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Review

Evaluation of energy-efficient design strategies: Comparison of the thermal performance of energy-efficient office buildings in composite climate, India

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ABSTRACT

The aim of this paper is to examine the energy consumption of and determine energy-efficient design strategies for mid-rise and high-rise office buildings in composite climate. For this purpose, a comparative study is performed of six energy-efficient office buildings in composite climate in India. The selected energy-efficient office buildings are situated in the major cities (Delhi, Gurgaon, and Hyderabad) of India with a composite climate. This study investigates the effectiveness of different design strategies for reducing the heating, ventilation, and air-conditioning (HVAC) and lighting loads of the six buildings. The effect of factors such as the building form, envelope configuration, placement of the service core, window-to-wall ratio (WWR), and percentage of air-conditioned space on the HVAC load are analyzed. Similarly, the effect of the plan depth and WWR on the lighting load is also determined. Finally, the findings of the study are used to recommend effective design strategies for high-rise office buildings in composite climate. Moreover, the energy performance data are compared with the national energy consumption benchmarks for composite climate. The comparison indicates the design strategies performed well, that lead to a decrease in the energy consumption of high-rise office buildings in composite climate.

1. Introduction

To make Indian cities sustainable and smart, the energy consumption of buildings must be reduced (Ministry of Urban Development, Government of India, 2015). Energy-conscious design requires the integration of climate-responsive design with the functionality of the building. Several studies have investigated the effect of design strategies on the energy consumption of high-rise office buildings. Ismail (2007) conducted a comparative study of six Malaysian high-rise office buildings (three bioclimatic and three typical) and found that bioclimatic high-rise office buildings provide a superior working environment for their users. These buildings also provide a high level of comfort with low energy usage. Zhang and Zhu (2013) analyzed four energy-efficient office buildings in four climate zones of China and determined the breakdown of the energy consumption patterns of these buildings. They reported that lighting and cooling account for the largest proportions of energy consumption in office buildings. Moreover, Raji et al. (2016) stated that additional considerations must be made in the design of high-rise buildings in tropical climate because the energy consumption of sustainable buildings is relatively higher than the energy benchmarks for a good-practice building.

The literature indicates that air conditioning and lighting are the main components of energy consumption in high-rise office buildings. The air-conditioning and lighting consumption can be reduced by incorporating climate-responsive features in the design. Moreover, there currently exists a lack of in-depth research on the influence of design strategies on the energy consumption of high-rise buildings in tropical climate (Raji et al., 2016). Therefore, in this study, appropriate design strategies for reducing the energy consumption of high-rise office buildings in composite climate (a type of tropical climate) are described by analyzing case studies of energy-efficient office buildings.

2. Methodology

India has various types of tropical climates due to its large land area, which spans a wide range of latitudes (Bureau of Energy Efficiency, Ministry of Power, 2016). According to the Energy conservation building code (ECBC) (2011) and National Building Code (NBC, 2016), India can be divided into five climate zones, namely hot and dry, warm and humid, composite, temperate, and cold, in terms of the thermal design of buildings. The composite zone covers the largest area in India (Fig. 1). Consequently, in this study, six sustainable high-rise office buildings located in different cities (New Delhi, Gurgaon, and Hyderabad) of India in the composite climate zone are considered as case

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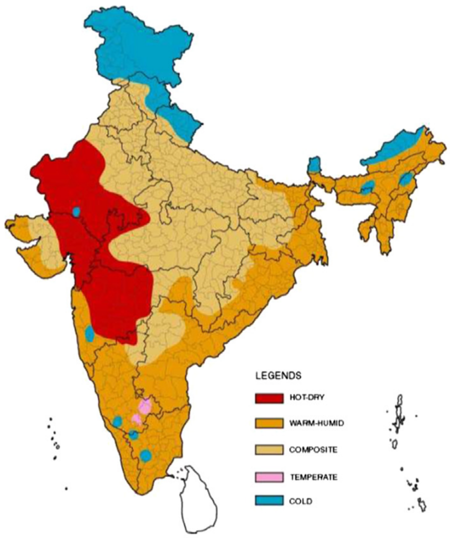


Climate Zone	Description	Mean Temperature (°C)					Mean Relative humidity	Annual Precipitation	Sky Conditions	Places
		Summer midday (High)	Summer night (Low)	Winter midday (High)	Winter night (Low)	Diurnal Variation				
Hot and Dry	High temperature | Low humidity and rainfall | Intense solar radiation and a generally clear sky | Hot winds during the day and cool winds at night | Sandy or rocky ground with little vegetation |Low underground water table and few sources of surface water.	40 to 45	20 to 30	5 to 25	0 to 10	15 to 20	Very Low 25-40%	Low <500 mm/yr.	Cloudless skies with high solar radiation, causing glare	Rajasthan, Gujarat, Western Madhya Pradesh,Central Maharashtra etc.
Warm and Humid	Temperature is moderately high during day and night | Very high humidity and rainfall | Diffused solar radiation if cloud cover is high and intense if sky is clear | Calm to very high winds from prevailing wind directions | Abundant vegetation | Provision for drainage of water is required	30 to 35	25 to 30	25 to 30	20 to 25	5 to 8	High 70 to 90%	High > 1200 mm/yr.	Overcast (cloud cover ranging between 40 and 80%), causing unpleasant glare	Kerela, Tamilnadu, Costal parts of Orissa and Andhra Pradesh etc.
Temperate	Moderate temperature | Moderate humidity and rainfall | Solar radiation same throughout the year and sky is generally clear | High winds during summer depending on topography | Hilly or high plateau region with abundant vegetation	30 to 34	17 to 24	27 to 33	16 to 18	8 to 13	High 60 to 85%	High > 1000 mm/yr	Mainly clear, occasionally overcast with dense low clouds in summer	Bangalore, Goa and parts of the Deccan
Cold (Sunny/ Cloudy)	Moderate summer temperatures and very low in winter | Low humidity in cold/sunny and high humidity in cold/cloudy | Low precipitation in cold/sunny and high in cold/cloudy | High solar radiation in cold/sunny and low in cold/cloudy | Cold winds in winter | Very little vegetation in cold/sunny and abundant vegetation in cold/cloudy	17 to 24/20 to 30	4 to 11/17 to 21	(-7) to 8 /4 to 8	(-14) to 0 /(-3) to 4	25 to 25 /5 to 15	Low: 10-50% /High: 70-80%	Low: < 200 mm/yr /Moderate 1000mm/yr	Clear with cloud cover < 50% / Overcast for most of the year	Jammu &Kashmir, Ladakh, Himachal Pradesh, Uttaranchal, Sikkim, Arunachal Pradesh
Composite	This applies when 6 months or more do not fall within any of the above categories | High temperature in summer and cold in winter | Low humidity in summer and high in monsoons | High direct solar radiation in all seasons except monsoons high diffused radiation | Occasional hazy sky Hot winds in summer, cold winds in winter and strong wind in monsoons | Variable landscape and seasonal vegetation	32 to 43	27 to 32	10 to 25	4 to 10	35 to 22	Variable Dry Periods= 20-50% Wet Periods= 50-95%	Variable 500-1300 mm/yr, during monsoon reaching 250 mm in the wettest month	Variable Overcast and dull in the monsoon	Uttar Pradesh, Haryana, Punjab, Bihar, Jharkhand, Chattisgarh, Madhya Pradesh etc.

