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Energy Saving Quantitative Analysis of Passive, Active, and Renewable Technologies in Different Climate Zones

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Abstract: The purpose of this study was to provide a guideline for the selection of technologies suitable for ASHRAE international climate zones when designing high-performance buildings. In this study, high-performance technologies were grouped as passive, active, and renewable energy systems. Energy saving technologies comprising 15 cases were categorized into passive, active, and renewable energy systems. EnergyPlus v9.5.0 was used to analyze the contribution of each technology in reducing the primary energy consumption. The energy consumption of each system was analyzed in different climates (Incheon, New Delhi, Minneapolis, Berlin), and the detailed contributions to saving energy were evaluated. Even when the same technology is applied, the energy saving rate differs according to the climatic characteristics. Shading systems are passive systems that are more effective in hot regions. In addition, the variable air volume (VAV) system, combined VAV–energy recovery ventilation (ERV), and combined VAV–underfloor air distribution (UFAD) are active systems that can convert hot and humid outdoor temperatures to create comfortable indoor environments. In cold and cool regions, passive systems that prevent heat loss, such as high-R insulation walls and windows, are effective. Active systems that utilize outdoor air or ventilation include the combined VAV-economizer, the active chilled beam with dedicated outdoor air system (DOAS), and the combined VAV-ERV. For renewable energy systems, the ground source heat pump (GSHP) is more effective. Selecting energy saving technologies that are suitable for the surrounding environment, and selecting design strategies that are appropriate for a given climate, are very important for the design of high-performance buildings globally.

Keywords: high-performance buildings; passive systems; active systems; renewable energy systems; ASHRAE international climate zones; EnergyPlus

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1. Introduction

Due to the environmental crisis and, in particular, fossil fuel depletion and greenhouse gas emissions, the attention paid to energy conservation is rapidly increasing globally [1,2]. To respond to climate change, environmentally sound and sustainable development has become the developmental goal for all fields. In particular, a new climate framework of POST-2020 will be enacted for all developed and developing countries to share the burden of reducing greenhouse gas emissions [3,4].

Therefore, the national need for building energy efficiency is also rising. Thirty percent of the world's overall primary energy is used by buildings, which also release greenhouse gases (GHGs) [5–7]. As the global necessity to conserve building energy has increased, high-performance buildings have become a crucial component to save energy and reduce global GHG emissions [8,9].

Furthermore, due to an increase in the number of buildings and increased demand for indoor comfort, building energy consumption is expected to continuously increase. Thus far, advanced countries have developed high-performance building technologies that can maximize building energy efficiency. Although the design and construction of high-performance buildings has been attempted globally, it is necessary to continuously develop effective energy saving technology [10–12]. However, if climate characteristics are not considered, energy saving technologies do not always increase energy efficiency. Applying high-performance technologies without consideration of the climate can incur high expense, but not be effective in saving energy. This study classified the energy saving technologies as passive, active, and renewable energy systems. The energy consumption of each system was analyzed in different climates, and the detailed contributions of each system in saving energy were evaluated. The purpose of this study was to provide information for selecting technologies that are suitable for different climatic regions when designing high-performance buildings. Figure 1 shows the study procedure to achieve these objectives.

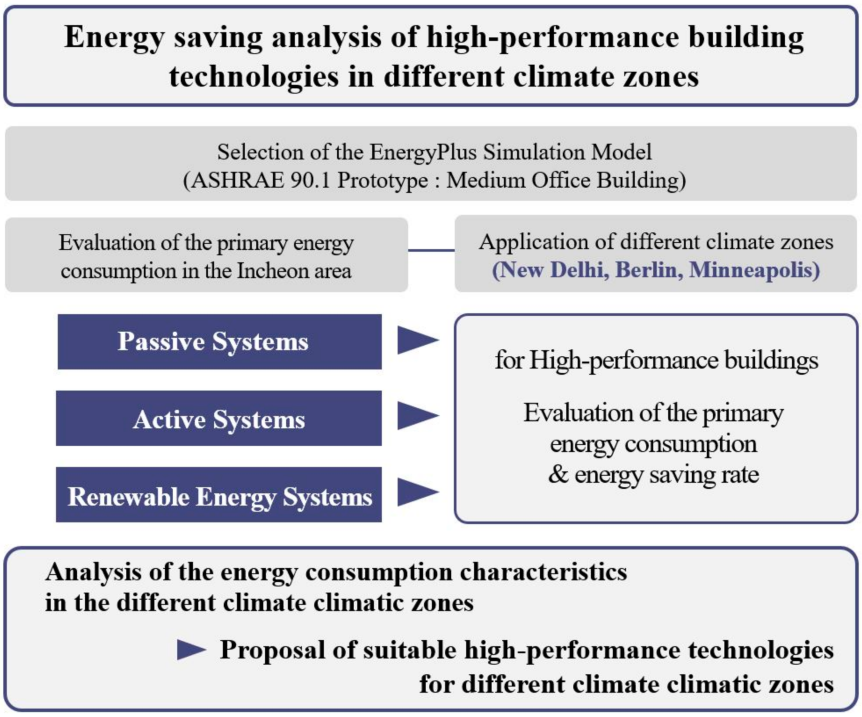


Figure 1. Flowchart of this study.

This study used the dynamic simulation program EnergyPlus v9.5.0 to analyze building energy. EnergyPlus uses the same engine as that used by Building Loads Analysis and System Thermodynamics (BLAST) and DOE-2. In addition, EnergyPlus, which calculates the building load using an energy balance algorithm, can be linked to Google SketchUp, and text-based input and selection are permissible [13]. In this study, energy saving technologies were selected based on the result of preceding studies [14–18] that analyzed the trend of technologies applied to each high-performance building, and the selected technologies were categorized into passive, active, and renewable energy systems.

To analyze how the energy saving technologies contribute to building energy performance, extensive simulations were conducted using the ASHRAE 90.1 prototype building models (Medium office) [19]. To evaluate the energy saving potential of each technology in different climates, four regional weather examples (Incheon: Seoul metropolitan area—South Korea (ASHRAE climate zone 4—Mixed humid), New Delhi—India (ASHRAE climate zone 2—Hot humid), Berlin–Germany (ASHRAE climate zone 5—Cool humid), and Minneapolis—U.S. (ASHRAE climate zone 6—Cold humid)) were used from the weather file of EnergyPlus [20]. We chose these four climates because they collectively represent most of the global climates. For comparison, the energy simulation results were compared with the target goals of the following domestic and foreign guidelines: the Commercial Buildings Energy Consumption Survey (CBECS) [21], ASHRAE 90.1 Standards 2004 and 2010 [22,23], and the National building energy efficiency rating system of Korea (1st grade) [24]. CBECS is a national sample survey that collects energy usage data and building features related to energy in the U.S., and has been performed from 1979 to the present day.

2. Literature Review

The Energy Policy Act and Energy Independence & Security Act in the U.S. [25,26] defines the term "high-performance building" as a building that integrates and optimizes the application of high-tech elements, high energy efficiency, durability, and life cycle, in addition to the comfort and productivity of occupants. Energy conservation in buildings and community systems—Annex 53 in the International Energy Agency (IEA) (2016) [2] dictates that the energy performance of buildings is driven by climate, the building envelope, and building equipment, as shown in Figure 2.

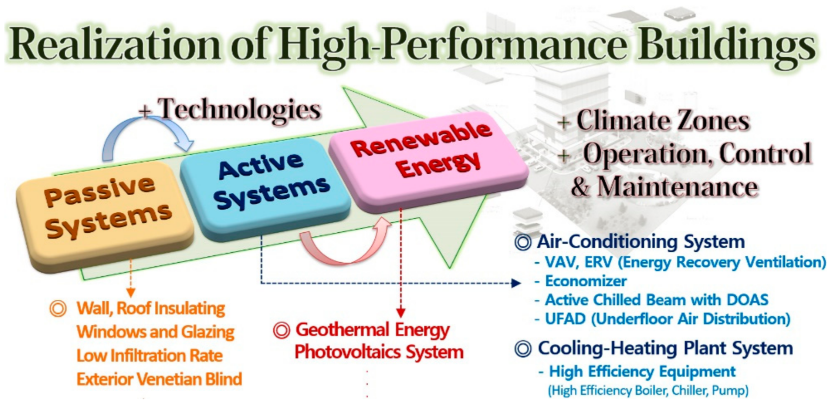


Figure 2. Method for the realization of high-performance buildings.

Numerous studies have undertaken simulations of energy saving technologies to realize high-performance buildings, in relation to the climate, building envelope, and HVAC, as discussed in the following. Krarti and Deneuville [27] conducted a study to identify a means to achieve the optimal energy efficiency in the application of energy saving technologies using ASHRAE 90.1 DOE medium office building-based simulations. In the study, the optimal systems of office buildings located in different climate regions, including major cities in the U.S. and Europe, were compared and examined on the basis of their life cycle cost. This study analyzed the energy saving rates when applying passive and active system technologies. However, this research focused more on an economic analysis than an analysis of energy simulations when applying new technologies, and the analysis of the plant system was also fixed to one system.

Boyano et al. [28] analyzed energy consumption in three different climatic zones of major European countries, and classified energy saving technologies into passive systems (window, insulation of external wall, and direction of building) and active systems (lighting and HVAC systems), to determine the influence on actual buildings when applying new technologies in different climatic zones. However, this study was focused on the thermal transmittance of walls and the orientation of buildings. Jiang et al. [29] adopted China's climate-responsive architectural design theory, and provided guidelines for designers in choosing the right climate-responsive architectural technology in different climatic regions. Inspired by China's diverse climatic zones, the study identified the common climate-responsive building technologies based on relevant literature reviews, and classified these technologies according to temperature, humidity, sunlight, and wind. In this study, the climatic zones were largely divided into a severe cold region, cold region, hot summer and cold winter region, warm winter region, and temperate region; and responsive technologies for certain climatic zones were evaluated in detail. However, subjective guidelines taken from literature reviews were suggested, rather than providing quantitative suggestions from tests and simulation data.

Hurtado et al. [30] investigated building design strategies in hot and cold climates from the aspect of energy consumption and thermal comfort, and focused on passive and active systems. They examined the influence of building technology on the energy performance that varies according to the design of the passive and active systems in a prototype office building. The energy performance of the energy saving technologies was analyzed by the application of three parameters for passive, active, and combined passive–active systems. However, this study did not review renewable energy, which is an alternative for realizing high-performance buildings. Lam et al. [31] performed energy simulations for office buildings located in five major climatic zones in China, ranging from Hong Kong with a hot summer and warm winter, to Harbin with a severe cold climate. This study analyzed office building energy performance in terms of heating and cooling energy in major climatic zones. Energy saving sensitivity was analyzed in each climatic region, and wall and window conduction, window solar, occupants, lighting, equipment, and infiltration were used as design parameters.

