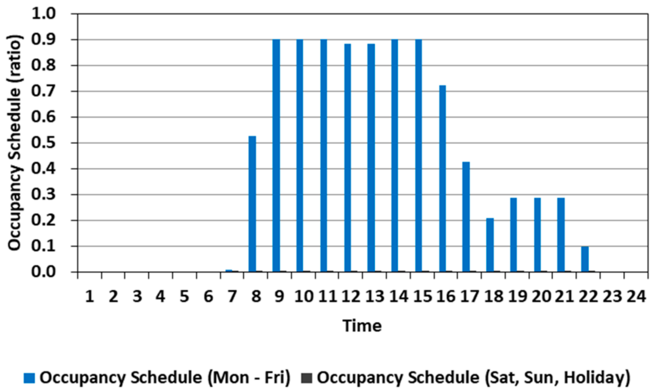

Figure 5. Occupancy schedules used for the office-building model.

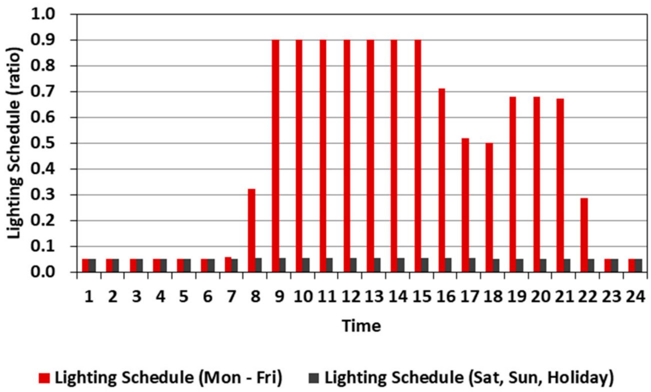

Figure 6. Lighting schedules used for the office-building model.

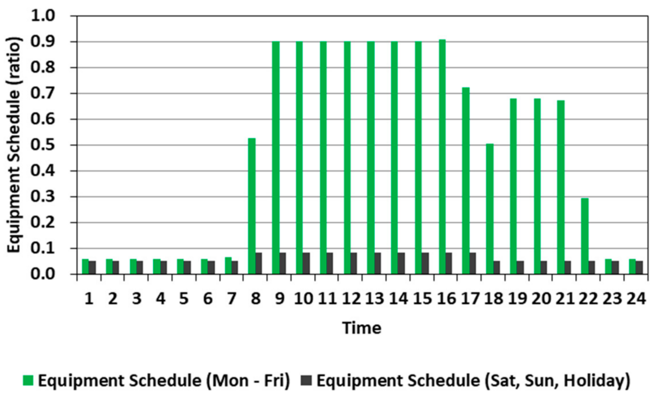

Figure 7. Equipment schedules used for the office-building model.

Using 1 years' worth of electricity and natural gas consumption data, the building energy model was calibrated by comparing the utility data to the predicted energy-use results obtained from the hourly simulation energy modeling. The calibration process was based on criteria set by the ASHRAE Guideline 14 using the coefficient of variance of the root-mean-square error (CV-RMSE) method as described by Equation (1) [19]. The calibrated model was obtained by adjusting operating input variables for the energy model, including occupancy, lighting, and equipment schedules. After the calibration, CV-RMSE values of 8% for electricity use and 15% for natural gas consumption were reached. These resulting CV-RMSE values were within the criteria set by ASHRAE [19]. Figures 8 and 9 compare the monthly electricity use and natural gas consumption on the basis of the utility data and those predicted by the hourly simulation tool.

$$\text{CV RMSE} = \frac{\sqrt{\sum_{i=1}^{N_i}\left[\frac{(M_i - S_i)^2}{N_i}\right]}}{\frac{\sum_{i=1}^{N_i} M_i}{N_i}} \tag{1}$$

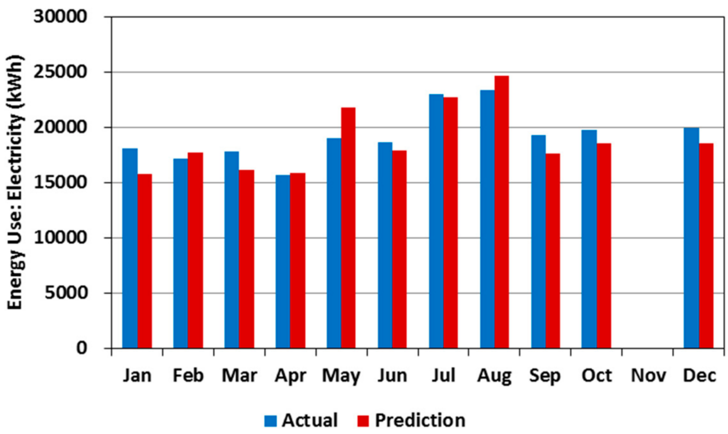

Figure 8. Calibration results of electricity use for the office-building energy model.

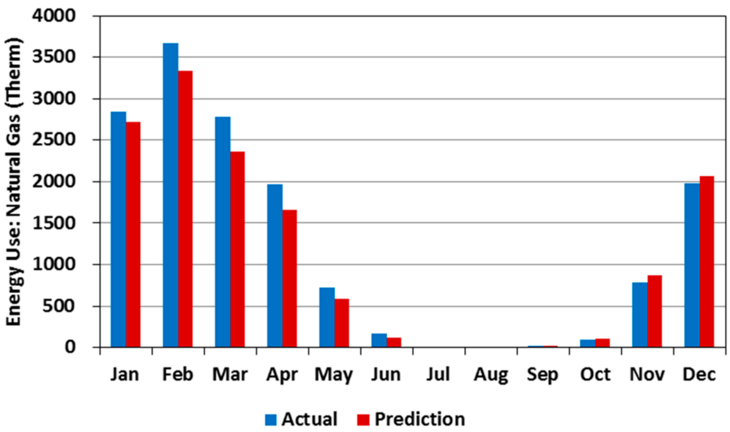

Figure 9. Calibration results of natural gas consumption for the office-building energy model.