Fig. 1. Climate zones in India.
Source: Appendix E, ECBC, 2011.

studies for analyzing the energy consumption patterns and design strategies used for energy efficiency in buildings. The energy data and design strategies of the selected high-performance buildings are collected through a literature review. The performance of the buildings is compared to analyze the effectiveness of the various design strategies used in the buildings. Finally, the inferences obtained from the case studies are used to define appropriate design measures for reducing the energy consumption of buildings situated in composite climate.

The energy performance index (EPI), which is expressed in k Wh/m^2/year, is commonly used to compare the energy use of buildings. The EPI is obtained by dividing the annual total energy consumed by a building in kilowatt hours by the gross floor area of the building in square meters (Eq. (1); Tahir et al., 2015). The EPI is expressed as follows:

$$EPI = \frac{Total\ \ Energy\ \ Consumed\ \ in\ \ a\ \ year\ \ (kWh)}{Total\ \ Floor\ \ Area\ \ of\ \ the\ \ building\ \ (m^2)} \tag{1}$$

The methodology adopted for the review of design strategies comprises the following steps (Fig. 2):

1. Case studies are selected according to the selection criteria described in Section 3.
2. The case studies are summarized to obtain insight regarding the selected projects. The summary includes the year of completion, significance of the project, energy rating, and sustainable design strategies employed in the building. (Table 1).
3. The heating, ventilation, and air-conditioning (HVAC) and lighting loads of the buildings are compared. The influence of the design variables, such as the building plan configuration, building envelope materials, window-to-wall ratio (WWR), shading devices, and percentage of air-conditioned space (mix-mode ventilation), on the HVAC performance index is analyzed. The effect of the WWR and plan depth on the lighting performance index is assessed. The effect of the equipment and daylight sensor efficiency on the energy consumption is also noted.
4. The overall EPI of the selected buildings is analyzed in light of the aforementioned parameters and conclusions are drawn to frame effective passive design strategies for high-rise office buildings in composite climate.

3. Selection criteria for the case studies

The selected buildings were already evaluated using one of the rating systems or standards for high-performance buildings, and their energy performance data (metered or simulated) was available. The selected buildings were occupied for at least 2 years and have at least five floors. To expand the analysis, six buildings with different plan profiles (square, rectangular, L-shape, and I-shape), energy-saving strategies, and building envelope materials are selected.

The buildings selected for the case study are as follows (Fig. 3):

1. ITC Green Centre, Gurgaon
2. Wipro Technologies, Gurgaon
3. Infosys, Hyderabad
4. Volvo-Eicher Corporate Headquarters, Gurgaon
5. Indra Paryavaran Bhawan, New Delhi
6. Skyview Corporate Park, Gurgaon

From the selected case studies except for Indra Paryavaran Bhawan (IPB), energy consumption data have been obtained through simulation while IPB building energy performance data has been acquired through energy audit of metered consumption.

4. Case studies

Table 1 lists the details of the energy consumption and design strategies used in the selected buildings. However, to have the overview of the case studies, they have been discussed in brief below.

4.1. ITC Green Centre, Gurgaon

ITC Green Centre, located in Sector 3, Gurgaon, was one of the first buildings in India to adopt green building practices and is still considered a benchmark for green buildings (Fig. 4). ITC Green Centre, constructed in 2004, was the first platinum-rated building (scored 52 out of 69 points) in India. ITC Green Centre achieved the twin aims of allowing abundant natural light and reducing heat gain in the interiors by using advanced high-performance glazing solutions (HPCB, 2010; ITC Green Centre, 2017).

With a built-in area of 15,799 m^2 (of which 9294 m^2 is air-conditioned and 6505 m^2 is non-air-conditioned), the ITC building includes features such as solar thermal technology, reflective high-albedo roof paint, minimal exterior lighting, separate smoking rooms with an exhaust system, and zero water discharge (Fig. 5). More than 10% of the building materials were refurbished from other sites, and 40% of the materials were obtained from within 500 miles of the project site

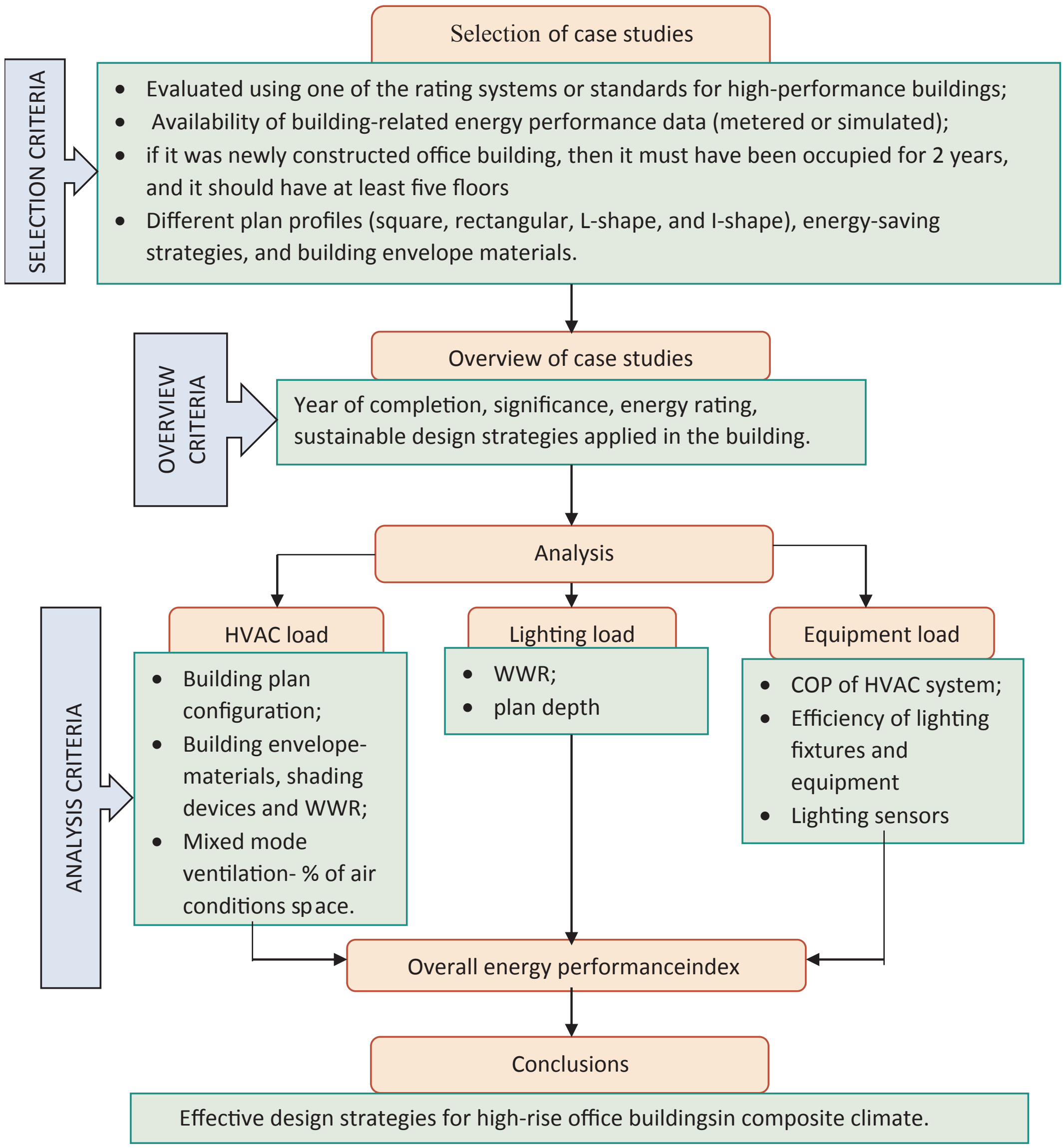


Fig. 2. Flowchart of the methodology used in the study.
Source: Author.