Various active technologies (VAV, DOAS, and chilled beam systems) were examined in DOE benchmark reference building models to examine their applicability in diverse climatic conditions of the U.S. [32]. Final efficiency recommendations for each climate zone were included, in addition to the energy simulation results. Primary energy saving measures, which include variable air volume (VAV), and radiant heating and cooling with a dedicated outdoor air system (DOAS), can provide energy savings of more than 40% over the Standard 90.1-2004 [22].

A number of studies have been conducted to realize high-performance buildings in different climate regions. However, most of the research has concentrated on limited types of technology. Moreover, few studies have examined passive, active, and renewable energy systems together, or provided quantitative analysis that took diverse climatic zones into account.

3. Simulation Methodology

3.1. Simulation Model and Setting Variables

In this study, simulations using EnergyPlus were performed to analyze each technology contribution to the energy saving rates in different climates. Figure 3 shows the simulation base model.

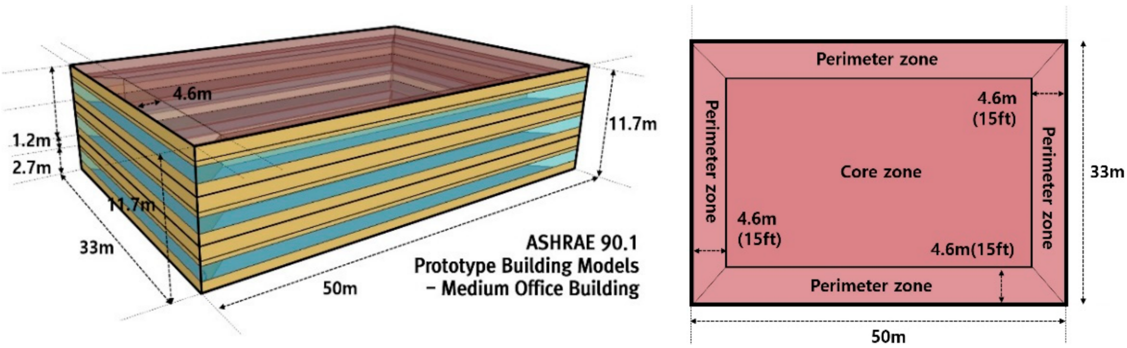


Figure 3. Simulation base model.

The U.S. Department of Energy (DOE) developed ASHRAE 90.1 prototype building models. These models can serve as references for approximately 70% of U.S. office buildings. According to the DOE's national renewable energy laboratory report [33], the models serve as a baseline for comparison, and improve the accuracy of energy simulation software.

Table 1 shows the base model envelope conditions, air conditioning and plant system outline, and detailed energy performance input conditions for the EnergyPlus simulation.

Table 1. Properties of the base simulation model.

Division		Specifications of Base Model
Usage		Office Building
Floor Area and Direction		1650 m^2 (50 m × 33 m × 11.7 m) and South
Simulation Program		EnergyPlus v9.5.0 (Dynamic simulation tool)
Base Model Envelope	U-Value of Wall	0.26 $W/m^2 \cdot K$
		The Korean energy saving design standards
	U-Value of Floor	0.22 $W/m^2 \cdot K$
		The Korean energy saving design standards
	U-Value of Roof	0.15 $W/m^2 \cdot K$
		The Korean energy saving design standards
	Glazing Type (Low-E 6T + 12A + 6CL)	Double Low-E Pane Glazing (U-value = 1.5 $W/m^2 \cdot K$, SHGC = 0.458, VLT = 0.698)
		The Korean energy saving design standards
Base Model System	Terminal Unit	CAV System
	AHU Fan type	Constant Air Volume
	SA Setpoint Temp. Relative Humidity	Cooling Temp. 20 °C, Heating Temp. 26 °C/Relative Humidity 50~60%
		The Korean energy saving design standards
	Cooling/Heating Operation Schedule	Cooling Operation (May—Oct): 07:00~18:00 (26.0 °C)
		Heating Operation (Nov—Apr): 07:00~18:00 (20.0 °C)
	Plant System	Absorption chiller-heaters (heating COP 0.8, cooling COP 1.0)
	Pump Efficiency	0.6 (Default)
	Lighting and Equipment Occupancy density	12 W/m^2, 11 W/m^2
		0.2 person/m^2
		The Korean energy saving design standards, The MOTIE and KICT report
	Infiltration	3.0 ACH50
		The Korean energy saving design standards
Schedule		Weekday—08:00~18:00, Weekend—Off
		The Korean energy saving design standards
Weather Data		Incheon, South Korea (ASHRAE climate zone 4)
		New Delhi, India (ASHRAE climate zone 2)
		Berlin, Germany (ASHRAE climate zone 5)
		Minneapolis, U.S. (ASHRAE climate zone 6)

For the base model envelope conditions, such as walls and glazing, the Korean energy saving design standard (Korea Ministry of Land, Infrastructure and Transport and Korea Energy Agency 2018) [24] was used to compare relative energy saving rates in each climate region. U-values of 0.26 and 1.5 $W/m^2 \cdot K$ for the wall and the glazing system, respectively, were used, which have been used as minimum standards until recently in Korea. The roof condition was treated as adiabatic, to assume that there is no heat exchange between different floors. For equipment, lighting, and people load, the Korean energy saving design standards, the Ministry of Land, Infrastructure and Transport (MOLIT), and the Korea Institute of Civil Engineering and Building Technology (KICT) report (2017) [34] was used.

The constant air volume (CAV) system, which is commonly used in Korea, was set as a base air-conditioning system, and the absorption chiller-heater (cooling COP 1.0, heating COP 0.8) was adopted as a base plant system [35]. The weather file including four regions (Incheon: Seoul metropolitan area—South Korea, New Delhi—India, Berlin—Germany, and Minneapolis—U.S.) provided by the International Weather for Energy Calculation (IWEC) [20] was used in this study.

Table 2 and Figure 4 show high-performance technologies and their specific properties. We selected technologies based on formal studies of high-performance buildings [14–18]. Energy saving technologies, consisting of 15 case models, were grouped as passive systems, active systems, or renewable energy systems.

Table 2. Set of simulation variables (passive, active, and renewable energy systems for energy saving) (Grey: base, Blue: passive systems *, Pink: air-conditioning systems **, Yellow: plant systems ***, Purple: renewable systems ****).

<table>
<tr><th rowspan="2">Model</th><th colspan="3">Building Envelope</th><th colspan="2">HVAC System</th></tr>
<tr><th>Wall (U-Value)</th><th>Glazing and Solar Shading System</th><th>Infiltration</th><th>Air-Conditioning System</th><th>Plant System</th></tr>
<tr><td>Base</td><td>0.47 W/m^2·K</td><td>Double Low-E (No Blind) (U-value 1.5 W/m^2·K, SHGC 0.458, VLT 0.698)</td><td>3.0 ACH</td><td>CAV System</td><td>Absorption Chiller-Heaters (Cooling COP 1.0, Heating COP 0.8)</td></tr>
<tr><td>Case 1 *</td><td>0.15 W/m^2·K</td><td>Double Low-E (No Blind)</td><td>3.0 ACH</td><td rowspan="5">CAV System</td><td rowspan="5">Absorption Chiller-Heaters (Cooling COP 1.0, Heating COP 0.8)</td></tr>
<tr><td>Case 2 *</td><td rowspan="4">0.47 W/m^2·K</td><td>Double Low-E (No Blind)</td><td>0.2 ACH</td></tr>
<tr><td>Case 3 *</td><td>Double Tinted Low-E (U-value 1.4 W/m^2·K, SHGC 0.353, VLT 0.511)</td><td rowspan="3">3.0 ACH</td></tr>
<tr><td>Case 4 *</td><td>Triple Low-E (U-value 1.1 W/m^2·K, SHGC 0.433, VLT 0.527)</td></tr>
<tr><td>Case 5 *</td><td>External Venetian Blind 45° (Double Low-E)</td></tr>
<tr><td>Case 6 **</td><td rowspan="5">0.47 W/m^2·K</td><td rowspan="5">Double Low-E (No Blind)</td><td rowspan="5">3.0 ACH</td><td>VAV System (Fan Pressure: 1000 Pa, Minimum air flow rate: 30%)</td><td rowspan="5">Absorption Chiller-Heaters (Cooling COP 1.0, Heating COP 0.8)</td></tr>
<tr><td>Case 7 **</td><td>VAV + Economizer (Fixed dry bulb control, Maximum limit dry bulb T: 24 °C)</td></tr>
<tr><td>Case 8 **</td><td>VAV + Rotary ERV (Sensible eff. 0.9, Latent eff. 0.7)</td></tr>
<tr><td>Case 9 **</td><td>VAV +UFAD (Underfloor Air Distribution)</td></tr>
<tr><td>Case 10 **</td><td>Active Chilled Beam with DOAS (Entering water T: 14~16 °C, Mean coil temperature to room design temperature difference: 2~4 °C)</td></tr>
</table>

Table 2. *Cont.*

Model	Building Envelope			HVAC System	
	Wall (U-Value)	Glazing and Solar Shading System	Infiltration	Air-Conditioning System	Plant System
Case 11 ***					HW Boiler (Eff.90%) + Cent. Chiller (COP 4.0)
Case 12 ***	0.47 W/m^2·K	Double Low-E (No Blind)	3.0 ACH	CAV System	HW Boiler (Eff.80%) + Cent. Chiller (COP 6.0)
Case 13 ***					HW Boiler (Eff.90%) + Cent. Chiller (COP 6.0)
Case 14 ****	0.47 W/m^2·K	Double Low-E (No Blind)	3.0 ACH	CAV System	GSHP (Heat Exchanger: Vertical ground-coupled, GSHP Capacity: 280 RT, System COP 3.75 (Cooling), System COP 3.15 (Heating))
Case 15 ****				Active Chilled Beam with DOAS	GSHP (Heat Exchanger: Vertical ground-coupled, GSHP Capacity: 280 RT, System COP 3.75 (Cooling), System COP 3.15 (Heating))