2.3. Evaluation of GS-VRF System

As noted earlier, one of the benefits of VRF systems is their high energy performance under part-load conditions. Figure 10 illustrates the part-load performance curves for a water-source VRF system considered in this study obtained under both heating and cooling modes [20]. As indicated in Figure 10, the performance curves were similar for both the heating and cooling modes. Moreover, the impact of part-load was rather small on the energy efficiency of the VRF system, particularly for high-part-load ratios [20]. Figures 11 and 12 provide, respectively, the energy efficiency and the capacity curves for the same water-source VRF system of Figure 10 as a function of condensing medium temperature [20]. The system capacity and energy input were normalized by the rated size and the rated energy efficiency as defined by ASHRAE Standard 90.1-2010 as well as by Air-Conditioning, Heating, & Refrigeration Institute (AHRI) Standards 1230-2010, 320-98, and 325 [21–24]. The rated conditions set by the AHRI standards for water-source VRF and GS-VRF systems are summarized in Table 3. In particular, the rated conditions for the closed-loop GS-VRF systems consisted of an entering water temperature (EWT) of 25 °C for the cooling operation and 0 °C for the heating operation, while the EWT was set at 30 °C during the cooling operation and at 20 °C during the heating operation for the water-source VRF systems. A dedicated outside air system (DOAS) is considered to provide the fresh air requirements.

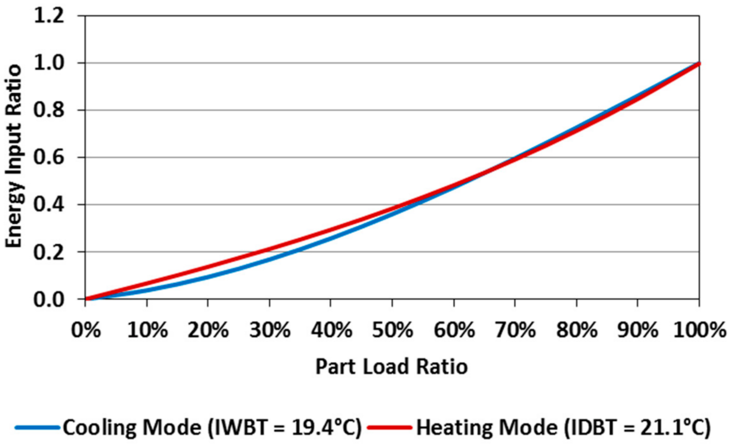

Figure 10. Part-load performance curves of a water-source variable refrigerant flow (VRF) system for both heating and cooling modes.

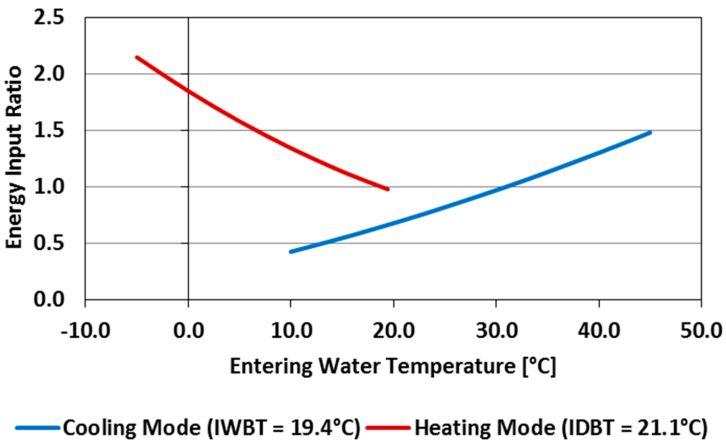

Figure 11. Energy efficiency curves of a water-source variable refrigerant flow (VRF) system as a function of condensing medium temperature for both heating and cooling modes.

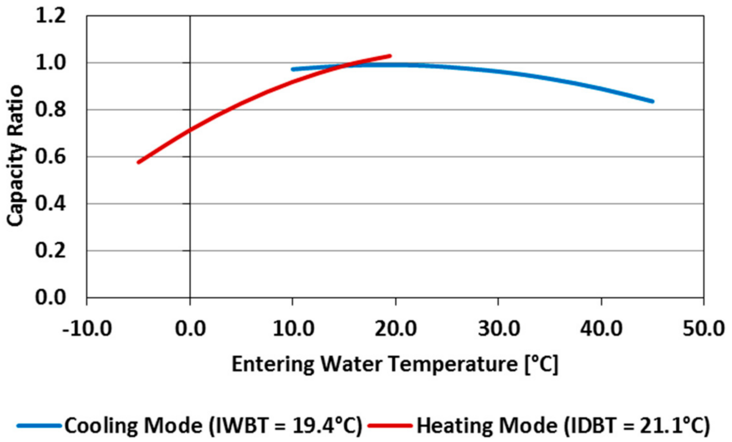

Figure 12. Capacity curves of a water-source variable refrigerant flow (VRF) system as a function of condensing medium temperature for both heating and cooling modes.

Table 3. Summary of performance data for water-source variable refrigerant flow (VRF) and ground-source variable refrigerant flow (GS-VRF) systems [20].

System	Water-Source VRF (WS-VRF)	Ground-Source VRF (GS-VRF)
Cooling efficiency	5.20 COP at EWT of 30 °C	6.14 COP at EWT of 25 °C
Heating efficiency	5.76 COP at EWT of 20 °C	2.99 COP at EWT of 0 °C
Fans	Constant volume (0.4660 kW/m^3/s)	Constant volume (0.4660 kW/m^3/s)
Outside air	DOAS	DOAS

In order to evaluate the performance of GS-VRF and water-source VRF systems to heat and cool office buildings in the United States, other HVAC systems were considered, including the baseline heating and cooling systems defined by ASHRAE Standard 90.1, as summarized in Table 4 [21].

Table 4. Performance indicators for baseline heating, ventilating, and air-conditioning (HVAC) systems on basis of ASHRAE Standard 90.1-2010 [21].