(HPCB, 2010; ITC Green Centre, 2017).

4.2. Wipro Technologies, Gurgaon

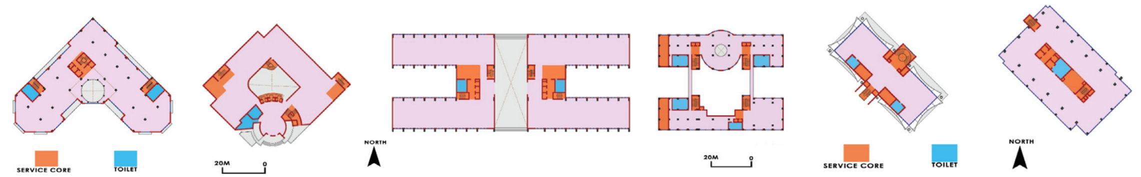
Wipro Technologies, Gurgaon, was honored by the US Green Building Council in 2005 with a Leadership in Energy and Environmental Design (LEED) platinum award (57 points), which makes it the second-highest platinum-rated green building in the world and the highest platinum-rated green building in India. The main focus of the design is the inverted cone strategically located at the cross junction of two roads, which provides visibility to the building (Fig. 6). The open-to-sky landscape courtyard is the most striking feature of the building, which keeps it cool during summers because the courtyard walls receive mutual shade and remain cooler than the outside walls (Fig. 7). Moreover, all the open office spaces overlook the courtyard, which consequently allows appropriate access to daylight and maximizes the outside view. The courtyard acts as a multifunction device, light well, microclimate generator, and social space (The 3C company, 2017).

A reduced overall heat conductance from the envelopes and features such as terrace gardens, high-performance glazing with optimum visual light transmittance, exterior light shelves, overhangs on all the windows, efficient chillers, efficient lighting, and sufficiently daylit interior spaces with photo sensor controls make Wipro Technologies an exemplary energy-efficient building (51% savings over the ASHRAE base case; ASHRAE, 2013). Moreover, the wood used for the construction of the building was sourced from shipwrecks at Jamnagar port (Design and Development, 2016).

4.3. Infosys, Hyderabad

Software Development Block 1 (SDB-1) in the Infosys campus, Hyderabad, has two cooling systems, namely a variable air volume (VAV) system and a radiant cooling system with a dedicated outdoor air system (Fig. 8), in the two halves of the building. Thus, the Infosys campus was the first radiantly cooled building in India, which resulted in the world's largest HVAC side-by-side comparison. Therefore, the building is highly instrumented to measure the influence of these two systems. After two years of operation, the radiant system, which is marginally cheaper than the VAV system, used 34% less energy and

Table 1
Details of the selected energy-efficient office buildings.



ITC Green Centre, Gurgaon — Wipro Technologies, Gurgaon — Infosys, Hyderabad — IPB, New Delhi — VECH, Gurgaon — Skyview Corporate Park, Gurgaon

		ITC	WIPRO	INFOSYS	IPB	VECH	SKYVIEW
Year of completion		2004	2005	2011	2014	2012	2015
Significance		Platinum-rated by LEED 52/69	Platinum-rated by LEED 57/69	Platinum-rated by LEED	Platinum-rated by LEED Five-star-rated by GRIHA	Platinum-rated by LEED World Architecture Award	Platinum-rated by LEED
Open plan/Cellular office		60% Cellular office + 40% Open plan	Open plan	Open + Cellular	Open + Cellular	Open	Open
% of air-conditioned space		59	65	70	38	100	100
Building configuration	Orientation	Long axis of the building oriented NE–NW	Square plan facades in the NE, SE, NW, and SW directions	N–S orientation	N–S orientation	NE–SW orientation	NE–SW orientation
	Placement of core	Central, East, and West	Central, East, and West	Central	Central and West	Central	Central
	Typical floor area (m^2)	2047	1726	4073	3150	1246	2730
	Total floor area (m^2)	15,799	16,258	24,730	31,400	9972	23,500
	No. of floors above ground	6 (2B + G + 5)	6 (2B + G + 5)	6 (G + 5)	8 (G + 7)	6 (2B + G + 5)	9 (G + 8)
	Floor-to-floor height (m)	3.6	3.6	3.6	3.9	3.6	3.6
	Aspect ratio	1:1	1:1	1:2.4	1:1.3	1:2.6	1:1.6
	Compactness ratio (perimeter/area)	9.9	9.5	9.7	16	17.5	10
	Plan depth (m) overall	24	13	18	15	17	34 (13 m from core)
Window parameters	**Overall WWR (%)**	33	35	25	20	80	55
	Shading device	Few windows shaded with horizontal louvers	Horizontal louvers	Recessed window	Box	Recycled railways sleepers used to make the double-curved louvers	No shading
	Sill level (m)	0.3	0.8	0.8	0.8	0	0
	Window height (m)	2.1	1.6	1.8	1.8	Full length	Full length

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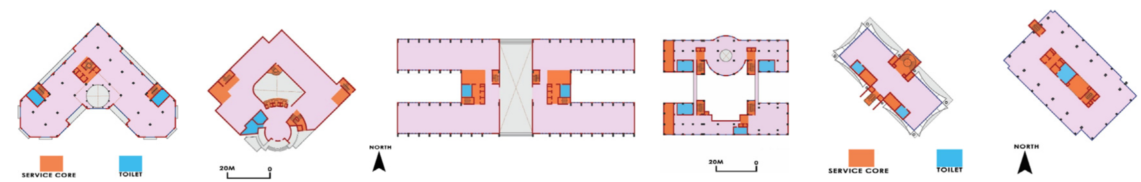
Table 1 (*continued*)



ITC Green Centre, Gurgaon | Wipro Technologies, Gurgaon | Infosys, Hyderabad | IPB, New Delhi | VECH, Gurgaon | Skyview Corporate Park, Gurgaon

		ITC	WIPRO	INFOSYS	IPB	VECH	SKYVIEW
Building envelope materials	**Wall assembly** U-value in W/m^{2}K	250-mm AAC block with 70-mm stone cladding and 12.5-mm plaster inside U-value: 0.607	Fly-ash-based AAC block blocks U-value: 0.63	Wall insulation and cavity wall with insulation U-value: 0.36	AAC block masonry wall and fly-ash-based plaster and mortar U-value: 0.34 Stone and ferrocement jaalis used in the circulation area	Cavity wall clad with tiles U-value: 1.1	Cavity wall U-value: 1.166
	Roof assembly U-value in W/m^{2}K	120-mm RCC roof with a 76-mm ISO board in the interior U-value: 0.335	75-mm extruded polystyrene reduces heat transmission by 50%. Roof finish with high-Reflection material Solar reflective index (SRI) > 78 U-value: 0.31	Roof with insulation U-value: 0.33 Cool roof: 2.6 million ft^2 area covered with a white roof Reduction of approximately 5% in the HVAC energy	150-mm RCC slab with insulation and local stones U-value: 0.5	Roof garden U-value: 0.25	Reflective insulated roof U-value: 0.3
	Glazing type U-value in W/m^{2}K	Double-glazing window (6-12-6), SC = 0.26, and U-value = 1.81 W/m^{2}K	6-mm glass + 12-mm air gap + 6-mm high-performance glass (ST150, light blue gray, U factor of 1.81 W/m^{2}K) 21% reflectance and 39% transmittance Reduction in the heat gain by 15–20%	Double-glazing with argon gas U-value less than 1.2 W/m^{2}K Low SHGC with low-e glass SHGC: 1.8	Double-glass windows with a high efficiency, visible light transmission (VLT = 0.6), and U-value (1.8) Light shelves for allowing the entry of diffused sunlight	Double-glass windows U-value: 2.1 SHGC = 0.697	Dual-pane low-e glass U-value: 1.8 SHGC = 0.629