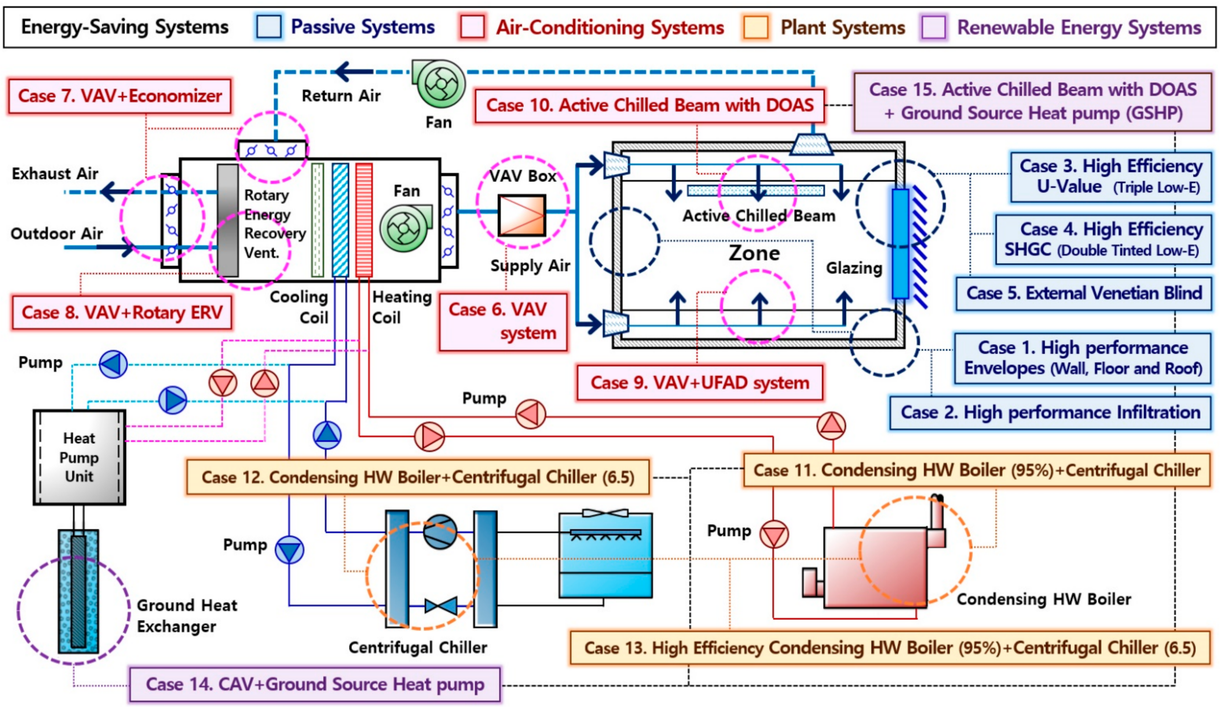


Figure 4. Simplified diagram of energy saving technologies.

Passive systems selected as variables were as follows: The improved wall U-value was 0.15 W/m^2·K (Case 1), and the improved air tightness was 0.2 ACH (Case 2). Windows and glazing system alternatives were double tinted low-e (Case 3) and triple low-e (Case 4), which reflect improved U-value, SHGC, and VLT. Venetian blinds were selected as a solar shading system. Blinds were installed on the outside of windows in Case 5, and their influences were analyzed on energy saving.

The active system was classified as the air-conditioning and plant system. When evaluating the air-conditioning system, the base performance of the absorption chiller-heater was COP 1.0 for cooling, and COP 0.8 for heating. The CAV system, which was the base air-conditioning system from Cases 1 to 5, was changed to the VAV system in Case 6. The VAV + economizer system was applied in Case 7, and the VAV + rotary type ERV was designed in Case 8. The VAV + UFAD system (Case 9), and active chilled beam with DOAS (Case 10), were also used as alternatives to evaluate the air-conditioning system's contribution to energy saving. The plant systems were modified to evaluate their contribution to energy saving from Cases 11 to 13. The base absorption chiller-heater (cooling COP 1.0, heating COP 0.8) was replaced by the hot water condensing boiler and centrifugal chiller with the same CAV systems. The primary energy consumption was examined when either the efficiency of the boiler or the COP of the chiller was changed (Cases 11 and 12), and also when both were changed simultaneously (Case 13). For renewable energy technologies, geothermal energy was used in Cases 14 and 15. When using geothermal energy from the GSHP, the air-conditioning system applied was the CAV system in Case 14, and the active chilled beam with the DOAS in Case 15.

3.2. Validation of the Model

As a final step in the development of the simulation model to be used in the study, a validation process was briefly carried out to ensure that the model could properly predict the thermal load and energy performance.

Actual energy usage of existing typical office buildings was evaluated for comparison with the simulations. According to the Korea Energy Agency (KEA) and Korea Appraisal Board (KAB) database [35], the actual primary energy consumption of the typical office building in the Incheon area is 457–489 kWh/m^2. When we performed a simulation using the Incheon weather file, the primary energy consumption was 464.1 kWh/m^2, which was within the Korea Energy Agency and Korea Appraisal Board range of 457–489 kWh/m^2.

First, in this study, the simulation results (CAV system model) confirmed that the base model's primary energy consumption (464.1 kWh/m^{2}a) met the 457–489 kWh/m^{2}a range requirement of the KEA and KAB database [35] for primary energy consumption of general office buildings. Second, the measurement data for selected Seoul metropolitan research buildings and building energy collected by the Korea Agency for Infrastructure Technology Advancement in the MOLIT were compared and verified with publicly available site data [36]. At this time, monthly building energy use was divided into electricity and gas, primary energy requirements were calculated, and error rates were compared. Office buildings in the Seoul metropolitan area with the same building area and HVAC systems were selected and verified.

Table 3 summarizes monthly electricity and gas data for seven buildings in the Seoul metropolitan area. The state must primarily provide fossil fuels to meet building energy requirements, so energy requirements were calculated by multiplying the conversion factor by country to apply losses such as power generation and fuel transportation.

The primary energy consumption values were calculated using a power conversion factor of 2.75 and a gas conversion factor of 1.1, both of which were set in the Korean building energy efficiency class certification system [37]. Table 4 shows the EnergyPlus simulation results of monthly electricity and gas energy use.

Table 3. The measurement data (primary energy consumption values) for selected Seoul metropolitan research office buildings.

Building Name	Area	Energy (kWh)	Monthly Site Energy Consumption												
			Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Total
1 Jonghap	2032 (m^2)	Elec.	36.5	35.9	27.6	25.7	20.6	25.7	31.0	34.2	31.8	21.7	23.6	29.1	345.5
		Gas	20.7	17.1	13.6	8.8	1.9	2.3	10.4	16.7	21.9	5.3	0.2	3.0	121.9
Total Primary Consumption			467.5												
2 Imkwang	20,409 (m^2)	Elec.	28.3	23.6	24.6	21.3	22.9	30.7	35.2	35.5	30.9	27.8	26.7	33.7	341.2
		Gas	16.7	13.8	9.7	1.3	2.0	12.4	16.6	21.7	14.0	2.8	3.5	15.9	130.4
Total Primary Consumption			471.6												
3 Chunglim	4253 (m^2)	Elec.	31.2	25.1	27.3	23.0	25.2	32.6	34.5	32.1	25.9	21.3	22.7	32.5	333.2
		Gas	15.9	18.4	14.2	13.1	2.7	4.7	14.0	15.4	15.8	8.3	0.4	7.4	130.4
Total Primary Consumption			463.4												
4 Gomuas	3671 (m^2)	Elec.	27.8	29.3	28.2	27.9	23.3	27.2	27.2	24.9	26.1	22.0	25.0	26.6	315.4
		Gas	16.6	13.2	9.3	3.5	8.6	18.1	19.3	22.8	13.0	9.4	3.5	15.8	153.2
Total Primary Consumption			468.6												
5 Wooshin	10,465 (m^2)	Elec.	35.8	34.1	27.0	24.5	21.3	27.3	35.2	40.0	35.1	24.7	22.8	22.8	350.6
		Gas	15.5	15.3	9.9	8.7	0.4	1.7	12.2	18.2	20.2	12.3	1.0	6.5	122.1
Total Primary Consumption			472.6												
6 KOITA	6218 (m^2)	Elec.	31.7	33.6	25.5	23.9	20.1	23.4	24.9	25.1	25.3	21.3	23.5	26.1	304.2
		Gas	24.1	21.9	17.4	10.8	2.4	6.6	17.8	20.5	20.8	13.4	5.4	8.8	169.9
Total Primary Consumption			474.1												
7 Bangbae	8157 (m^2)	Elec.	30.0	29.7	23.1	24.2	21.1	26.7	31.4	35.1	32.5	22.0	20.0	22.5	318.3
		Gas	26.3	19.4	14.0	5.7	4.5	13.9	16.1	19.1	7.0	0.7	7.7	17.0	151.5
Total Primary Consumption			469.8												

Table 4. The EnergyPlus simulated data (primary energy consumption values) for the base model.

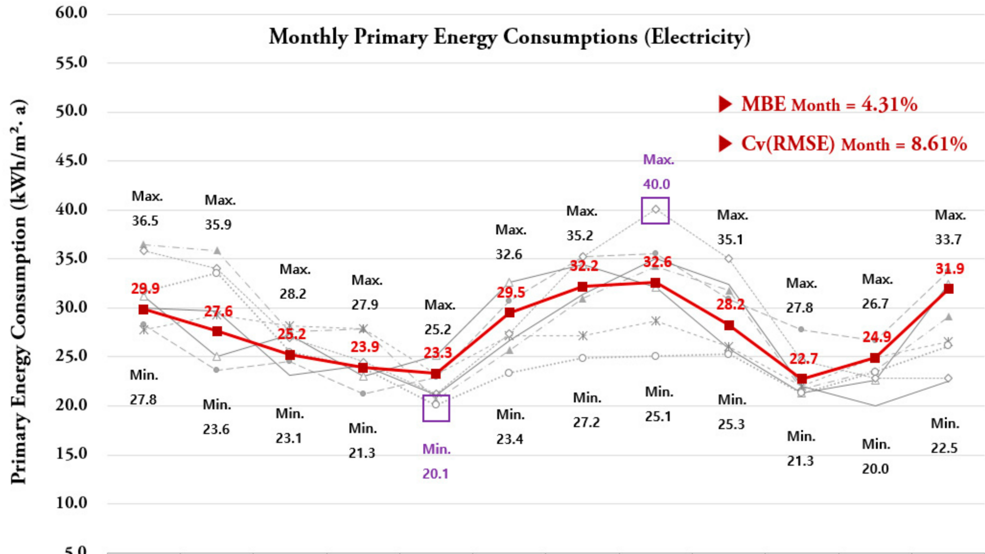
	Area	Energy (kWh)	Monthly Site Energy Consumption												
			Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Total
Simulation Result	4500 (m^2)	Elec.	29.9	27.6	25.2	24.3	23.3	29.5	32.1	32.3	28.2	22.8	24.9	31.9	332.0
		Gas	18.2	15.2	11.5	5.1	3.6	7.5	17.8	19.3	14.7	5.3	3.7	10.2	132.1
Total Primary Consumption			464.1												

Based on Tables 3 and 4, Figure 5 compares the average values of the buildings' electrical measurements with the simulated electrical energy use.

The mean bias error (MBE) and coefficient of variation of the root mean squared error (Cv(RMSE)) methods, which are statistical methods mentioned in the M & V Guidelines 3.0 [38], were used to validate the simulation. An MBE range of −5% to 5% and a Cv(RMSE) of within 15% showed that the model was suitable for analyzing monthly data [38]. The MBE was 4.31% and the Cv(RMSE) was 8.61% when comparing actual and EnergyPlus simulation electrical energy consumption values. Simulation electrical energy values were similar.