System	Baseline 1	Baseline 2	Baseline 3
	Packaged Terminal Air-Conditioner (PTAC)	Water-Source Heat Pump (WSHP)	Ground-Source Heat Pump (GSHP)
Cooling efficiency	COP = 2.73 (Direct expansion cooling)	COP = 3.52 (at EWT of 30°C)	COP = 3.93 (at EWT of 25 °C)
Heating efficiency	Hot-water boiler (Efficiency = 80%)	COP = 4.2 (at EWT of 20 °C) Hot-water boiler (Efficiency = 80%)	COP = 3.10 (at EWT of 0 °C)
Fans	Constant volume (0.6383 kW/m^3/s)	Constant volume (0.6383 kW/m^3/s)	Constant volume (0.6383 kW/m^3/s)
Outside air	DOAS	DOAS	DOAS

2.4. Climate Zones

In order to evaluate the impact of climate conditions on GS-VRF and water-source VRF systems, various representative U.S. climate zones were considered [25]. Table 5 summarizes the design heating and cooling temperatures and average deep-ground temperatures for 11 locations representing different U.S. climate zones. Hourly weather data of each city listed in Table 5 were obtained for BEM using the typical meteorological year 2 (TMY2) data format [26]. For each climate zone, the envelope characteristics of the baseline office-building model of Table 2 were adjusted on the basis of the minimum requirements set by ASHRAE Standard 90.1, as indicated in Table 6 [21].

Table 5. Main climatic characteristics for 11 selected U.S. locations.

Location	Climate Zone	Design Temperature		Average Ground Temperature	Ambient Air Conditions
		Cooling	Heating		
Miami, Florida	1A	32.2 °C	7.8 °C	24.5 °C	Very Hot, Humid
Houston, Texas	2A	34.4 °C	−2.8 °C	20.2 °C	Hot, Humid
Phoenix, Arizona	2B	42.2 °C	1.1 °C	22.7 °C	Hot, Dry
Atlanta, Georgia	3A	32.8 °C	−7.8 °C	16.0 °C	Warm, Humid
Los Angeles, California	3B	27.2 °C	6.1 °C	16.8 °C	Warm, Dry
San Francisco, California	3C	25.6 °C	2.8 °C	13.3 °C	Warm, Marine
Baltimore, Maryland	4A	32.8 °C	−11.7 °C	12.7 °C	Mixed, Humid
Albuquerque, New Mexico	4B	33.9 °C	−10.6 °C	13.4 °C	Mixed, Dry
Seattle, Washington	4C	27.2 °C	−5.0 °C	11.0 °C	Mixed, Marine
Chicago, Illinois	5A	31.1 °C	−21.1 °C	9.9 °C	Cool, Humid
Boulder, Colorado	5B	32.2 °C	−19.4 °C	10.0 °C	Cool, Dry
Minneapolis, Minnesota	6A	31.1 °C	−26.7 °C	7.4 °C	Cold, Humid
Helena, Montana	6B	30.6 °C	−27.8 °C	7.0 °C	Cold, Dry

Table 6. Envelope characteristics for the baseline office-building models for U.S. climate zones considered in the analysis.

Climate Zone	Roof U-Value (W/m^2·°C)	Wall U-Value (W/m^2·°C)	Floor U-Value (W/m^2·°C)	Glazing U-Value (W/m^2·°C)	Glazing SHGC
1 (A)	0.36	3.29	1.83	6.81	0.25
2 (A, B)	0.27	0.86	0.61	4.26	0.25
3 (A, B, C)	0.27	0.70	0.61	3.69	0.25
4 (A, B, C)	0.27	0.59	0.49	3.12	0.35
5 (A, B)	0.27	0.51	0.42	3.12	0.35
6 (A, B)	0.27	0.45	0.36	3.12	0.4

2.5. High-Performance Buildings

In addition to the baseline models for the office buildings set to meet the requirements of ASHRAE Standard 90.1 as outlined in Tables 2 and 6, this study evaluates the performance of VRF systems for high-performance office buildings designed on the basis of ASHRAE Standard 189.1 for various representative U.S. climate zones. In particular, Tables 7 and 8 summarize the building envelope characteristics and the HVAC energy-efficiency settings considered for the high-performance office-building models used in the analysis for various climate zones [27]. In addition, the high-performance models had a lighting power density of 9.26 W/m^2 and were equipped with daylighting controls and occupancy sensors [27].

Table 7. Envelope characteristics for the high-performance office-building models for U.S. climate zones considered in the analysis.

Climate Zone	Roof U-Value (W/m^2·°C)	Wall U-Value (W/m^2·°C)	Floor U-Value (W/m^2·°C)	Glazing U-Value (W/m^2·°C)	Glazing SHGC
1 (A)	0.27	0.86	0.78	6.81	0.25
2 (A, B)	0.22	0.70	0.61	4.26	0.25
3 (A, B, C)	0.22	0.59	0.61	3.12	0.25
4 (A, B, C)	0.22	0.51	0.42	2.56	0.35
5 (A, B)	0.22	0.45	0.36	2.56	0.35
6 (A, B)	0.18	0.40	0.32	2.56	0.4

Table 8. Energy-efficiency levels for heating, ventilating, and air-conditioning (HVAC) systems specific to high-performance office-building models.

System	Baseline 1	Baseline 2	Baseline 3
	Packaged Terminal Air-Conditioner	**Water-Source Heat Pump**	**Ground-Source Heat Pump**
Cooling efficiency	COP = 2.78 (Direct expansion cooling)	COP = 4.10 (at EWT of 30°C)	COP = 3.93 (at EWT of 25°C)
Heating efficiency	Hot-water boiler (Efficiency = 89%)	4.2 COP = 4.20 (at EWT of 20°C) Hot-water boiler (Efficiency = 89%)	COP = 3.10 (at EWT of 0 °C)
Fans	Constant volume (0.5745 kW/m^3/s)	Constant volume (0.5745 kW/m^3/s)	Constant volume (0.5745 kW/m^3/s)

3. Results and Discussion

3.1. Energy Performance of GS-VRF Systems Compared to Other HVAC Systems

For the baseline office-building energy models developed for each climate zone established from the calibrated model of the existing office building as discussed in Section 2.2, a series of simulation analyses was carried out to compare the energy performances of water-source VRF and GS-VRF systems to those obtained for the other HVAC systems listed in Table 4. Figures 13 and 14 provide the monthly energy consumption for electricity and natural gas, respectively, for all the HVAC systems considered in the analysis. Typical hourly building electricity-use profiles for a peak cooling day are shown in Figure 15 for all the HVAC systems. Table 9 lists the annual energy end-uses for the various HVAC systems considered to heat and cool the existing office building located in Barberton, OH (climate zone 5A). As clearly shown in Figures 13–15 and Table 9, GS-VRF systems had the lowest energy consumption when compared to all HVAC systems. In particular, GS-VRF systems achieved the highest energy-use savings of 58.3% relative to the PTAC units. Moreover, the GS-VRF system reduced the annual HVAC energy consumption by 22.1% relative to GSHPs. As noted earlier, GS-VRF as well as water-source VRF systems have better energy performance at low loads, particularly when compared to PTAC units that utilize electric direct expansion (DX) cooling coils and natural-gas-fired boilers. In addition, ground-source systems (i.e., GSHPs and GS-VRF systems) required less energy to heat and cool the office building when compared to water-source systems (i.e., WSHPs and WS-VRFs). Indeed, while water-source systems need to use cooling towers for the heat sink and hot-water boilers for the heat source, ground-source systems utilize the ground medium as both the heat source and sink. Moreover, the condensing water temperature of ground-source systems is set to be lower than that of water-source systems during space cooling mode.