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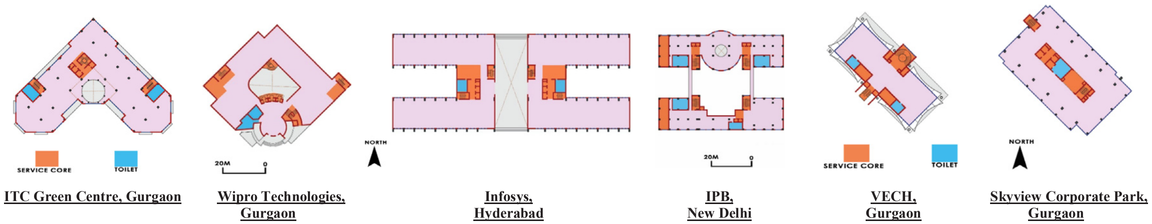
Table 1 (*continued*)



		ITC	WIPRO	INFOSYS	IPB	VECH	SKYVIEW
Occupancy & energy consumption	**Working hours**	10 h (5 days per week)	10 h (5 days per week)	8.5 h (5 days per week)	10 am–5 pm (5 days per week)	10 am–5 pm (5 days per week)	10 am–5 pm (6 days per week)
	Occupancy	not available (NA)	1305 people	2600 people	1000 people	NA	NA
	HVAC type and capacity ECBC recommends COP: 5.4	Central, 2850 kW capacity, 18 m^2/TR COP: 6.1	Central, 2285 kW capacity, 25 m^2/TR COP: 6.5	Central, 1400 kW capacity, 75 m^2/TR COP: 7	Chilled beam system of HVAC, geothermal technology for heat rejection, 563 kW capacity, 45 m^2/TR COP: 6.7	HVAC under the floor reduces energy consumption by 30% 2335 kW capacity, 15 m^2/TR COP: 6	High-efficiency filters in the HVAC system 6357 kW capacity, 13 m^2/TR COP : 5.4
	Lighting fixtures	T5 and CFL lamps (daylight sensors)	Light shelves, T-5, and CFL	Light shelves, T-5, and LED fixtures (daylight sensors)	Light shelves, T-5, and LED fixtures (daylight sensors)	Lights work on motion sensors and 95% are LEDs	T-5 and LED fixtures (daylight sensors)
	LPD ECBC recommends 10.8 W/m^2	7.2 W/m^2	5.4 W/m^2	4.8 W/m^2	5 W/m^2	4 W/m^2	9.5 W/m^2
	Method of acquiring energy consumption data (in available literature)	simulated	simulated	simulated	metered (energy audit report)	simulated	simulated
	Lighting performance index (kWh/m^2/year)	13	10	8.8	9.2	7	16.9
	HVAC performance index (kWh/m^2/year)	64	58	32.25	27	71	79
	EPI (kWh/m^2/year) ECBC energy benchmark: 179 kWh/m^2/year	93 (48% reduction)	85 (53% reduction)	51.85 (71% reduction)	45.25 (75% reduction)	96 (46% reduction)	112 (37% reduction)
	Renewable energy (kWp)	Photovoltaic cells for emergency lighting	NA	44 kWp SPV panels	930 kWp SPV panels	NA	NA

Sources:
HPCB (2010) for ITC Green Centre, Gurgaon.
The 3C company (2017) and Design and Development (2016) for Wipro Technologies, Gurgaon.
GRIHA (2018), Sagar (2013), and Sastry (2014) for Infosys, Hyderabad.
Prashad and Chetia (2014) and GRIHA (2017) for IPB, New Delhi.
Khosla (2017) and Singhal (2014) for VECH, Gurgaon.
Skyview Corporate Park (2017) for Skyview Corporate Park, Gurgaon.
NBC (2016) for the U-value of the wall, roof, and glazing assembly.

Fig. 3. Selected case studies of energy-efficient office buildings in composite climate.
Source: Various.

improved thermal satisfaction (Sagar, 2013).

Other strategies adopted to reduce energy consumption include suitably orienting the building (north–south orientation) and optimizing the WWR (< 30%) to reduce solar heat gain (Fig. 8). The use of external shading and light shelves maximizes the amount of daylight in the living area and reduces glare (Fig. 9). Features such as natural ventilation, an ECBC-compliant building envelope (Srinivas, 2005), water-efficient landscaping, low-energy green building materials, solar panels, energy-efficient fixtures with occupancy sensors, and wastewater recycling and reuse enabled SBD-1 to achieve a five-star rating from GRIHA (GRIHA, 2018).

4.4. Volvo-Eicher Corporate Headquarters (VECH), Gurgaon

VECH, located in Sector 32, Gurgaon, was designed by Romi Khosla Design Studios. The building received the World Architecture Award and LEED platinum rating in 2012. VECH was intended to be a state-of-the-art steel building with the minimum possible usage of energy and resources in its construction and operation (Singhal, 2014).

The VECH building has unique diagonally braced steel structure sets outside the main building envelope, behind which two square-shaped building blocks made almost entirely of glass and steel are placed to the east and west of a central circulation core (Fig. 9). The building structure is designed to have column-free space, which increases the amount of workspace available for offices, thereby allowing better daylight penetration in the building and providing flexibility for future realignments and reuse of the building space (Fig. 10). Moreover, a series of double-curved louvers are installed in the building. The louvers are inclined at certain angles for reflecting the sunlight such that an even light intensity is achieved throughout the office space. Therefore, negligible artificial light is required in the workspaces (Romi Khosla Design Studio, 2017).

A large proportion of reused materials and an extremely high percentage of renewable materials, specifically railway sleepers and tiles made from 30% recycled content, were used during the construction of the building (Fig. 11). The HVAC system runs under the floor and comprises a heat recovery system that reduces the air-conditioning load of the building by 30% (Khosla, 2017). Moreover, all the lights work on motion sensors, and the toilet and kitchen water is recycled.

4.5. Indira Paryavaran Bhawan (IPB), New Delhi

IPB has the highest green rating in India and is situated at Aliganj, Jor Bagh Road, New Delhi. The building has implemented energy and water conversation measures to comply with GRIHA's five-star certification and the LEED platinum rating. The building has two blocks facing the north–south direction, with a large open-to-sky court in the center, which allows cross ventilation and deep penetration of daylight into the interior office space (Fig. 12). The building is oriented such that it conserves natural areas and trees, which reduces adverse environmental impact (Fig. 13; Prashad and Chetia, 2014).