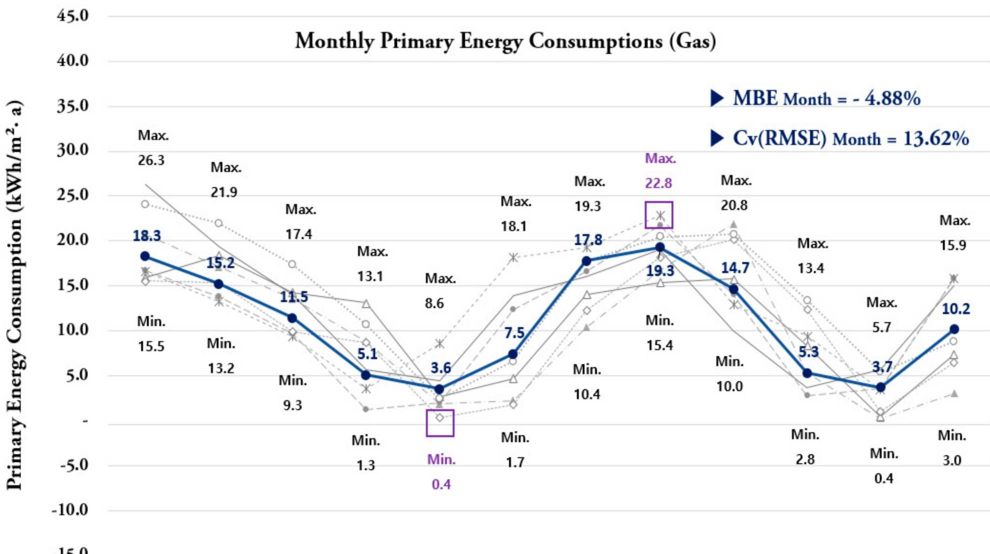
Both the measured and simulated data exhibited high electrical energy consumption during the summer season (Jun–August) and winter season (December–February), with particularly high peaks in August and December. Intermediate season use was relatively low, with the lowest consumption occurring in May and October.

Figure 6 compares the average values of the buildings' gas measurements with the simulated gas energy use. MBE and Cv(RMSE) methods, which are statistical methods mentioned in the M & V Guidelines 3.0, were also used to validate the simulation.



	Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Building 1	36.5	35.9	27.6	27.9	20.6	25.7	31.0	34.2	31.8	21.7	23.6	29.1
Building 2	28.3	23.6	24.6	21.3	22.9	30.7	35.2	35.5	30.9	27.8	26.7	33.7
Building 3	31.2	25.1	27.3	23.0	25.2	32.6	34.5	32.1	25.9	21.3	22.7	32.5
Building 4	27.8	29.3	28.2	27.9	23.3	27.2	27.2	28.7	26.1	22.0	25.0	26.6
Building 5	35.8	34.1	27.0	24.5	21.3	27.3	35.2	40.0	35.1	24.7	22.8	22.8
Building 6	31.7	33.6	25.5	23.9	20.1	23.4	24.9	25.1	25.3	21.3	23.5	26.1
Building 7	30.0	29.7	23.1	24.2	21.1	26.7	31.4	35.1	32.5	22.0	20.0	22.5
EnergyPlus	29.9	27.6	25.2	23.9	23.3	29.5	32.2	32.6	28.2	22.7	24.9	31.9

Figure 5. Comparison of electrical measurement data and base model simulation data.



	Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Building 1	20.7	17.1	13.6	8.8	1.9	2.3	10.4	16.7	21.9	5.3	0.2	3.0
Building 2	16.7	13.8	9.7	1.3	2.0	12.4	16.6	21.7	14.0	2.8	3.5	15.9
Building 3	15.9	18.4	14.2	13.1	2.7	4.7	14.0	15.4	15.8	8.3	0.4	7.4
Building 4	16.6	13.2	9.3	3.5	8.6	18.1	19.3	22.8	13.0	9.4	3.5	15.8
Building 5	15.5	15.3	9.9	8.7	0.4	1.7	12.2	18.2	20.2	12.3	1.0	6.5
Building 6	24.1	21.9	17.4	10.8	2.4	6.6	17.8	20.5	20.8	13.4	5.4	8.8
Building 7	26.3	19.4	14.0	5.7	4.5	13.9	16.1	19.1	10.0	3.7	5.7	15.0
EnergyPlus	18.3	15.2	11.5	5.1	3.6	7.5	17.8	19.3	14.7	5.3	3.7	10.2

Figure 6. Comparison of gas measurement data and base model simulation data.

The MBE was −4.88% and the Cv(RMSE) was 13.62% when comparing actual and EnergyPlus simulation gas energy consumption. Simulation gas energy values were similar. Both the measured and simulated data exhibited high gas energy consumption during the summer season (Jun–August) and winter season (December–February), with particularly high peaks in August and December. Intermediate season use was relatively low, with the lowest consumption occurring in May and October.

3.3. Weather Conditions of the Four Regions Selected for This Study

The ASHRAE 90.1-2009 international climate zone definition, which classifies world climate based on heating and cooling degree days, was used to classify climatic zones in this study [39]. Four regions, namely, Incheon: Seoul metropolitan area—South Korea, New Delhi—India, Berlin—Germany, and Minneapolis—U.S., were selected, and they show typical characteristics of each climatic zone. The weather files were obtained from the U.S. DOE weather data (2017) [20], and Table 5 and Figure 7 show the detailed values.

Table 5. Detailed climate characteristics of the four regions.

Regions	ASHRAE Climate	Köppen Climate	Latitude N(°)	Longitude E(°)	Outdoor Air Temperature (Average Monthly) Min. Avg. Max (°C)	Relative Humidity (Average Monthly) Min. Avg. Max (%)	HDD (18 °C)	CDD (18 °C)
Incheon	4A	Dwa	37.48	126.55	−2.2/11.8/25.0	46.5/68.8/86.3	2762	611
New Delhi	2A	Aw	26.62	77.20	14.1/24.7/33.2	63.1/73.5/86.6	286	3010
Berlin	5A	Cfb	52.52	13.39	0.3/9.8/19.1	38.4/62.5/74.6	3283	147
Minneapolis	6A	Dfb	46.97	−93.26	−9.9/4.8/17.5	49.7/67.3/77.2	4202	417

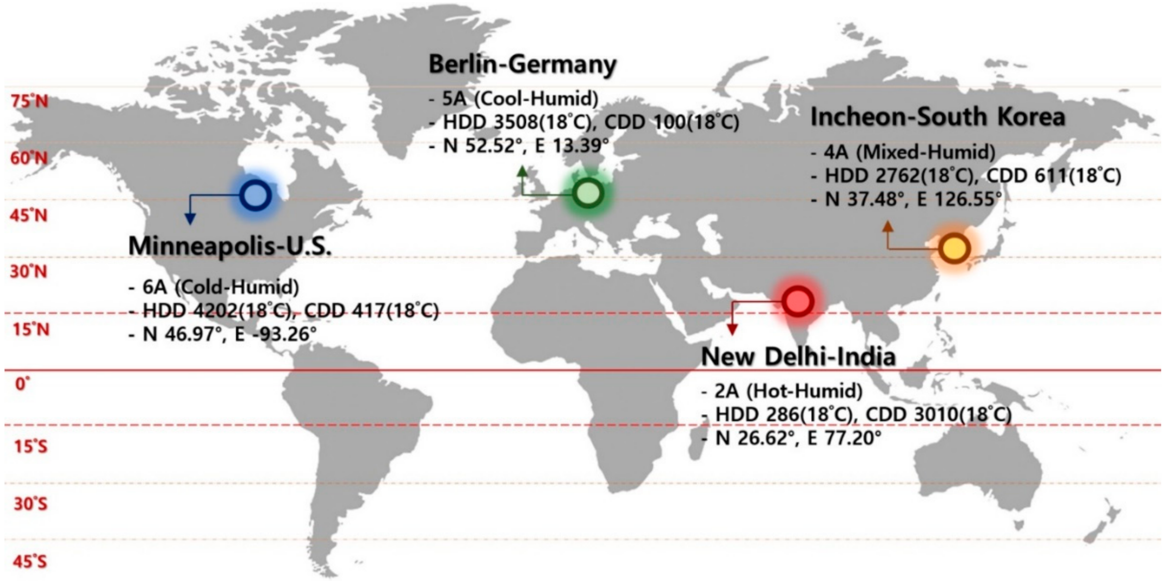


Figure 7. Selection of the four regions for the EnergyPlus simulation.

Incheon belongs to the ASHRAE 4A Mixed-humid climatic zone, and its climate according to the Köppen climate classification is Dwa (cold and dry winter, and hot summer). The maximum average monthly temperature is 25.0 °C in August, and it has a hot and humid summer, with maximum average monthly relative humidity of 86.3% in July. The minimum average monthly temperature is −2.2 °C in January, and it has a cold and dry winter, with minimum average monthly relative humidity of 46.5% in January.

Incheon has 2762 heating degree days (HDD, 18 °C), and 611 cooling degree days (CDD, 18 °C). New Delhi belongs to the ASHRAE 2A Hot-humid climatic zone, and its climate according to the Köppen climate classification is Aw (tropical and dry winter). This weather has 286 heating degree days (HDD, 18 °C), and 3010 cooling degree days (CDD, 18 °C). It is also very hot and humid, with a maximum average monthly temperature of 33.2 °C in June, and maximum average monthly relative humidity of 86.6% in August. Berlin belongs to the ASHRAE 5A Cool-humid climatic zone, and its climate according to the Köppen climate classification is Cfb (temperate and warm summer). It has 3283 heating degree days (HDD, 18 °C), and 147 cooling degree days (CDD, 18 °C). The maximum average monthly temperature is 19.1 °C in July. Its average maximum monthly relative humidity is 74.6% in December. Minneapolis belongs to ASHRAE 6A Cold-humid climatic zone, and its climate according to the Köppen climate classification is Dfb (cold winter and cool summer). It has the greatest number of HDD of all four regions in this study, with 4202 heating degree days (HDD, 18 °C), and 417 cooling degree days (CDD, 18 °C). Its maximum average monthly temperature (17.5 °C), minimum average monthly temperature (−9.9 °C), and average monthly temperature (4.8 °C) are the lowest among the four regions.

Figure 8 compares the monthly outdoor temperature and relative humidity in the four regions. The average monthly temperature in New Delhi is higher than that of Incheon throughout the year, with a difference of about 12.9 °C. The average annual relative humidity in New Delhi is 4.7% (73.5 − 68.8%) lower than that of Incheon. Berlin's (5A) average monthly temperature is about 7 °C lower than that of Incheon. Its average relative humidity is higher than that of Incheon during the winter, and it is lower in summer. Overall, the average yearly relative humidity of Berlin is about 6.3% (68.8 − 62.5%) lower than that of Incheon. The average monthly temperature in Minneapolis (6A) is about 5.3 °C, which is a lower value than that of Incheon throughout the year. Its average annual relative humidity is slightly lower than that of Incheon, with a difference of 1.5% (68.8 − 67.3%).