Table 9. Annual site energy end-uses for various heating, ventilating, and air-conditioning (HVAC) systems for the office building in Barberton, OH.

		Space Cool	Heat Rejection	Space Heat	Fans	Pumps	Sum	HVAC Sum	Savings by GS-VRF
PTAC	Electricity (GJ)	118	0	0	105	5	228	986	58.3%
	Natural gas (GJ)	0	0	759	0	0	759		
WSHP	Electricity (GJ)	103	2	88	105	55	353	941	56.3%
	Natural gas (GJ)	0	0	588	0	0	588		
GSHP	Electricity (GJ)	87	0	121	105	55	369	528	22.1%
	Natural gas (GJ)	0	0	159	0	0	159		
WS VRF	Electricity (GJ)	58	1	54	30	39	181	835	50.7%
	Natural gas (GJ)	0	0	653	0	0	653		
GS VRF	Electricity (GJ)	46	0	116	39	50	252	411	—
	Natural gas (GJ)	0	0	159	0	0	159		

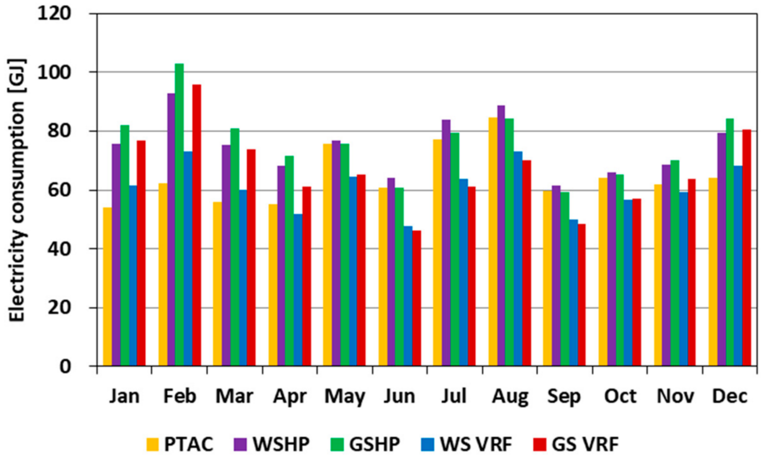

Figure 13. Monthly electricity consumption of various heating, ventilating, and air-conditioning (HVAC) systems for the office building located in Barberton, OH.

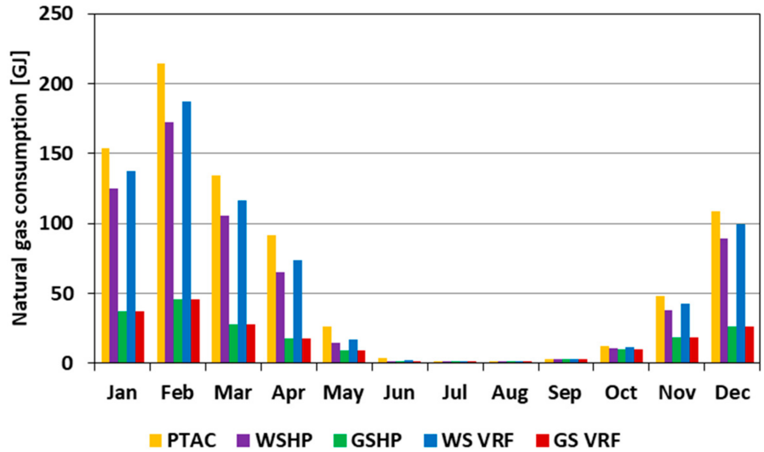

Figure 14. Monthly natural gas consumption of various heating, ventilating, and air-conditioning (HVAC) systems for the office building in Barberton, OH.

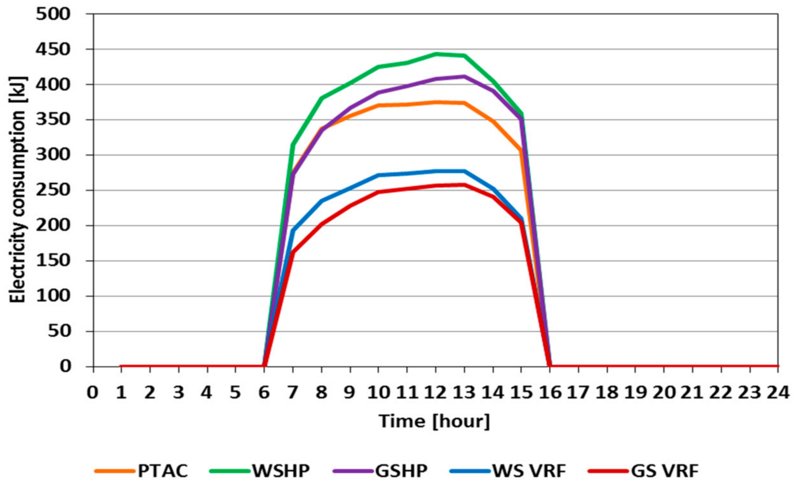

Figure 15. Hourly electricity use for various heating, ventilating, and air-conditioning (HVAC) systems during the cooling design day (July 21) for the office building in Barberton, OH.

Table 10 summarizes the annual HVAC energy costs of the existing office building in Barberton, OH. The cost analysis shown in Table 10 is based on 2016 electricity and natural gas price rates provided for Ohio [28,29]: specifically, an electricity rate of $26.864 per GJ and a natural gas rate of $4.932 per GJ. As indicated in Table 10, the HVAC energy-cost savings by the GS-VRF system to heat and cool the existing office building in Barberton, OH were 23% relative to the PTAC, 39% relative to the WSHP, 29% relative to the GSHP, and 7% relative to the water-source VRF. These energy-cost savings were generally due to the different energy prices for the heating source (i.e., natural gas) and cooling source (i.e., electricity). The energy costs associated to heating were significantly lower than those associated to cooling, resulting in lower overall energy-cost savings than site energy-use savings.