Other passive design features incorporated in the building for reducing its operational energy requirements include shaded landscaped areas to reduce the ambient temperature, insulated walls and double-

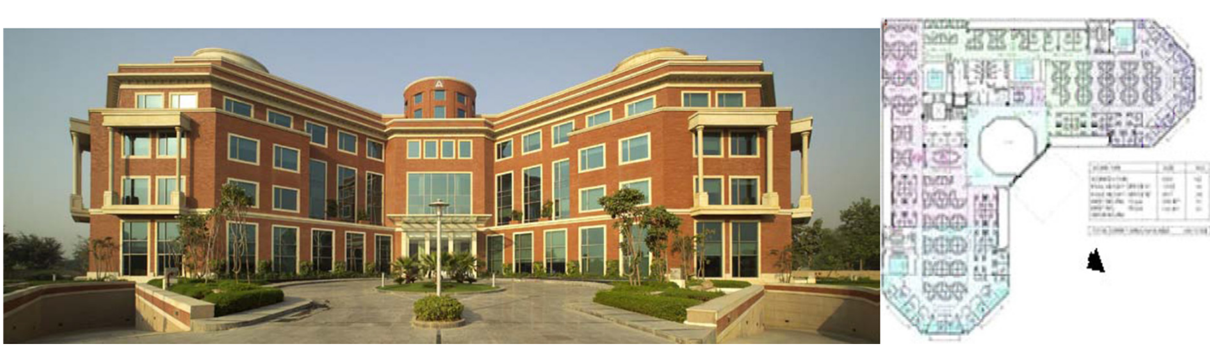


Fig. 4. View and plan of ITC Green Centre, Gurgaon.
Source: HPCB, 2010; ITC Green Centre, 2017.

Fig. 5. Shading devices and central atrium of ITC Green Centre.
Source: HPCB, 2010.

glass in fenestration to reduce heat transfer, use of recycled and locally available materials, and a user-friendly built environment (Fig. 13; GRIHA, 2017).

4.6. Skyview Corporate Park, Gurgaon

Skyview Corporate Park is a multiphase project developed on a 21-acre site that faces National Highway 8 (NH-8). Phase I of the corporate park was completed in 2015. The project achieved platinum certification under the Indian Green Building Council's LEED India program in 2015. The dual-pane, low-e, high-performance glass in the facade of the building decreases heat transfer, and the air-conditioning system, which includes a microfilter, increases the comfort of the office space (Fig. 14; Skyview Corporate Park, 2017).

5. Comparison of the design strategies used in the selected office buildings for energy efficiency

Table 1 presents the design strategies and energy consumption data for the selected buildings in composite climate. Areas with composite climate experience a constant high temperature and intense radiation throughout the year (excluding two or three months). Hence, design strategies that restrict heat gains and maximize daylight into the interiors reduce the total energy consumption in office buildings (Bano and Tahseen, 2017). Minimizing the surface-to-volume ratio (compactness ratio), placing service areas as thermal buffers on the hot sides, constructing a low U-value and shaded building envelope, and optimizing the WWR and plan depth are some of the strategies that reduce the HVAC and lighting loads of an office building in composite climate (Raji et al., 2016). The case studies are analyzed to investigate the effectiveness of the aforementioned strategies for reducing the HVAC and lighting loads of a building. Moreover, the ITC and Wipro; Infosys and IPB; and VECH and Skyview buildings were compared with each other because they had similar shapes, plan configurations, and energy consumption (Table 1).

5.1. HVAC load

In composite climate, approximately 50–60% of the operational energy of an office building is used for cooling. A decrease in the cooling load reduces the electricity bill. The design strategies used in the selected buildings for reducing the HVAC load are analyzed and discussed in the following text. The HVAC load is represented by the HVAC performance index (expressed in kWh/m2/year) in the Table 1. The HVAC performance is the total energy used by an HVAC system in 1 year divided by total floor area of the building.

5.1.1. Building plan configuration

The ITC and Wipro buildings have a similar aspect ratio (nearly 1), compactness ratio of the building plan (9.9 for ITC and 9.5 for Wipro), and orientation (plan rotated by 45°). Therefore, their design strategies and energy consumption are compared. The solar radiation from the east and west is reduced by mutual shading because of the L-shaped plan of ITC Green Centre, whose longer facades are in the northeast and northwest directions. By contrast, the Wipro building does not have any specific orientation. However, its compact square form reduces heat gains and losses from the building envelope (Raji et al., 2017). The courtyard of Wipro has multifaceted advantages. It acts as a light well, microclimate generator, and landscape element (Fig. 7). Moreover, it provides mutual shading to the courtyard walls, which keeps them cooler than the outside walls (The 3C company, 2017). The placement of the service core at an appropriate location in both buildings further minimizes heat transfer and reduces unpleasant glare from the east and west directions (Table 1). Moreover, the L-shaped plan of ITC Green Centre and square plan of Wipro Technologies (with a courtyard in the center) reduces the width of the floor plate (24 m for ITC Green Centre and 13 m for Wipro Technologies), allows daylight to penetrate deep into interior spaces, and provides an external view of almost every open office space (Figs. 4–7). The octagonal atrium has a side light at the top, which allows glare-free light to be directed into the interiors.

The Infosys and IPB buildings comprise twin blocks connected by a vertical atrium and horizontal courtyard and have aspect ratios of 1:2.4

Fig. 6. West-side view, east-side view, and site plan of Wipro Technologies, Gurgaon.
Source: Design and Development, 2016.

Fig. 7. View of the open-to-sky courtyard and terrace garden at Wipro Technologies, Gurgaon.
Source: Design and Development, 2016.

and 1:1.3, respectively (Figs. 8 and 13). Both buildings are oriented according to the path of the sun's rays, with the long axis oriented along the east–west direction to reduce solar heat gain. Moreover, they also provide mutual shading because of their plan configurations. The service core of the IPB building is placed in the west direction. Thus, the core acts as a buffer between the sun and the interior working area. By contrast, the service core of the Infosys building is placed centrally on the east and west facades. The slender shape (plan depth of 18 m for the Infosys building and 15 m for the IPB building) of both the buildings allows increased daylight penetration and a view of the scenic surroundings from most locations on the office floor plate (Prashad and Chetia, 2014).

VECH and Skyview Corporate Park are rectangular in shape, with aspect ratios of 1:2.6 and 1:1.6, respectively (Figs. 10 and 14). Both buildings are oriented in the northeast–southwest direction. The building orientation and plan configuration of both the buildings appear to be derived from the urban grid for maximizing the view. Environmental concerns were not taken into account in the design. The service core could have been used as a solar buffer on the hot east and west sides; however, the core is placed centrally. This could be the reason for the high HVAC performance index of these two buildings.

5.1.2. Shaded energy-efficient building envelope

The ITC and Wipro buildings have thermal-resistive building envelopes, which comprise 250 mm aerated concrete (AAC) block walls with a 70-mm-thick stone cladding, 12-mm-thick internal plaster (U-value of approx. 0.6 W/m^2/K), 75-mm thick extruded polystyrene slab (XPS) roof insulated on a 120-mm reinforced cement concrete (RCC) slab (U-value of approx. 0.3 W/m^2/K), and double-glazed window (U-value of 1.81 W/m^2/K) having a shading coefficient of 0.26. Consequently, the heat gain or loss and HVAC load of both the buildings decreases (HPCB, 2010). However, the HVAC performance index of ITC Green Centre is higher than that of Wipro Technologies possibly because only 20% of the windows are shaded and horizontal louvers are used in ITC Green Centre.