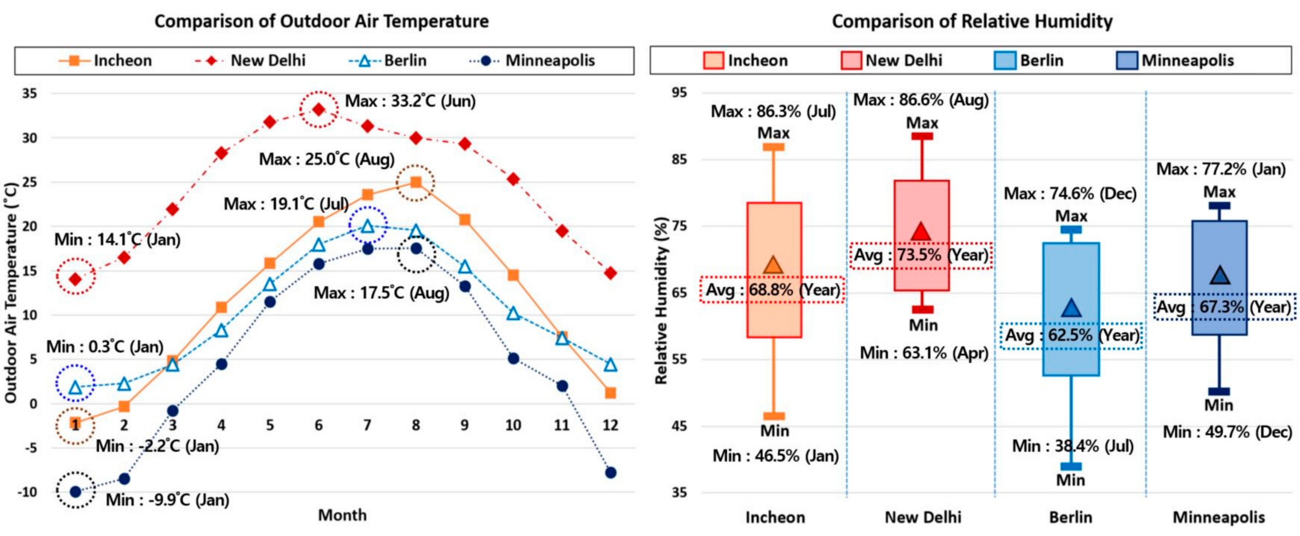


Figure 8. Climate characteristics of the four regions (average monthly outdoor air temperature and relative humidity).

4. EnergyPlus Simulation Results

4.1. Analysis of Energy Saving Rate in Different Climate Zones

Figure 9 shows the influence of each technology on energy saving when compared with the base system using the Incheon weather file.

When passive systems (Cases 1–5) were applied, the energy conservation rates were 5.2–15.4% when compared with the base system. In detail, when the U-value of walls was changed from 0.47 (Base) to 0.15 W/m^2·K (Case 1), the energy conservation rate was 5.2%. When the infiltration rate was improved from 0.6 (Base) to 0.2 ACH (Case 2), the rate was 6.6%. When double low-e (Base) was replaced with double tinted low-e (Case 3) and triple low-e (Case 4), respectively, the conservation rates were 7.4 and 9.9%. When Venetian blinds were installed on the outside of double low-e (Case 5), the conservation rate was 15.4%. Up to 29.9–45.6% of the primary energy can be saved from the air-conditioning system and plant system (Cases 6–13).

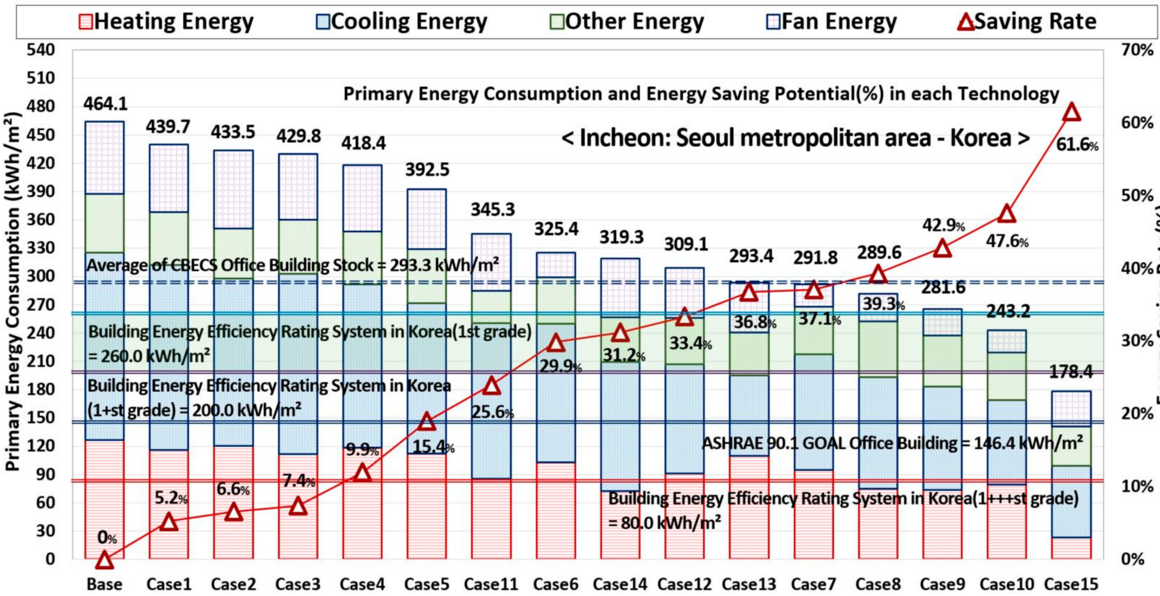


Figure 9. Primary energy consumption values and energy saving potential (%) in each technology—Incheon.

In detail, when the VAV system was applied (Case 6), 29.9% of the energy was saved compared to the CAV system. When an economizer system was applied to the VAV system in Case 7, 39.3% of the energy was saved. When applying ERV, which is a technology that utilizes ventilation (Case 8), 37.1% of the energy was saved. The application of VAV + UFAD system (Case 9) saved 42.9% of the energy. Furthermore, the active chilled beam and DOAS (Case 10) saved 47.6% of the energy when compared with the base case. Therefore, after changing passive and air-conditioning systems, the primary energy consumption was decreased from 464.1 (Base) to as low as 243.2 kWh/m^2. In the plant system alternatives, the absorption chiller-heater was replaced by the hot water condensing boiler and centrifugal chiller. When the efficiency of the hot water condensing boiler was improved from 0.8 to 0.9, or the COP of the centrifugal chiller from 4.0 to 6.0 (Cases 11 and 12), the energy saving rates were 25.6 and 33.4%, respectively. When both the hot water condensing boiler efficiency (0.8→0.9) and the centrifugal chiller's COP (4.0→6.0) were improved in Case 13, the energy efficiency was increased by 36.8%. Therefore, the primary energy consumption was decreased from 464.1 (Base) to as low as 293.4 kWh/m^2, considering the after-plant systems. When the plant system was changed from the base system to the GSHP (Case 14), 31.2% of the energy was saved. When the active chilled beam with the DOAS + GSHP was used (Case 15), 61.6% of the energy was saved. Therefore, the primary energy consumption was decreased from 464.1 (Base) in Case 14 to 319.3 kWh/m^2, and in Case 15 to 178.4 kWh/m^2. Up to 31.2–61.6% of the primary energy could be saved from the renewable energy alternatives.

The primary energy consumption and energy saving rates of each technology in New Delhi, Minneapolis, and Berlin, when the same high-performance technologies in the 15 cases were applied as in Incheon, can be seen in Figure A1 (New Delhi), Figure A2 (Minneapolis), and Figure A3 (Berlin).

Figure 10 shows each technology's contribution to energy saving when the weather data of the four regions were applied. The technologies that are effective in each climate region compared to Incheon are marked (New Delhi: red rectangle, Minneapolis: blue triangle, Berlin: sky blue circle).

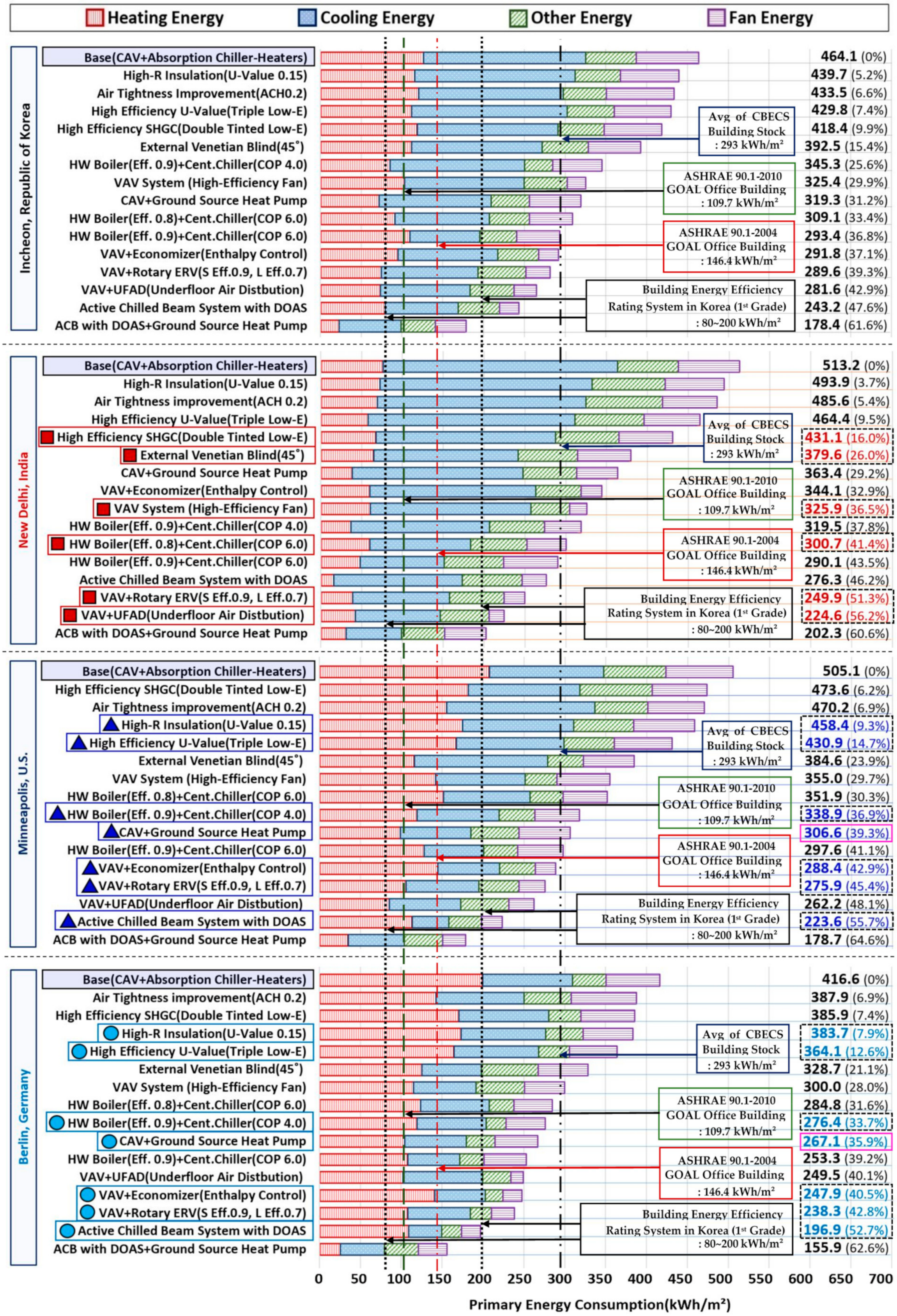


Figure 10. Primary energy consumption and energy saving potential (%) in each technology (four regions).