Table 10. Annual heating, ventilating, and air-conditioning (HVAC) energy costs of the existing office building in Barberton, OH.

	PTAC	WSHP	GSHP	WS VRF	GS-VRF
Electricity	$6114	$9481	$9901	$4872	$6763
Natural gas	$3743	$2900	$786	$3222	$786
HVAC sum	$9857	$12,381	$10,687	$8094	$7549
Saving by GS-VRF (%)	23%	39%	29%	7%	—

Table 11 summarizes the peak energy demand incurred by all the HVAC systems to maintain indoor thermal comfort for the office building in Barberton, OH. As shown in Table 11, both the water-source VRF and GS-VRF systems had a lower peak energy demand than the other HVAC systems as a result of their high energy performance, including lower power requirements for VRF condensing units and air terminal fans. However, because of low heating efficiency of the GS-VRF system at the rated conditions, as shown in Table 3, the peak energy demand of the GS-VRF system occurred during heating mode (i.e., natural gas use rate during winter time), while the peak energy demand of the other HVAC systems occurred during cooling mode (i.e., electrical power demand during summer time).

Table 11. Peak energy demand of heating, ventilating, and air-conditioning (HVAC) systems for the office building in Barberton, OH.

Peak Demand	PTAC	WSHP	GSHP	WS-VRF	GS-VRF
Electricity (kW)	104 (July 21, 13:00)	123 (July 21, 13:00)	114 (July 21, 14:00)	77 (July 21, 14:00)	84 (Jan 19, 09:00)
Natural gas (kW)	521 (Jan 19, 07:00)	539 (Jan 19, 06:00)	84 (Feb 17, 08:00)	540 (Jan 19, 06:00)	84 (Feb 17, 08:00)

3.2. Performance of GS-VRF Systems for Various U.S. Climates

The simulation analysis was extended to consider the impact of the HVAC selection on the energy consumption, peak demand, and energy cost for baseline office-building models in the U.S. climate zones outlined in Tables 5 and 6. Figures 16 and 17 provide the analysis results for site and source energy consumption specific to the HVAC systems obtained for the various U.S. climate zones. Figures 18 and 19 compare the performance of GS-VRF to other HVAC systems for all U.S. climate zones. It is clear that GS-VRF systems could save both site and source HVAC energy consumption by averages of, respectively, 56.5% and 40.9% relative to PTACs, 55.0% and 46.6% relative to WSHPs, 31.4% and 35.3% relative to GSHPs, and 41.5% and 18.8% relative to water-source VRFs.

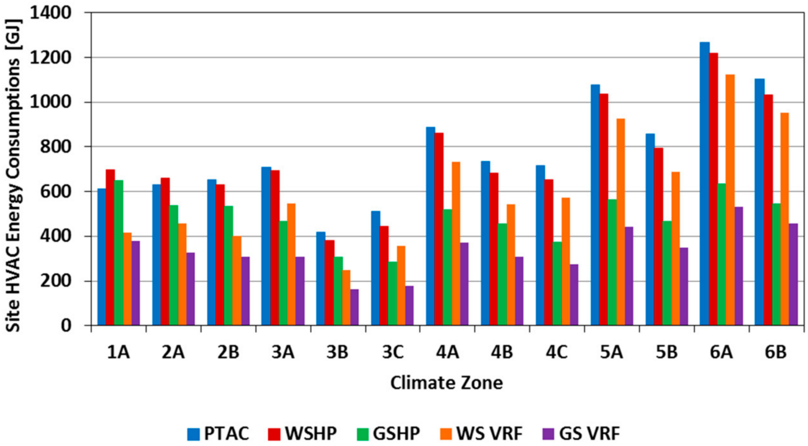

Figure 16. Site heating, ventilating, and air-conditioning (HVAC) energy use for baseline office-building models in various U.S. climate zones.

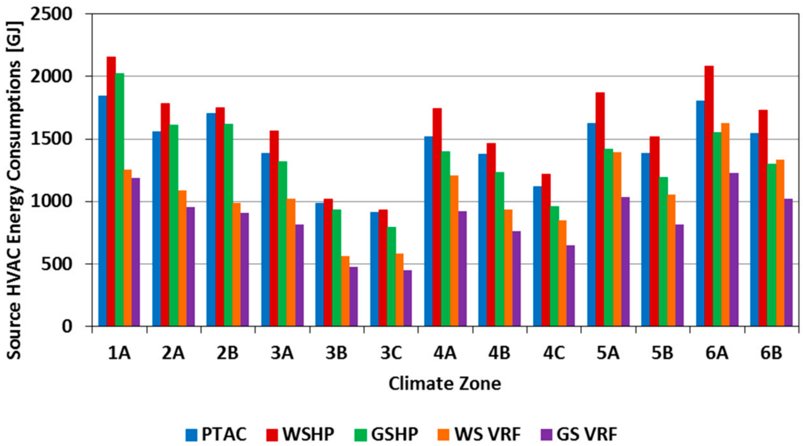

Figure 17. Source heating, ventilating, and air-conditioning (HVAC) energy use for baseline office-building models in various U.S. climate zones.

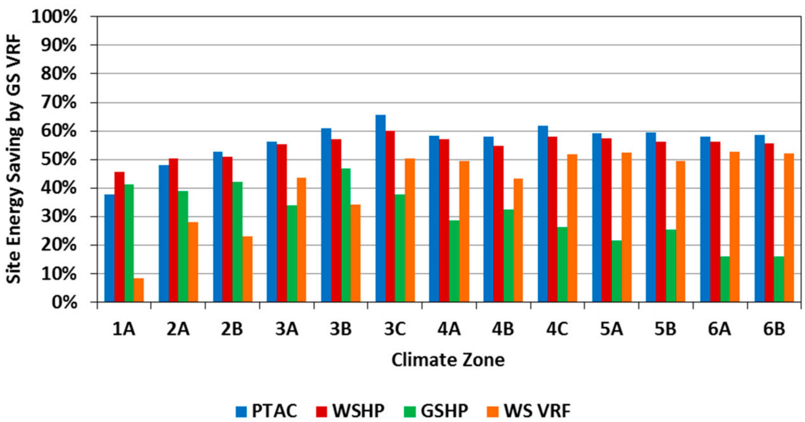

Figure 18. Site heating, ventilating, and air-conditioning (HVAC) energy savings of ground-source variable refrigerant flow (GS-VRF) systems compared to other HVAC systems for baseline office-building models in various U.S. climate zones.