Similar to the ITC and Wipro buildings, the Infosys and IPB buildings also include an energy-efficient building envelope that decreases the HVAC load. A reflective roof, AAC block walls, a un-plasticized poly vinyl chloride (uPVC) window with composite sections, and a high-performance glazing (double-glazed with low-e coating) are used in IPB, which lowers the thermal transfer through the envelope (Prashad and Chetia, 2014). Similarly, the building envelope of the Infosys building allows a heat transfer of less than 0.75 W/ft^2 (Sastry, 2014). Moreover, a low WWR (28% for the Infosys building and 20% for IPB) and shaded (recessed) windows reduce the heat gain and requirement for high-efficiency glass.

The VECH and Skyview office buildings are completely air-conditioned, with their facades almost completely covered with full-height high-performance glass. The VECH and Skyview buildings have a WWR of 80% and 55%, respectively. Thus, the cooling load of the buildings increases because even a very-high-performance glazing allows approximately one-third of the solar radiation (solar heat gain coefficient (SHGC) = 0.3) to enter the building. However, the service core, which has a thick concrete wall along the center of the southwest facade, acts as a thermal buffer on the hot side and reduces the cooling load of VECH. Moreover, correctly angled doubly curved louvers restrict direct radiation and allow evenly distributed indirect radiation in the building. HVAC diffusers with a heat recovery system are installed under the floor, which results in a 30% reduction in the energy consumption for cooling. Therefore, the cooling load of VECH (66 kWh/m^2/year) is less than that of Skyview Corporate Park (74 kWh/m^2/year).

5.1.3. Mixed-mode ventilation system

A mixed-mode (natural and mechanical) ventilation system can effectively reduce the HVAC load. Circulation areas with tolerable marginal discomfort, such as lobbies and passages, can be naturally ventilated to reduce the load on the HVAC system. A large number of spaces, such as corridors and lobbies, in the ITC, Wipro, Infosys, and IPB buildings are non-air-conditioned spaces (Fig. 15a) with adequate natural ventilation (through jaalis in IPB). IPB has the lowest HVAC performance index (27 kWh/m^2/year) among the selected buildings because of its non-dependency on the mechanical system (62% of its area is naturally ventilated; Fig. 15b). The ITC, Wipro, and Infosys

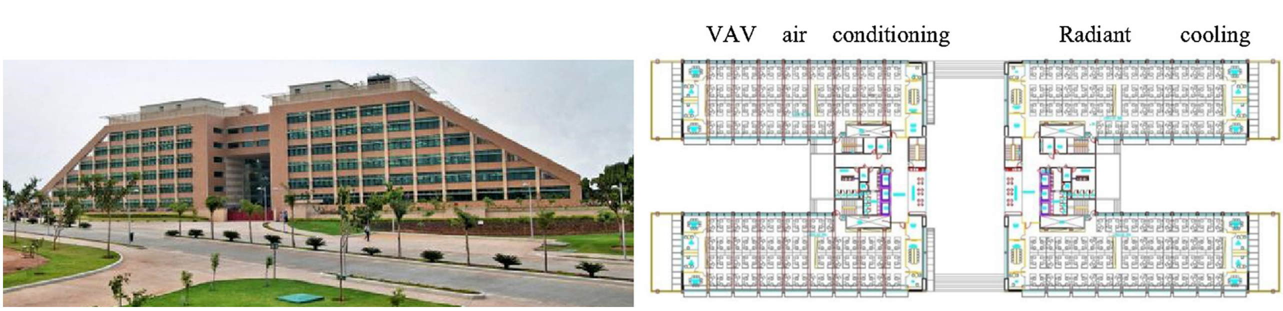


Fig. 8. North-side view and plan of Infosys, Hyderabad.
Source: Sagar, 2013; GRIHA, 2018.

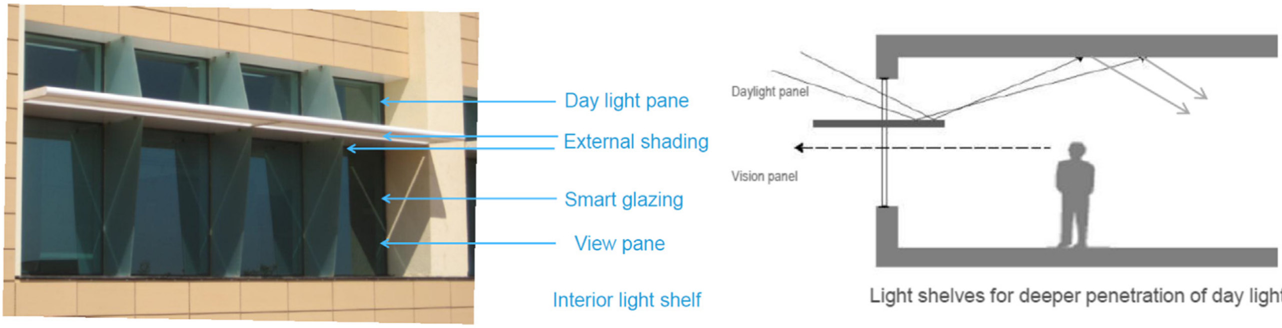


Fig. 9. External shading and light shelves used in SBD-1, Infosys, Hyderabad.
Source: Sagar, 2013.

buildings have an air-conditioned area ranging from 60% to 70% (Fig. 15a). Thus, the HVAC loads in these buildings may vary because of other reasons. However, the HVAC loads of the VECH and Skyview buildings are comparatively high possibly because the total area of the buildings is mechanically ventilated.

5.2. Lighting load

The lighting load is represented in terms of the lighting performance index (expressed in kWh/m2/year). The lighting performance index is the total energy used by the artificial lighting system in 1 year divided by the total floor area of the building.

The VECH building has the highest transparency (WWR of 85%) among the six studied buildings, with a depth of 8.5 m from the facade to the center (Fig. 16a). The slender shape of the building and its high WWR results in approximately 95% daylit office space. Moreover, the column-less building structure allows superior natural light penetration through the building and flexibility in workstation layout. Doubly curved louvers inclined at a specific angle are installed for the deep penetration and even distribution of daylight throughout the office space. All the lights work on motion sensors, and 95% of the lights are LEDs. Consequently, the VECH building has the lowest electricity consumption for lighting (7 kWh/m^2/year) among the selected buildings (Fig. 16b).

The Infosys and IPB buildings rank second and third, respectively, with regard to energy consumption for lighting (approximately 8.8 and 9.2 kWh/m^2/year, respectively). The Infosys and IPB buildings comprise two environmentally oriented (N–S) parallel blocks with a central void. The Infosys and IPB buildings have a plan depth (from the facade to the center) of 9 and 7.5 m, respectively. Thus, the offices in these buildings receive daylight from two sides. The WWR of the Infosys and IPB buildings are similar. However, the optimum plan depth of the IPB building causes a higher reduction in its lighting load compared with that of the Infosys building.

Similar to the Infosys and IPB buildings, the Wipro building has a central courtyard, which reduces the plan depth and WWR to 6.5 m and less than 40%, respectively. However, the unsuitable orientation and low central void width of the Wipro building may be cause of low distribution of natural light in the interior, which marginally increases the lighting performance index (10 kWh/m^2/year).