When Incheon and New Delhi's energy saving rates are compared, the cooling energy was greater than the heating energy in New Delhi, due to a high number of cooling degree days (CDD). Thus, the base model primary energy consumption in New Delhi was 513.2 kWh/m^2, which was higher than that of Incheon. Passive systems that are effective in New Delhi are high efficiency SHGC windows (double tinted low-e) and external blinds. Their energy saving rates were 16.0 and 26.0%, respectively. Among the active systems, the VAV system, the high efficiency centrifugal chiller, the combined VAV-ERV system, and the combined VAV-UFAD system are effective in New Delhi. These are air-conditioning and plant systems that can change hot and humid outdoor air to a comfortable indoor environment. The energy saving rates of these technologies, when compared with the base model in New Delhi, were 36.5, 41.4, 51.3, and 56.2%, respectively.

The heating energy consumption was greater than the cooling energy consumption in Minneapolis, because of a high number of heating degree days (HDD). The primary energy consumption in the Minneapolis base model was 505.1 kWh/m^2, which was higher than that of Incheon. Passive systems that are effective in Minneapolis are the high-R insulation wall and the high efficiency U-value window (triple low-e), which significantly prevent heat loss. Their energy saving rates were 9.3 and 14.7%, respectively, when compared with the base case.

The active systems that save more energy in Minneapolis than in Incheon are the high efficiency heating system, the combined VAV-economizer, the combined VAV-ERV system, and the active chilled beam with DOAS. The energy saving rates of these technologies, when compared with the base model in Minneapolis, were 36.9, 42.9, 45.4, and 55.7%, respectively. The effective technologies in Minneapolis are the control of the low outdoor temperature to create comfortable indoor environments, and technologies that utilize outdoor air or heat recovery. When the GSHP was applied in Minneapolis as a renewable energy system, the energy saving rate was 39.3%.

Berlin has a higher HDD value and a lower CDD value than Incheon. Thus, its actual heating energy is higher than that of Incheon, whereas the cooling energy in Berlin is lower. The base model primary energy consumption in Berlin was 416.6 kWh/m^2, lower than that of Incheon. The technologies that are effective in Berlin are the high-R insulation wall and high efficiency U-value window (triple low-e), which are envelope systems that prevent most heat loss. Their energy saving rates were 7.9 and 12.6%, respectively. Among the active systems, the high efficiency heating system, the combined VAV-economizer, the combined VAV-ERV system, and the active chilled beam with DOAS showed higher energy saving rates in Berlin. The energy saving rates of these technologies for Berlin were 33.7, 40.5, 42.8, and 52.7%, respectively, when compared with the base case in Berlin. When the GSHP was applied in Berlin as a renewable energy system, the energy saving rate was 35.9%. The technologies that showed higher energy saving rates in Minneapolis showed similar trends to those in Berlin.

Figure 11 compares the primary energy saving rates in four regions when using high-performance technologies.

The energy saving rate of a technology differs according to the characteristics of the climate in which it is applied. The technologies that are more effective in hot regions are shading systems, such as the high-efficiency SHGC windows in Case 4 (16.0%), and the external Venetian blind in Case 5 (26.0%). In addition, air-conditioning and plant systems that can convert hot and humid outdoor temperatures to create comfortable indoor environments are the VAV system in Case 6 (36.5%), the combined VAV-rotary ERV in Case 8 (51.3%), the combined VAV-UFAD in Case 9 (56.2%), and the high-efficiency centrifugal chiller in Case 12 (41.4%). In cool and cold regions, envelope systems that prevent heat loss, such as the high-R insulation wall in Case 1 (12.2%), and the high-efficiency U-value window in Case 3 (14.7%), are effective. In addition, air-conditioning and plant systems that utilize outdoor air or ventilation, such as the combined VAV-economizer in Case 7 (42.9%), the active chilled beam with DOAS in Case 10 (56.8%), the high efficiency heating system in Case 11 (37.8%), CAV + GSHP in Case 14 (39.3%), and the active chilled beam with DOAS + GSHP in Case 15 (64.6%), are more efficient.

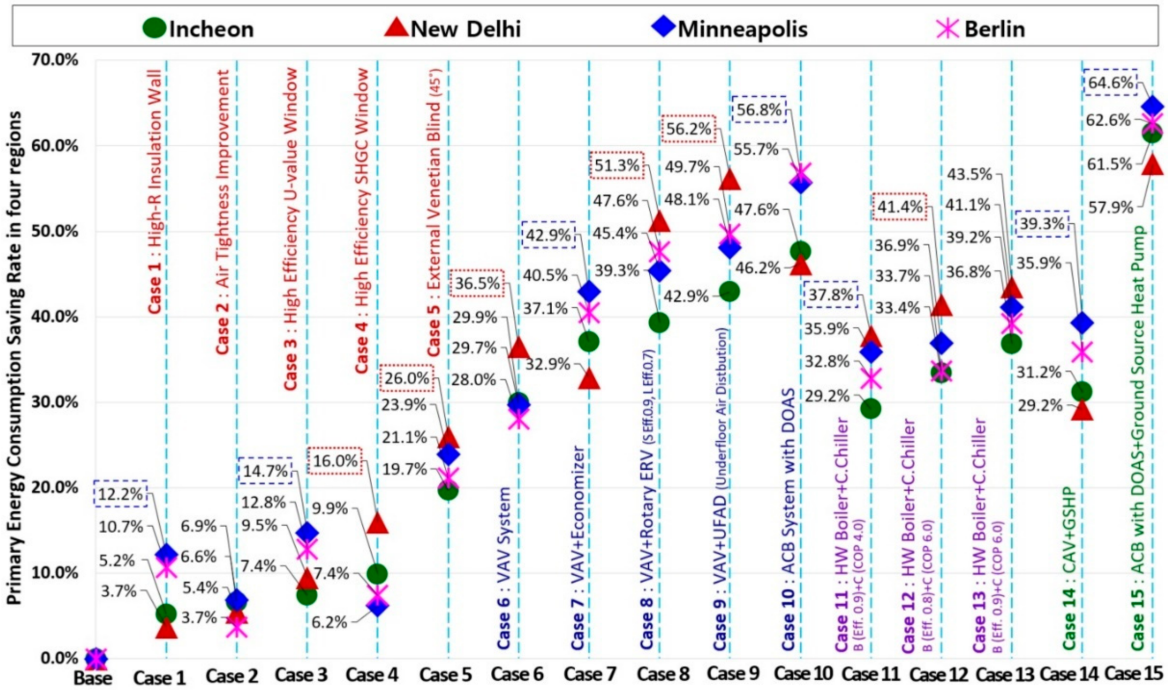


Figure 11. Comparative results of the energy saving rates in the four regions when using high-performance technologies.

In climates that have four distinct seasons, including a hot summer and a cold winter, thick insulation and solar heat should be utilized during the winter, whereas solar shading should be considered in summer. Furthermore, the plant and air-conditioning systems also need to be able to create a comfortable indoor environment in both the hot summer and cold winter. Therefore, a design strategy that fits the given climate is important.

4.2. Comparison of Specific Energy Performance Simulation Results and Summary of Energy Saving Technologies in Different Climate Zones

In Section 4.1, technologies that are effective in each climate were identified according to the simulation results. In Section 4.2, the technologies that were applied to a hot climate (New Delhi) and cold weather (Minneapolis) are compared with those in Incheon. In this section, the primary energy consumption values are divided into heating, cooling, and fan energy for the analysis of each component. Table 6 shows the specific energy consumption and saving rates in New Delhi (Hot humid zone_2A) and Incheon (Mixed zone_4A).

When the high efficiency SHGC window was applied in New Delhi, the energy saving rate was 6.1% (16.0 − 9.9%) higher than that in Incheon. Among heating, cooling, and fan energy, cooling energy showed the highest saving of 23.4%. The solar heat gain coefficient (SHGC) of glazing systems is most influenced by the solar radiation. The influence is greater in hot regions, where the solar radiation is stronger than that in cold regions. Because the solar radiation is strong in hot and humid climate zones, SHGC is important for energy saving in the New Delhi climate.

The energy saving rate of the external Venetian blind is 10.6% (26.0 − 15.4%) higher in New Delhi than that in Incheon. Among the three major components in New Delhi, the cooling energy saving is highest (38.4%). Shading systems, such as external blinds, are effective in reducing cooling energy consumption in hot and humid climate zones. Appropriate solar shading systems in hot regions can greatly contribute to save cooling energy consumption.

Table 6. Breakdown of the energy consumption and saving rate (comparison of Incheon and New Delhi).

Conservation System	Classification	Incheon		New Delhi	
		Primary Energy Consumption (kWh/m^2)	Energy Saving Rate	Primary Energy Consumption (kWh/m^2)	Energy Saving Rate
Base	Total	464.1	-	513.2	-
	Heating	126.5		76.3	
	Cooling	198.7		287.1	
	Fan	76.8		75.2	
High Efficiency SHGC Window	Total	418.4	9.9%	431.1	16.0%
	Heating	118.8	6.1%	67.7	11.2%
	Cooling	172.8	13.1%	215.8	23.4%
	Fan	70.5	8.2%	65.8	12.5%
External Venetian Blind	Total	392.5	15.4%	379.6	26.0%
	Heating	112.0	11.5%	64.8	15.1%
	Cooling	159.7	19.6%	180.9	38.4%
	Fan	63.7	17.1%	65.1	13.5%
VAV System	Total	325.4	29.9%	325.9	36.5%
	Heating	103.1	18.5%	60.9	20.2%
	Cooling	157.0	26.1%	199.5	31.6%
	Fan	52.7	70.5%	20.9	72.2%
High Efficiency Cooling System	Total	319.3	31.2%	300.7	41.4%
	Heating	72.2	27.8%	59.9	21.4%
	Cooling	137.0	41.8%	123.5	56.9%
	Fan	62.8	31.4%	48.2	35.9%
VAV + ERV (Energy Recovery Ventilation)	Total	289.6	39.3%	249.9	51.3%
	Heating	74.7	40.9%	39.0	48.8%
	Cooling	118.8	40.2%	122.6	58.7%
	Fan	29.6	61.5%	25.3	66.4%
VAV + UFAD	Total	243.2	42.9%	224.6	56.2%
	Heating	79.5	41.8%	42.5	44.3%
	Cooling	89.4	44.8%	105.0	63.8%
	Fan	23.6	63.8%	18.4	75.5%

The VAV system result showed 6.6% (36.5 − 29.9%) more energy can be saved in New Delhi than in Incheon. In particular, the cooling energy and fan energy showed significant saving rates of 31.6 and 72.2%, respectively. When VAV systems were applied to office buildings in warm and hot climate zones (ASHRAE Climate Zone 1–3C), they showed relatively higher saving rates (Thornton et al. 2009). In addition, in a hot and humid climate (ASHRAE Climate Zone 1–2A), the VAV system was more effective than the CAV or FCU system [40].