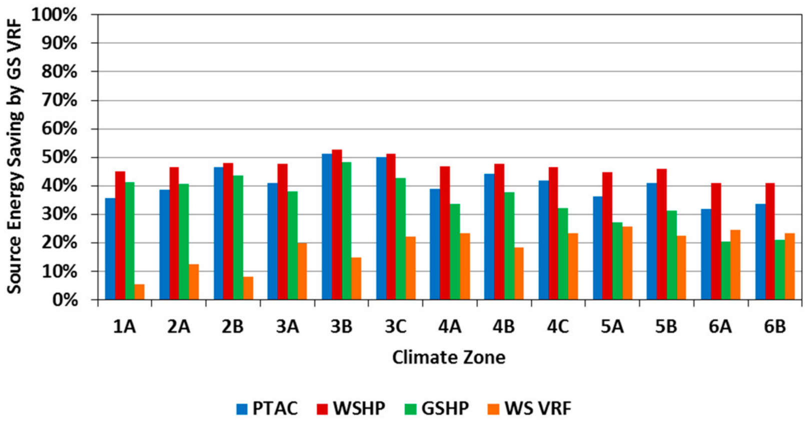

Figure 19. Source heating, ventilating, and air-conditioning (HVAC) energy savings of ground-source variable refrigerant flow (GS-VRF) systems compared to other HVAC systems for baseline office-building models in various U.S. climate zones.

In order to estimate the annual energy costs for various HVAC systems, utility rates were obtained as indicated in Table 12 for locations representative of U.S. climate zones (refer to Table 5). Table 13 provides the annual HVAC energy costs to heat and cool the baseline office buildings in various U.S. climates. Figure 20 shows the annual HVAC energy-cost savings obtained for GS-VRF systems for the office buildings located in various U.S. climates when compared to other HVAC systems. As shown in Figure 20, higher energy-cost savings could be achieved by GS-VRF systems in climate zone 3B compared to most other HVAC systems. Typically, GS-VRF systems provided greater energy-cost savings when compared to WSHPs in all climates.

Table 12. U.S. Energy Information Administration (EIA) energy rates [24,25].

$/GJ	1A	2A	2B	3A	3B	3C	4A	4B	4C	5A	5B	6A	6B
Electricity	26.9	22.7	27.5	27.5	40.0	40.0	30.3	26.2	25.8	23.9	26.4	26.8	27.9
Natural Gas	10.1	7.2	8.4	7.4	7.9	7.9	8.7	5.6	7.2	5.7	6.1	6.0	6.8

Table 13. Annual heating, ventilating, and air-conditioning (HVAC) energy costs of the medium-size office building in various climate zones.

System	PTAC		WSHP		GSHP		WS-VRF		GS-VRF	
Utility	Elec.	Natural Gas	Elec.	Natural Gas	Elec.	Natural Gas	Elec.	Natural Gas	Elec.	Natural Gas
1A	$15,537	$342	$18,365	$176	$17,347	$32	$10,574	$232	$10,149	$32
2A	$9678	$1477	$11,798	$1005	$11,343	$260	$6644	$1175	$6608	$260
2B	$13,421	$1377	$14,387	$889	$13,937	$221	$7531	$1059	$7749	$221
3A	$8438	$2984	$11,020	$2178	$10,848	$547	$5843	$2496	$6478	$547
3B	$10,462	$1229	$11,785	$681	$11,623	$125	$5792	$823	$5891	$125
3C	$7138	$2649	$8950	$1741	$9431	$383	$4040	$2015	$5130	$383
4A	$8467	$5271	$12,168	$3991	$12,291	$987	$6370	$4527	$7768	$987
4B	$7587	$2492	$9434	$1802	$9415	$540	$4594	$2066	$5546	$540
4C	$4526	$3902	$6565	$2863	$7005	$726	$3076	$3265	$4479	$726
5A	$5649	$4776	$8967	$3747	$9470	$952	$4780	$4131	$6540	$952
5B	$6146	$3780	$8609	$2838	$8870	$796	$4238	$3197	$5724	$796
6A	$6064	$6261	$10,316	$5010	$11,309	$1272	$5720	$5479	$8589	$1272
6B	$5150	$6236	$8686	$4893	$9697	$1340	$4488	$5388	$7254	$1340

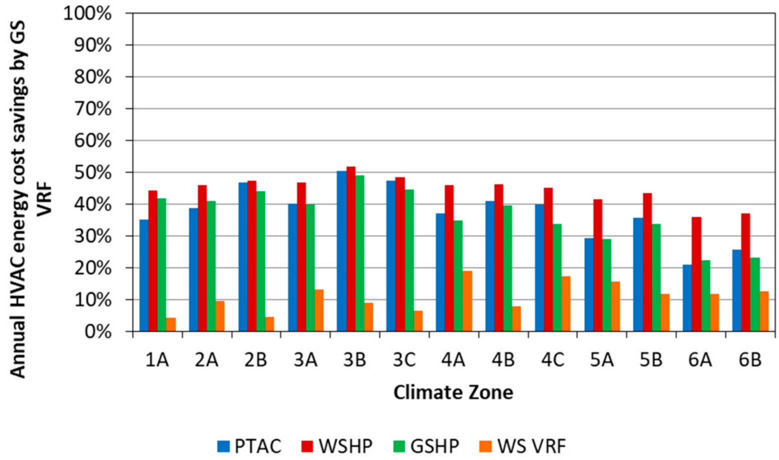

Figure 20. Annual heating, ventilating, and air-conditioning (HVAC) energy-cost savings achieved by ground-source variable refrigerant flow (GS-VRF) systems compared to other HVAC systems for the baseline building-office models in various U.S. climate zones.

Table 14 provides the peak electricity demand associated with the HVAC systems in various U.S. climates. As shown in Table 14, the peak electricity demand values for both water-source VRF and GS-VRF systems were lower than for those obtained for PTACs, WSHPs, and GSHPs.