In contrast to the other four buildings, the ITC and Skyview buildings have deep plan offices, with plan depths of 12 m from the center and 13 m from the service core, respectively. Although the Skyview building has a high WWR (55%), its broad plan with a central service core has the highest artificial lighting demand (16.9 kWh/m^2/year). However, the placement of the service core on the external facade and near the central atrium with clearstory vertical windows reduces the lighting load of the ITC building.

5.3. Fixtures and equipment

Efficient HVAC systems having a coefficient of performance (COP) higher than 6 and energy-efficient lighting fixtures with motion sensors are installed in all the selected buildings. An energy-efficient chilled beam system is used in the Wipro and IPB buildings for air conditioning, which reduces the cooling load by 40% (Prashad and Chetia, 2014). In this air-conditioning system, the air flows around beams through which chilled water is circulated. Furthermore, geothermal technology is used in the IPB building for heat rejection from the water used for the cooling condenser. The radiant cooling system in the Infosys building and the installation of diffusers with a heat recovery system under the floor in the VECH building reduces the energy consumption by 30% (Sagar, 2013). Cooled surfaces are used to remove the sensible heat by radiation and convection through the radiant cooling system.

5.4. Comparison of the EPI of the selected buildings

The EPI of IPB is the lowest (45.25 kWh/m^2/year) among the selected buildings (Fig. 17) because of the passive features adopted in the

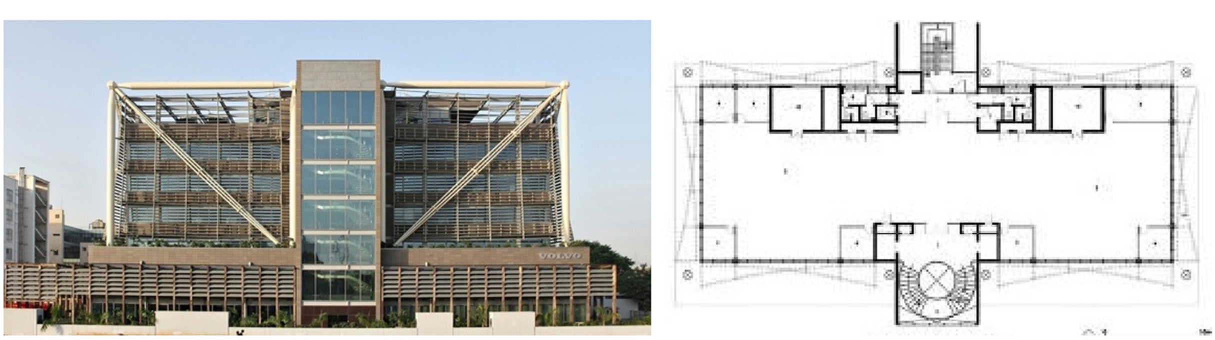


Fig. 10. Northeast-side view and typical floor plan of VECH, Gurgaon.
Source: Romi Khosla Design Studio, 2017; Singhal, 2014.

Fig. 11. Recycled wood used to clad columns and recycled railway sleepers used for making the louvers.
Source: Singhal, 2014.

Fig. 12. North-side elevation and view of the central atrium of IPB.
Source: Ministry of Environment and Forests, 2011.

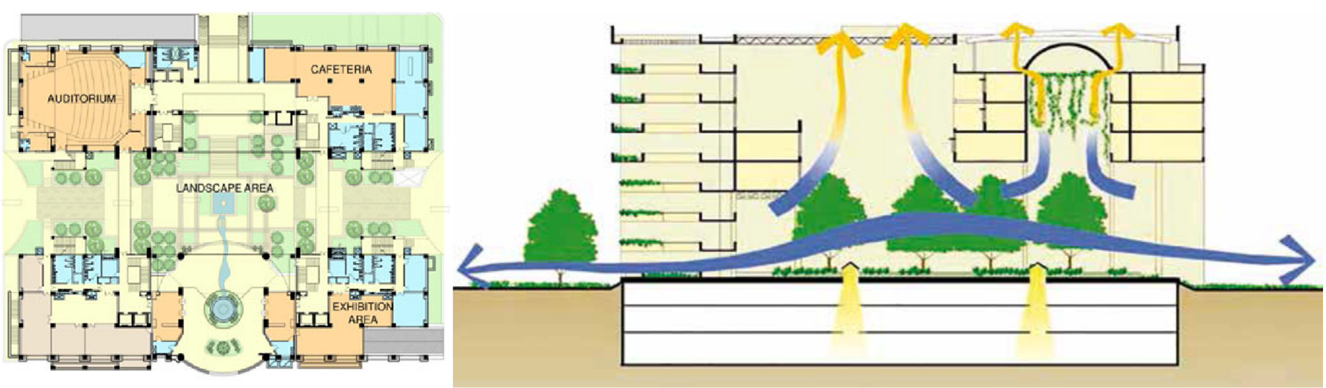


Fig. 13. Site plan and section indicating cross ventilation in IPB.
Source: Prashad and Chetia, 2014.

building design, namely the climate-responsive form and orientation, optimum plan depth and WWR, high percentage of naturally ventilated spaces, service core acting as a buffer space, highly insulated and shaded building envelope and HVAC system, chiller beams, and geothermal heat rejection system. Moreover, solar photovoltaic cells with a capacity of 930 kWp are installed on the terraces and projections. The solar cells produce an energy of 14,91,000 kWh/year, which exceeds the building's consumption (14,21,000 kWh/year). Thus, IPB is an energy-positive building.

Despite possessing all the passive design features of IPB, the Infosys building ranks second with regard to total energy consumption, which may be due to its high dependency on the air-conditioning system (70% air-conditioned space; Fig. 17).

The Wipro and ITC buildings have the same orientation, the same plan aspect ratio, an optimum WWR, and a mixed-mode ventilation system. However, the EPI of Wipro Technologies (85 kWh/m^2/year) is lower than that of ITC Green Centre (90 kWh/m^2/year) possibly because Wipro Technologies has a compact square plan; a reduced plan depth (6.5 m from the center to the outer facade) due to the presence of a central landscaped courtyard, a shaded external facade, and courtyard walls; and an environmentally placed service core.

The VECH and Skyview buildings are completely air-conditioned and have a high WWR. Although the facade of VECH is almost completely covered with full-height dual-pane glass (WWR 80%), its EPI

Fig. 14. Northeast-side view and typical floor plan of Skyview Corporate Park. Source: Skyview Corporate Park, 2017.