When the VAV + ERV system was applied, 12.0% (51.3 − 39.3%) more energy was saved in New Delhi than in Incheon. The difference was caused by the fact that the VAV + ERV system removes a large amount of moisture when it is applied in New Delhi. The VAV + ERV system showed a cooling energy saving of 58.7%, and a fan energy saving of 66.4%. The ERV is more efficient in humid climates having large disparity between outdoor and indoor relative humidity than in dry regions. In particular, the ERV can effectively reduce latent heat load [41]. When the applicability of the ERV and HRV in various climates is considered, the ERV is more effective than the HRV in hot and humid climates. In intermediate seasons, when the difference between indoor and outdoor temperature is small, a by-pass control can be used [42].

When the VAV + underfloor air distribution (UFAD) system was applied in New Delhi, 13.3% (56.2 − 42.9%) more energy could be saved compared to Incheon, and the cooling energy saving rate (63.8%) and fan energy saving rate (75.5%) were significant. When the applicability of the UFAD system in the hot climate was evaluated, the UFAD was able to save more energy than the CAV system, and provide better thermal comfort for the occupants [43]. In addition, the UFAD can save more energy than the CAV system in terms of annual energy consumption and peak load. Thus, the UFAD is effective in hot and humid climate regions [44,45].

Table 7 shows the details of the energy saving rates when the high-performance technologies were applied to Minneapolis (Cold humid zone_6A), in comparison with the Incheon climate (Mixed zone_4A). The energy saving rate of the high-R insulation wall was 8.0% (13.2 − 5.2%) more than the rate of Minneapolis when compared with the base case. The heating energy showed the highest reduction rate of 15.8%. In a related study performed in hot and cold regions, this indicated that the insulation performance is more effective in cold climates than in hot climates [46]. Analysis of the insulation thickness on energy performance also suggested that increasing the insulation in hot weather is not as effective at increasing the energy efficiency [47].

Table 7. Breakdown of the energy consumption and saving rate (comparison of Incheon and Minneapolis).

Conservation System	Classification	Incheon		Minneapolis	
		Primary Energy Consumption (kWh/m^2)	Energy Saving Rate	Primary Energy Consumption (kWh/m^2)	Energy Saving Rate
Base	Total	464.1	-	505.1	-
	Heating	126.5		208.0	
	Cooling	198.7		139.3	
	Fan	76.8		81.8	
High-R Insulation Wall (0.15 $W/m^2{\cdot}K$)	Total	418.4	5.2%	458.4	9.3%
	Heating	115.9	8.4%	175.1	15.8%
	Cooling	196.3	1.2%	135.9	2.4%
	Fan	71.8	6.6%	74.5	8.9%
High Efficiency U-value Window	Total	373.5	7.4%	430.9	14.7%
	Heating	111.6	11.8%	167.2	19.6%
	Cooling	191.1	3.8%	131.8	5.3%
	Fan	69.6	9.3%	61.8	13.4%
High Efficiency Heating System	Total	325.4	25.6%	338.9	36.9%
	Heating	79.5	32.6%	119.2	42.7%
	Cooling	157.0	17.0%	100.6	27.8%
	Fan	52.7	21.0%	54.3	33.6%
CAV + GSHP	Total	319.3	31.2%	306.6	39.3%
	Heating	72.2	42.9%	98.8	52.5%
	Cooling	137.0	31.1%	86.3	38.0%
	Fan	62.8	18.2%	62.4	23.7%
VAV + Economizer	Total	291.9	37.1%	288.4	42.9%
	Heating	95.1	24.8%	144.7	30.4%
	Cooling	122.3	38.4%	75.2	45.9%
	Fan	24.1	61.7%	24.6	69.9%
VAV + ERV (Energy Recovery Ventilation)	Total	289.6	39.3%	275.9	45.4%
	Heating	74.7	40.9%	105.6	49.1%
	Cooling	118.8	40.2%	88.9	36.1%
	Fan	29.6	53.5%	32.1	60.8%
Active Chilled Beam System with DOAS	Total	189.4	59.2%	223.6	55.7%
	Heating	43.0	64.9%	113.5	45.4%
	Cooling	33,1	54.2%	44.9	67.8%
	Fan	21.3	72.2%	25.4	68.9%

The energy saving rate of the high U-value window was 7.4% (14.7 − 7.4%) more in Minneapolis than in Incheon. In this cold weather, the heating energy saving is high, and showed the highest saving rate of 19.6%. Glazing with better insulation performance minimized heat transfer. This resulted in saving heating energy and increasing thermal comfort for the occupants. When the glazing U-value and investment cost in various climates were analyzed, a glazing system with optimized insulation was more suitable in cold climates than in hot and humid climates [48,49].

According to the results from applying the CAV + GSHP, the energy saving rate was 8.1% (39.3 − 31.2%) more in Minneapolis than in Incheon. In Minneapolis, heating energy showed the highest saving of 52.5%. The ground source heat pump (GSHP) is a highly efficient technology for heating in cold regions [50]. A related study also showed the minimum and maximum values of COP during the heating season were higher in the GSHP than those of the air source heat pump (ASHP). The GSHP provides a COP that is up to three times higher than that of the ASHP [51]. The ASHP becomes less efficient in the heating season due to the low outdoor air temperature. Applying high-performance GSHP systems is more effective in cool and cold climates compared to conventional heating systems [52].

The energy saving rate of the VAV + economizer was 8.8% (42.9 − 37.1%) more in Minneapolis than in Incheon, due to the appropriate outdoor air cooling in the intermediate season. The cooling energy (45.9%) and fan energy (69.9%) savings were particularly high. The outdoor air intake using an economizer is inefficient in hot-humid climates and the cooling season of mixed climates. When applying an economizer in cool and cold climates, outdoor air temperature control or enthalpy control can also be used.

The energy saving rate of the ERV in Minneapolis was 12.1% (45.4 − 39.3%) more than that in Incheon. This was due to the heat recovery from the low outdoor air temperature in the heating season. The heating energy (49.1%) and fan energy (60.8%) savings were particularly high. When the VAV + ERV is applied to office buildings, the efficiency of the operation of the ERV can be increased by controlling the VAV system damper. The VAV + ERV system typically shows high heating energy saving rates in cool and cold regions [53].

When the active chilled beam with DOAS was applied in Minneapolis, its energy saving rate was 8.1% (55.7 − 47.6%) more than that applied in Incheon. Specifically, the heating energy (67.8%) and fan energy (68.9%) saving rates were high. When the DOAS is applied in various climates, the energy efficiency is lower in hot and humid regions [54,55]. Hot and humid outdoor heat is exchanged with cold and dry exhaust air in hot climates, which increases the cooling coil energy consumption. However, because the system can utilize relatively cool outdoor air in cool and cold climates, and due to the heat recovery from the exhaust air, the DOAS can save a large proportion of the heating and dehumidification load in cool and cold climates [56].

The details of energy saving rates when the high-performance technologies are applied to Berlin (Cool humid zone_5A) in comparison with the Incheon climate (Mixed zone_4A) are shown in Table A1. Based on previous research and simulation results, the effective technologies in each climate zone are summarized in Table A2.

5. Conclusions and Discussions

5.1. Summary and Conclusions

This study classified the high-performance technologies as passive, active, and renewable energy systems, and evaluated their primary energy consumption in different climatic regions. In addition, this study performed detailed analyses of energy saving rates, in order to suggest a guideline for selecting appropriate technologies for different climatic regions when designing high-performance buildings. Some conclusions that can be drawn from this research are as follows:

The actual energy usage of existing typical office buildings was evaluated to prepare the simulations. According to the Korea Energy Agency and Korea Appraisal Board DB, the actual primary energy consumption of typical office buildings in the Incheon area is 457–489 kWh/m^2. Simulation using the Incheon weather file showed that the primary energy consumption was 464.1 kWh/m^2, which was within the Korea Energy Agency and Korea Appraisal Board DB range of 457–489 kWh/m^2.

When the high-performance technologies of the 15 cases were applied in the Incheon area, the primary energy consumption in Incheon was reduced by as much as 178.4 kWh/m^2 compared to the base case value of 464.1 kWh/m^2. When passive systems were applied, energy saving rates of 5.2–20.9% were determined. When active systems (air-conditioning and plant systems) were applied, 29.9–45.6% of the energy was saved. In renewable energy system alternatives, the energy saving rate was 31.2–61.6%.

When the primary energy consumption in New Delhi was compared with that of Incheon, the cooling energy was greater than the heating energy in New Delhi. The primary energy consumption of the base model was 513.2 kWh/m^2, which was larger than that in Incheon. When passive systems were applied, 3.7–26.0% of the energy was saved, compared to the New Delhi base case. The active systems (air-conditioning and plant systems) saved 32.9–56.2% of the energy, whereas renewable energy systems saved 31.2–60.6%.

The passive systems that were efficient in a hot climate, such as New Delhi, as shown in the result of Section 4.2, were the high-efficiency SHGC window and the external blind related to solar heat gain control. The active systems (air-conditioning and plant system) that were effective in the hot climate were the VAV system, the combined VAV-ERV system, the combined VAV-UFAD system, and the high efficiency centrifugal chiller, which was able to alter the hot and humid outdoor air to create a comfortable indoor environment.

A comparison of the primary energy consumption of Minneapolis and Incheon showed that the heating energy is greater than the cooling energy. The primary energy consumption of the base model was higher than that in Incheon, of 505.1 kWh/m^2. When high-performance technologies were applied in Minneapolis, the primary energy consumption was reduced to 178.7 kWh/m^2 of the base case. When passive systems were applied, 6.2–23.9% of the energy was saved. Application of active systems (air-conditioning and plant systems) allowed energy saving rates of 29.7–55.7%. In renewable energy system alternatives, 39.3–64.6% of the energy could be saved.

When compared to the energy saving rates of Incheon, the heating energy was also greater than the cooling energy in Berlin. The primary energy consumption of the base case in Berlin was 416.6 kWh/m^2, which was comparatively lower than that in Incheon. When high-performance technologies were applied in Berlin, the primary energy was reduced to as much as 155.9 kWh/m^2. When passive systems were applied in Berlin, the energy saving rates were 6.9–21.1%. The application of active systems (air-conditioning and plant systems) saved 28.0–52.7% of the energy, whereas renewable energy system alternatives saved 35.9–62.6%.