Table 14. Peak electricity demand specific to all heating, ventilating, and air-conditioning (HVAC) systems for the baseline office building located in various U.S. climates.

Electricity (kW)	PTAC	WSHP	GSHP	WS-VRF	GS-VRF
1A	118 (Sep 7, 15:00)	143 (Sep 7, 15:00)	128 (Sep 7, 15:00)	87 (July 29, 15:00)	82 (July 29, 14:00)
2A	116 (July 30, 12:00)	135 (July 30, 12:00)	125 (July 30, 12:00)	89 (July 30, 12:00)	82 (July 30, 12:00)
2B	125 (July 19, 15:00)	124 (Jun 8, 15:00)	118 (Jun 8, 15:00)	77 (July 19, 15:00)	75 (July 19, 15:00)
3A	101 (July 29, 13:00)	122 (July 29, 13:00)	114 (July 29, 13:00)	79 (July 29, 13:00)	72 (July 29, 13:00)
3B	73 (Sep 9, 12:00)	86 (Sep 9, 12:00)	84 (Sep 9, 12:00)	49 (Sep 9, 12:00)	44 (Sep 9, 12:00)
3C	51 (Sep 15, 14:00)	58 (Sep 2, 15:00)	57 (May 26, 14:00)	32 (Sep 2, 15:00)	46 (Dec 20, 09:00)
4A	95 (Aug 17, 15:00)	115 (Aug 17, 15:00)	110 (July 26, 11:00)	77 (Aug 17, 15:00)	81 (Dec 20, 09:00)
4B	89 (July 19, 15:00)	96 (July 19, 15:00)	95 (July 19, 15:00)	54 (July 19, 15:00)	68 (Dec 27, 09:00)
4C	83 (Sep 2, 15:00)	94 (Sep 2, 15:00)	85 (Sep 2, 15:00)	54 (Sep 2, 15:00)	62 (Dec 20, 09:00)
5A	101 (Jun 8, 14:00)	120 (Jun 8, 14:00)	105 (July 19, 12:00)	78 (Jun 8, 14:00)	76 (Dec 27, 09:00)
5B	88 (July 19, 14:00)	99 (July 19, 14:00)	93 (July 19, 14:00)	57 (July 19, 14:00)	73 (Feb 16, 09:00)
6A	99 (July 15, 15:00)	121 (July 15, 15:00)	111 (Dec 20, 09:00)	86 (Dec 20, 09:00)	93 (Dec 20, 09:00)
6B	78 (July 19, 15:00)	89 (July 19, 15:00)	95 (Dec 27, 09:00)	56 (Dec 27, 09:00)	82 (Dec 13, 09:00)

3.3. Performance of GS-VRF Systems for High-Performance Buildings in Various U.S. Climates

In order to consider the impact of the building design specifications on the performance and suitability of GS-VRF systems, an analysis was carried out for the high-performance office-building energy models defined in Tables 7 and 8. The results of the analysis are summarized in Figure 21, which lists the source energy savings achieved by the high-performance design compared to the baseline design for the office buildings in various U.S. climates. As indicated in Figure 21, the high-performance buildings (designed on the basis of ASHRAE Standard 189.1 recommendations) had lower source energy consumption relative to the baseline buildings (designed based on the basis of ASHRAE Standard 90.1 requirements) by a range from 20% to 29% depending on the HVAC system type and the U.S. climate.

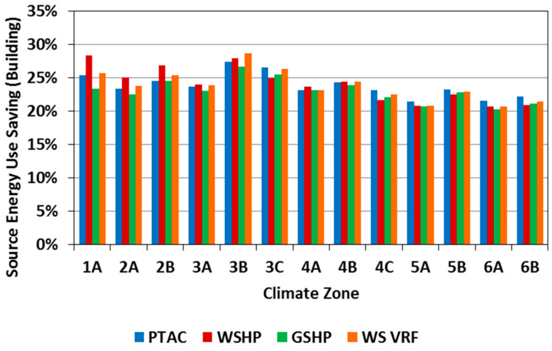

Figure 21. Source energy-use savings achieved by the high-performance designs compared to the baseline designs for office buildings located in various U.S. climates.

Figures 22 and 23 provide the analysis results for, respectively, site and source HVAC energy consumption specific to the high-performance office buildings obtained for various U.S. climates considered in the study. Figures 24 and 25 compare the performance of GS-VRF systems to other HVAC systems using, respectively, site and source energy savings. It is clear that GS-VRF systems could save both site and source HVAC energy consumption, when considering all U.S. climates, by averages of 54.7% and 36.7% relative to PTACs, 52.0% and 41.9% relative to WSHPs, 29.2% and 33.0% relative to GSHPs, and 41.1% and 17.5% relative to water-source VRFs. Therefore, the relative energy savings achieved by the GS-VRF systems for the high-performance office buildings were lower than those obtained for GS-VRF systems for the baseline office buildings. There reduced relative savings were due to the lower space cooling and heating thermal loads associated with high-performance office buildings that have higher thermal resistance envelope components, lower lighting power density, and higher-energy-efficiency HVAC systems.

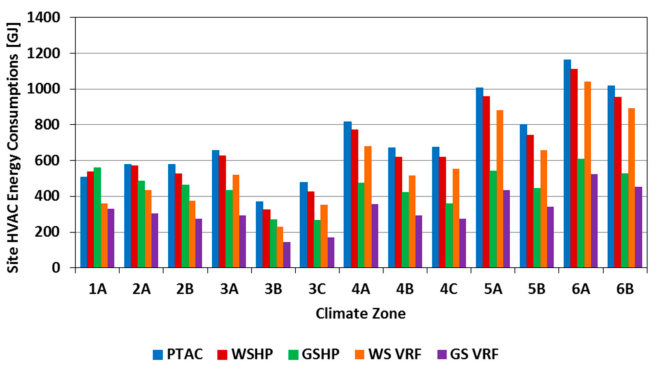

Figure 22. Site heating, ventilating, and air-conditioning (HVAC) energy use for high-performance office buildings in various U.S. climates.