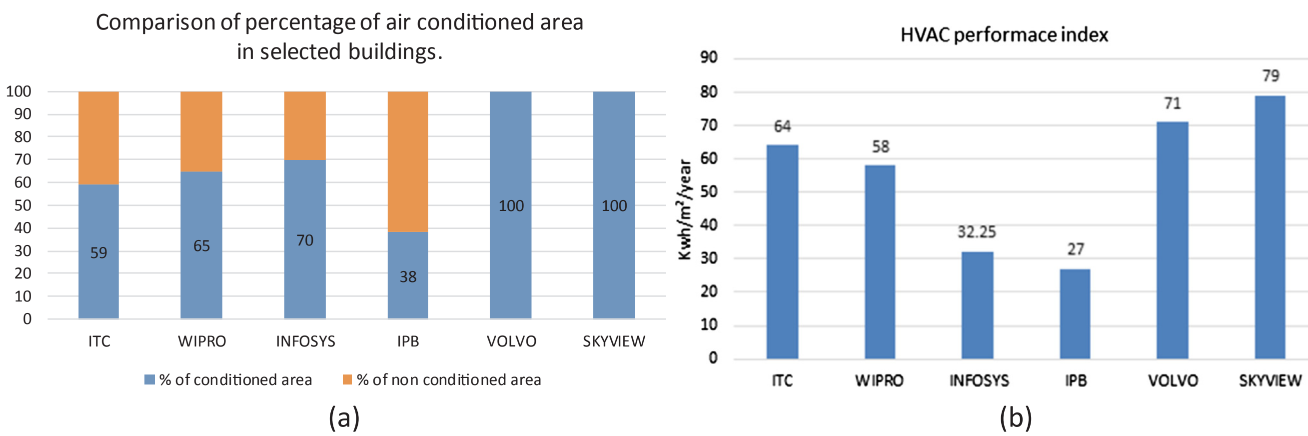


Fig. 15. Influence of the air-conditioned area on the HVAC performance of the selected buildings.

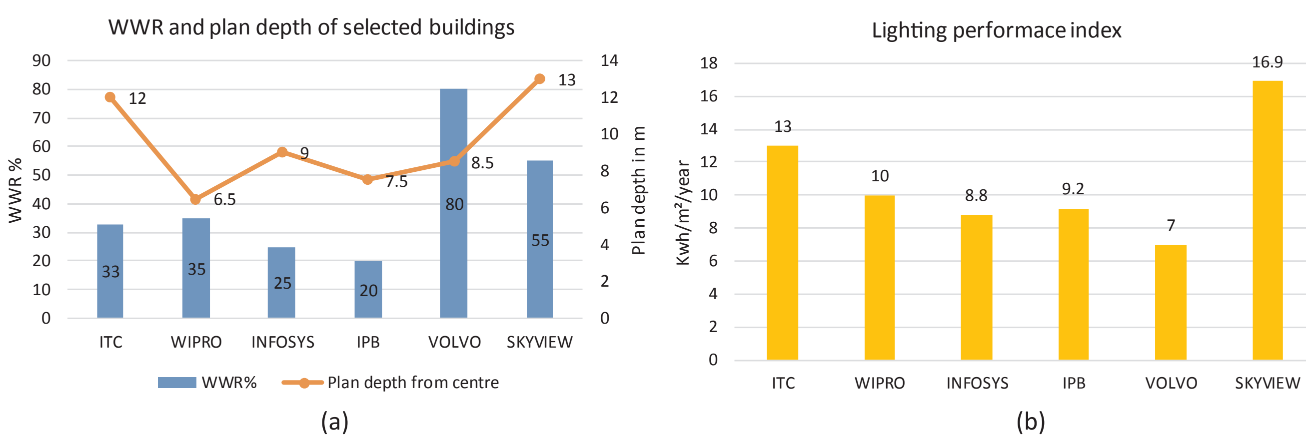


Fig. 16. Influence of the air-conditioned area on the energy performance of the selected buildings.

(96 kWh/m^2/year) is less than that of the Skyview building (112 kWh/m^2/year) because the location of the service core, presence of an angled doubly curved series of louvers shading the envelope, and location of the HVAC system under the floor reduce the HVAC load of VECH. Moreover, the slender plan and high transparency of the facade reduces the lighting load of the VECH building. The working hours of the Skyview building (6 days per week) are higher than those of VECH (5 days per week), which may be one of the reasons for the higher energy consumption in the Skyview building (Skyview Corporate Park, 2017; Khosla, 2017).

6. Conclusions

Effective design strategies for high-rise office buildings in composite climate are investigated through a comparative study of six sustainable office buildings. Although some design strategies reduce the lighting load, they increase the HVAC load of the building. Therefore, a linear building may sometimes exhibit better energy performance than a compact building. This research aims to determine the most-effective design strategies for reducing the HVAC and lighting energy consumption in energy-efficient mid- and high-rise office buildings in composite climate. The effective design strategies for buildings in composite climate are as follows:

1. Building envelope: The use of insulated (low U-value) walls, an insulated roof, high-performance dual-pane glass in fenestrations, and shaded windows can effectively reduce the HVAC load of buildings in composite climate.

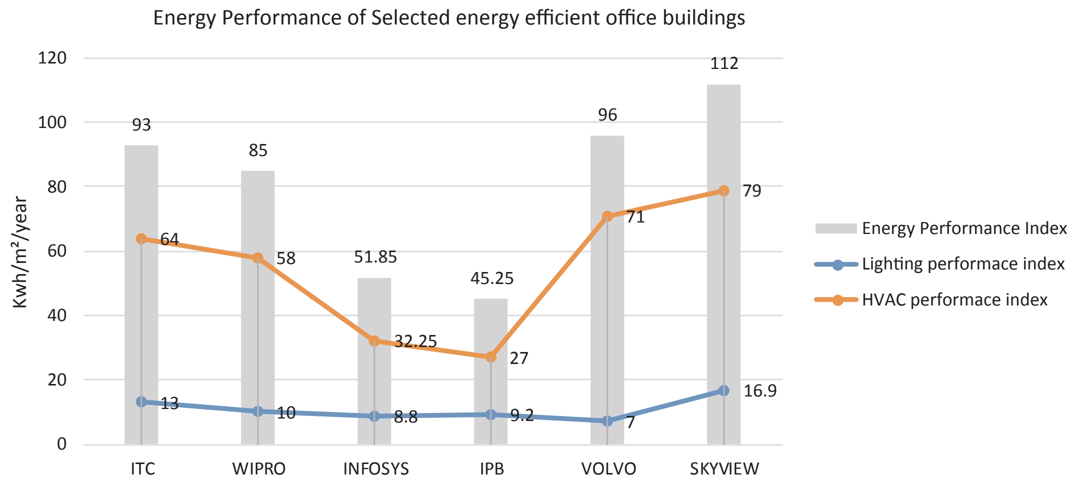


Fig. 17. Energy performance of the selected green-rated buildings.

2. Building plan configuration: Placing service areas with limited openings as thermal buffers on the west side and minimizing the surface-area-to-volume ratio are some of the strategies for controlling the heat gain and consequently reducing the cooling load. Moreover, placing the service core along the facade allows natural ventilation and lighting.
3. Mixed-mode ventilation system: The mixed-mode ventilation system can effectively reduce the energy consumption for cooling. The effectiveness of ventilation can be improved using special design elements, such as atriums and landscaped courtyards, which can increase the penetration of daylight into the plan.
4. WWR: A very low WWR reduces the cooling load. However, it also reduces the availability of natural light inside the building, which increases the lighting and heating load. The case studies indicate that the cooling and lighting loads of a building are reduced if the WWR is less than 40% and the maximum plan depth (between external facades) is 15 m.

The EPI of the six selected energy-efficient office buildings ranges from 45 to 112 kWh/m^2/year. The EPI benchmark for conventional office buildings in composite climate is 177 kWh/m^2/year (Bassi, 2015). Therefore, the energy savings of the selected buildings range from 37% to 75%.

A comprehensive analysis of the energy consumption for heating, cooling, and lighting can be performed by determining the monthly volatility in the total energy consumption of the selected buildings. Moreover, the influence of occupancy on the EPI of the buildings can be examined in future studies.

Conflict of interest

The authors declared that there is no conflict of interest.

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