When passive systems that can reduce heat loss and utilize solar heat (high-R insulation wall, high efficiency U-value) are applied in cool and cold regions, such as Berlin and Minneapolis, the energy saving rates are high. Among active systems, the combined VAV-ERV system, the combined VAV-economizer system, the high efficiency heating system, the active chilled beam with DOAS, which changes the low outdoor air temperature to create a comfortable indoor environment, or technologies that use outdoor air or ventilation systems, were effective. For renewable energy systems in cool and cold regions, when the GSHP was applied, the energy saving rate was high.

Analysis showed that the energy saving rates of technology differ due to the characteristics of the climate in which it is applied. Thus, simply applying technologies without considering the climate and indoor conditions will not result in effective energy savings. When designing high-performance buildings globally, it is important to select energy saving technologies that are suited to the surrounding environment, and design strategies that are appropriate for the given climate.

5.2. Limitation of Research and Future Work

This study emphasized that, the ability of technology to save energy in buildings is affected by the climate. Thus, it is necessary to use efficient technology that is suited to the specific climate regime. Implementing the energy saving technologies, while understanding the energy conservation principles underpinning each system under certain climate conditions, is important for energy efficiency considerations when designing high-performance buildings in the future. However, a building's energy performance can be driven by other factors additional to technology and climatic conditions, such as operating hours and occupant behavior. Unfortunately, this information is predicted based on the assumptions adopted by the programmer at the simulation stage and, because real life data can only be obtained from existing buildings measured in real time, an impact analysis of these factors was not possible in this study. However, this is an appropriate topic for future building performance studies.

Our conclusion that no single technology factor determines building energy performance means that the precise nature of the factors driving building energy use, in addition to the climate, remain unclear. Therefore, an energy saving strategy must consider all factors that can affect the actual energy use of a building. Building use and occupant behavior can influence a building's operating schedule and energy usage. An integrated design approach that considers all factors offers the greatest potential for planning and building energy-efficient buildings informed by real world data.

In this study, representative ASHRAE international climate zones were selected and simulations were carried out, but data reflecting all of the global climate zones was unavailable. To address this, in the "Supplementary Materials" we present a reference list of the potential energy saving rates suggested in various papers. In addition, it is necessary to propose a more realistic solution for energy performance information by region and system in connection with the optimization process of passive, active, and renewable energy systems. In a future study, we will conduct research to identify the optimal cost-effective combination by region, by undertaking an economic analysis of each type of technology. Therefore, the future research will analyze and discuss the results of the actual system operation through an experimental study.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/app11157115/s1, Table S1: Review of researches on energy saving potential of energy saving technologies for simulation verification (Passive systems), Table S2: Review of researches on energy saving potential of energy saving technologies for simulation verification (Active and renewable energy systems).

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Abbreviations

The following abbreviations are used in this manuscript:

ACH	Air Change per Hour
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BLAST	Building Loads Analysis and System Thermodynamics
CAV	Constant Air Volume
CBECS	Commercial Buildings Energy Consumption Survey
CDD	Cooling Degree Days
COP	Coefficient of Performance
DOAS	Dedicated Outdoor Air System
DOE	U.S. Department of Energy
EIA	Energy Information Administration
ERV	Energy Recovery Ventilation
EPW	EnergyPlus Weather File
GSHP	Ground Source Heat Pump
HDD	Heating Degree Days
HVAC	Heating, Ventilation and Air Conditioning
HW Boiler	Hot Water Condensing Boiler
SHCG	Solar Heat Gain Coefficient
UFAD	Underfloor Air Distribution
VAV	Variable Air Volume
VLT	Visible Light Transmittance

Appendix A

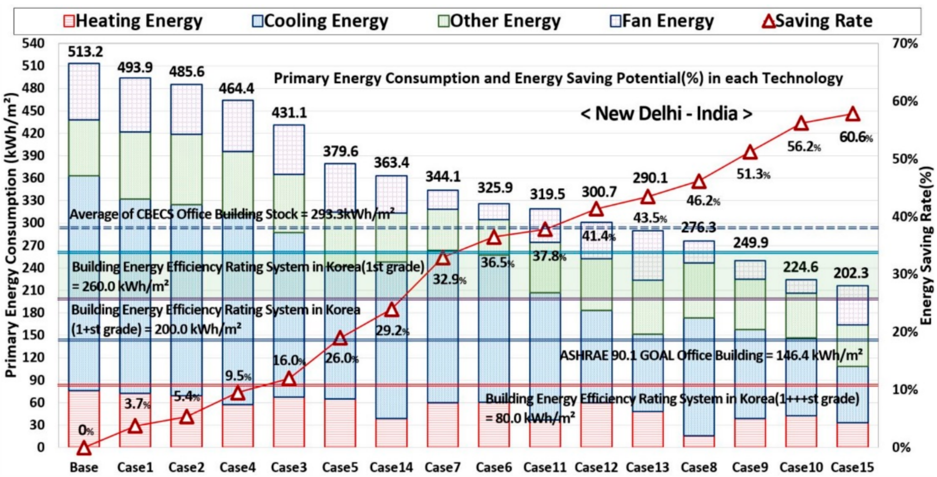

Figure A1. Primary energy consumption and energy saving potential (%)—New Delhi.

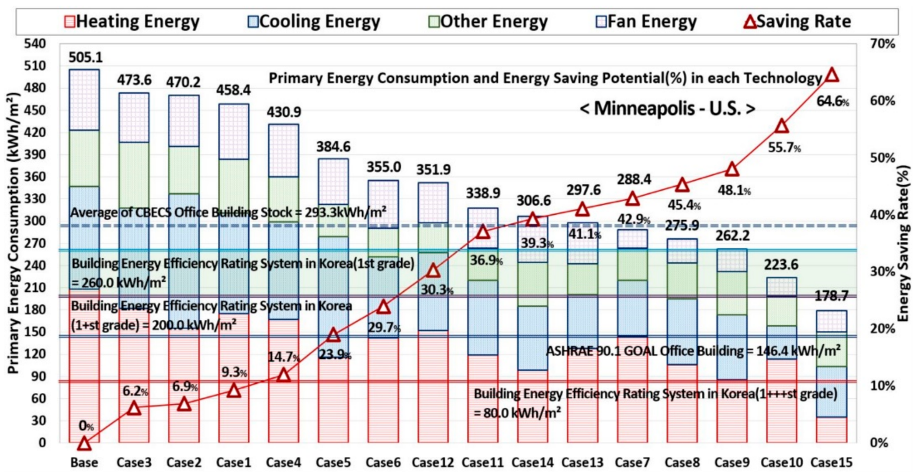

Figure A2. Primary energy consumption and energy saving potential (%)—Minneapolis.

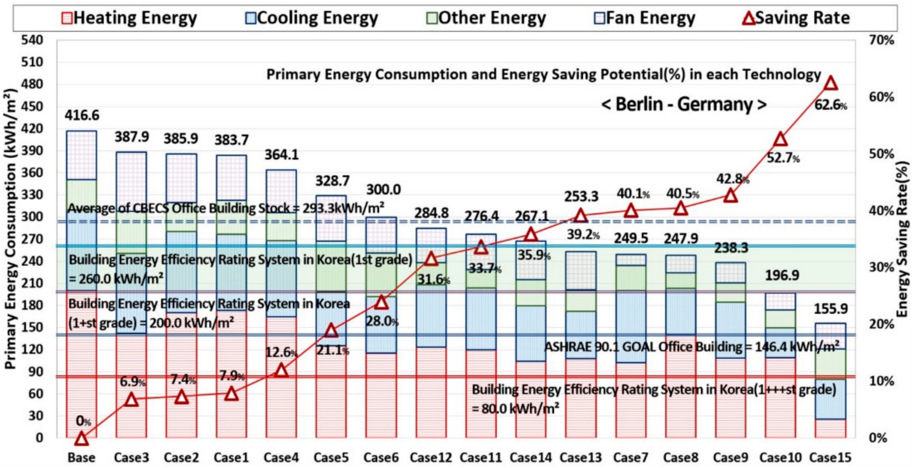

Figure A3. Primary energy consumption and energy saving potential (%)—Berlin.

Table A1. Breakdown of the energy consumption and saving rate (comparison of Incheon and Berlin).

Conservation System	Classification	Incheon		Berlin	
		Primary Energy Consumption (kWh/m^2)	Energy Saving Rate	Primary Energy Consumption (kWh/m^2)	Energy Saving Rate
Base	Total	464.1	-	416.6	-
	Heating	126.5		208.0	
	Cooling	198.7		139.3	
	Fan	76.8		81.8	
High-R Insulation Wall (0.15 W/m^2·K)	Total	418.4	5.2%	383.7	7.9%
	Heating	115.9	8.4%	175.1	13.2%
	Cooling	196.3	1.2%	135.9	6.1%
	Fan	71.8	6.6%	74.5	7.6%
High Efficiency U-value Window	Total	373.5	7.4%	364.1	12.6%
	Heating	111.6	11.8%	176.1	17.5%
	Cooling	191.1	3.8%	130.7	6.2%
	Fan	69.6	9.3%	72.3	11.5%
High Efficiency Heating System	Total	325.4	25.6%	276.4	33.7%
	Heating	79.5	32.6%	123.5	40.6%
	Cooling	157.0	17.0%	106.9	23.2%
	Fan	52.7	21.0%	58.2	28.9%
CAV + GSHP	Total	319.3	31.2%	267.1	35.9%
	Heating	72.2	42.9%	99.6	47.9%
	Cooling	137.0	31.1%	95.7	31.3%
	Fan	62.8	18.2%	64.7	20.9%
VAV + Economizer	Total	291.9	37.1%	247.9	40.5%
	Heating	95.1	24.8%	146.6	29.5%
	Cooling	122.3	38.4%	78.9	43.3%
	Fan	24.1	68.7%	29.1	64.4%
VAV + ERV (Energy Recovery Ventilation)	Total	289.6	39.3%	238.3	42.8%
	Heating	74.7	40.9%	95.3	45.8%
	Cooling	118.8	40.2%	42.9	30.8%
	Fan	29.6	61.5%	47.4	57.9%
Active Chilled Beam System with DOAS	Total	189.4	47.6%	176.9	52.7%
	Heating	43.0	37.1%	113.9	45.2%
	Cooling	33,1	55.0%	50.8	63.5%
	Fan	21.3	69.3%	28.9	64.7%

Table A2. Design strategies for saving energy in different climate zones.

Systems	ASHRAE Climate Zone	
	Warm-Hot and Mixed Zone (Cooling Season)	**Cool-Cold and Mixed Zone (Heating Season)**
Passive systems	High efficiency Solar Heat Gain Coefficient (SHGC) window External Venetian blind (shading device)	High-R insulation wall High efficiency U-value window
Active and renewable energy systems	VAV system (High-efficiency variable fan) Combined VAV-ERV system (Variable Air Volume, Energy Recovery Ventilation) Combined VAV-UFAD system (Underfloor Air Distribution) High-efficiency cooling equipment (High efficiency centrifugal chiller)	Combined VAV-economizer system Combined VAV-ERV system (Energy recovery ventilation) Active chilled beam with DOAS (Dedicated Outdoor Air System) Ground source heat pump High-efficiency cooling equipment (High efficiency hot water condensing boiler)

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