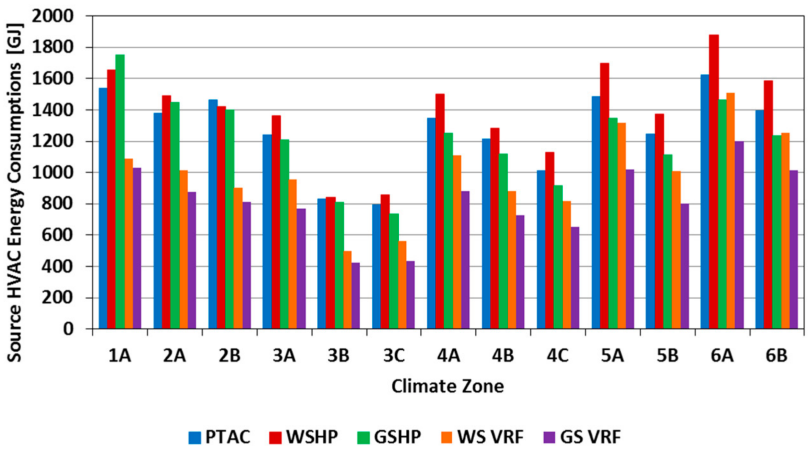

Figure 23. Source heating, ventilating, and air-conditioning (HVAC) energy use for high-performance office buildings in various U.S. climates.

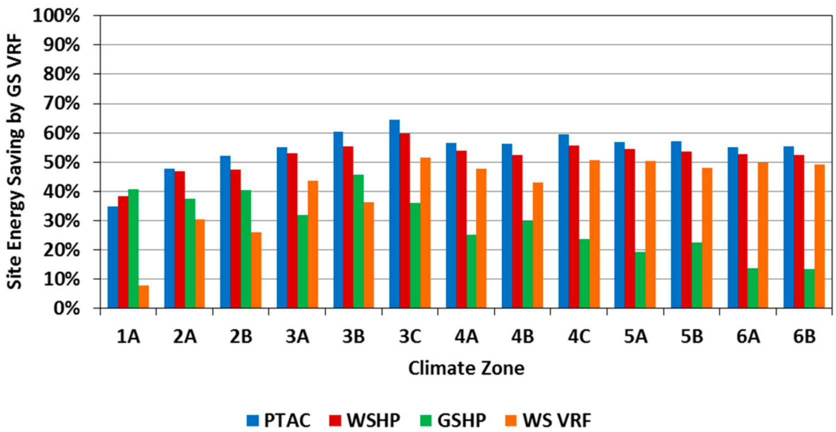

Figure 24. Site energy savings achieved by ground-source variable refrigerant flow (GS-VRF) systems compared to other HVAC systems for high-performance office buildings in various U.S. climates.

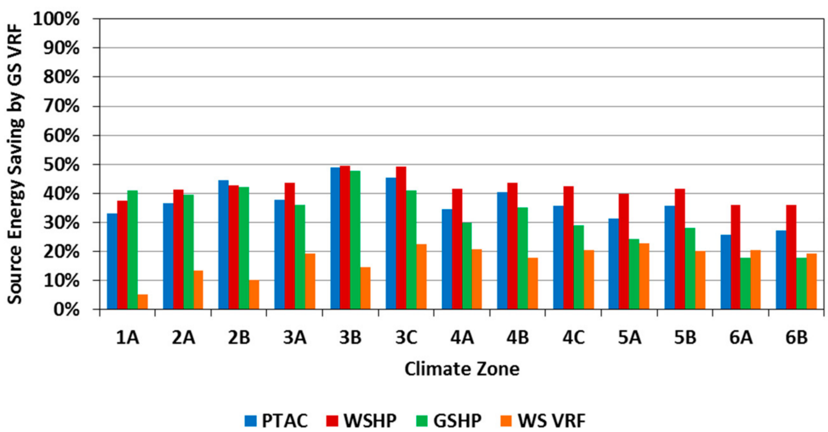

Figure 25. Source energy savings achieved by ground-source variable refrigerant flow (GS-VRF) systems compared to other heating, ventilating, and air-conditioning (HVAC) systems for high-performance office buildings in various U.S. climates.

4. Summary and Conclusions

The purpose of the study summarized in this paper was to evaluate the energy performance of GS-VRF systems when compared to various other HVAC systems suitable to heat and cool office buildings located in representative U.S. climates. First, a whole-building energy simulation tool was used to develop a calibrated model for an office building. The dynamic energy performance for GS-VRF systems utilizes a thermal response factor method to model vertical ground heat exchanger loops and performance curves to model variations of energy efficiency with part-load ratios and condensing water temperatures.

On the basis of a comparative analysis results, the energy consumptions associated to both heating and cooling an office building in Ohio were lowered by 58.3%, 56.3%, 50.7%, and 22.1% when a GS-VRF was used instead of, respectively, PTACs, WSHPs, water-source VRFs, and GSHPs. This higher energy performance of the GS-VRF systems was mainly attributed to a higher energy efficiency of the condensing units and fans, particularly at low-part-load ratios, with free heating and cooling resources from the ground medium avoiding the use of cooling towers and hot-water boilers.

Using a series of parametric analyses, the performance of the GS-VRF systems was evaluated for office buildings located in representative U.S. climates and was compared against several other HVAC systems. It was found that the GS-VRF systems could outperform the HVAC systems for both baseline and high-performance building designs under all U.S. climates. Specifically, the GS-VRF systems could achieve average site and source HVAC energy savings of 56.5% and 40.9% compared to PTACs, 55.0% and 46.6% compared to WSHPs, 31.4% and 35.3% compared to GSHPs, and 41.5% and 18.8% compared to water-source VRF systems for baseline office-building designs produced on the basis of ASHRAE Standard 90.1 for all U.S. climates considered in the analysis. Similarly, the average site and source energy savings associated to the GS-VRF systems were 55.7% and 41.1% relative to PTACs, 50.4% and 42.7% relative to WSHPs, 32.0% and 36.1% relative to GSHPs, and 37.2% and 15.6% relative to water-source VRF systems for the high-performance designs produced on the basis of ASHRAE Standard 189.1.

While the results presented in this paper clearly indicate that GS-VRF systems provide energy-efficient HVAC systems for U.S. office buildings for wide range of designs and climatic conditions, future work needs to assess the cost-effectiveness of these systems compared to other heating and cooling options when installation as well as maintenance costs are considered. Optimal design of ground heat exchangers would be also required to minimize the energy use and cost of utilizing GS-VRF systems for U.S. office buildings and climates.

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