Cost-effectiveness of active and passive design strategies in existing building retrofits in tropical climate: Case study of a zero energy building

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Abstract: This research investigated the first zero energy building (ZEB) in Southeast Asia which was retrofitted from an existing building and incorporated diverse passive and active design strategies for the tropical climate. The study disclosed the efficiency improvement through each individual design strategy and also compared the cost-effectiveness of active and passive categories. The most cost effective active strategy was efficient lighting; and the second was efficient air conditioning systems. The most cost effective passive strategy was lighting pies; and the second was lighting controls. Generally, passive strategies might have longer period of payback. It should be noted that the ZEB was a test-bedding project; therefore, the finding on passive design cost-effectiveness should be cautiously interpreted considering the scale of applications. The research suggests that active and passive strategies should be integrated into building design to optimize the energy performance. Particularly, passive design shall be applied in a large scale to have significant energy improvements.

Keywords: existing building; retrofitting; passive design; active design; zero energy building; cost-effectiveness

Acronym:

AHU	Air Handling Unit
AVA	Variable Volume Air
BMS	Building Management System
CAV	Constant Air Volume
DV	Displacement Ventilation
ETTV	Envelope Thermal Transfer Value
FCU	Fan Coil Unit
HVAC	Heating, Ventilation and Air-Conditioning
kWh	Kilowatt Hours
LPD	Lighting Power Density
MWh	Megawatt Hours
PV	Personalized ventilation
SC	Shading Coefficient
SCTF	Single Coil Twin Fan

1. Introduction

Energy consumed in the buildings sector accounts for 20.1% of the total delivered energy in worldwide (EIA, 2017). With more and more knowledge and deeper and deeper understanding of the amount of resources that buildings consume and their resultant impact on the environment, the building sector came under the spotlight of climate change and energy efficiency policy making (Berardi, 2017). Improving the energy efficiency of the existing building stock is one of most effective measures to reducing energy consumptions and carbon emissions in the building sector (Yudelso, 2009). Therefore, many governments and international organizations have put significant efforts towards energy efficiency improvement in existing buildings (Gou and Lau, 2014; Ma et al., 2012).

On the other hand, existing building retrofits attracted worldwide research attentions. It has been widely demonstrated that the largest source of energy consumption in buildings is

the HVAC (Heating, Ventilation and Air-conditioning) system (Bureau of Energy Efficiency, 2007). Therefore, a large proportion of building energy related research has been conducted on how to improve the performance of HVAC systems and reduce energy consumption by enhancing HVAC efficacy (Ma et al., 2013; Minh Thu and Sato, 2013; Vakiloroya et al., 2013).

In addition to HVAC, lighting retrofits hold great potential to reduce the energy use of existing buildings. Relevant strategies that had been investigated for retrofitting existing buildings include upgrading lighting systems (Benya, 2011; Kini, 2011; Nan Chen and Chung, 2011), implementing lighting controls (Poland, 2014; Ye et al., 2015) and optimizing daylighting (Acosta et al., 2015; Campo et al., 2010; Slobin, 2011).

Research has been widely conducted on glazing retrofits that aimed to reduce heat loss in winter or to reduce heat gain in summer (Cetiner and Özkan, 2005; Sekhar and Lim Cher Toon, 1998). Besides windows, another important envelope element that needs to be updated for most existing buildings is the exterior wall (Huang et al., 2012; Joanne et al., 2012; Pérez et al., 2014). Roof retrofitting including improving insulation, enhancing reflectivity and greening is another strategy that had been widely investigated (Al-Sallal, 2003; Jo et al., 2010; La Roche and Berardi, 2014).

Generally, energy efficiency retrofitting strategies can be categorized into passive and active solutions: active solutions involve refining heating, ventilation, HVAC systems, lighting and any other building services applications; while passive solutions aim to provide more energy efficient architectural components (such as building envelopes and roofs) to reduce the reliance on active solutions (Sadineni et al., 2011). Research usually showed that passive strategies had low extra capital investment cost compared to the potential benefit in energy saving (Abro, 1994; Jafari and Haghighi Poshtiri, 2017). Therefore, passive design is recommended in many green and sustainable design guidelines (Chen et al., 2015; Chen et al.,

2017a; Huo et al., 2017). However, passive solutions, such as daylighting and natural ventilation, are sensitive to climatic and outdoor conditions and therefore, have their limitations of applications (Al-Obaidi et al., 2014; Chen et al., 2017b; Gamage et al., 2017; Khambadkone and Jain, 2017). The debate about the two solutions (Zhang et al., 2011) call for research to provide further evidence on their efficiency and effectiveness in certain climatic context (Chen et al., 2017b).

This research investigates a real retrofitting project that incorporated diverse passive and active solutions in the tropical climate. The tropical zone has a hot and humid climate from 10° to 15° (north and south) of the equator. The tropical zone is an uncomfortable climate zone that receives a large amount of solar radiation, high temperature and high level of relative humidity (Al-Obaidi et al., 2014; Gou et al., 2018). The investigation has two objectives. The first objective is to understand the efficiency improvement through each individual design strategy and the second is to compare cost-effectiveness of active and passive design strategies for existing building retrofits in tropical climates. One of the main barriers for retrofitting existing buildings is financial risk and uncertainty (Miller and Buys, 2008). This research provides stakeholders and investors with a real retrofitting project and related evidence to support their decision making.

2 Building Specifications

The selected project is the first zero energy building (ZEB) in South-east Asia. The ZEB, located in Singapore, is retrofitted from an existing building (Figure 1). The main retrofitting project was completed in 2009 and continuous retrofits and tests are being conducted to this building, which provided rich resources and data for analyses. The ZEB had a series of retrofits involving envelope, green roof, lighting, shading system, HAVC and Building Management System (BMS). The basic information of ZEB is disclosed in Table 1. Figure 2 shows the floor plans of ZEB which was conceived with two primary objectives: 1) to serve

81 as a laboratory for the integration of green building technologies in existing buildings and 2)
 82 to be a hub for the study of energy efficiency and green buildings.

83
 84 Figure 1 Before (right) and after (left) retrofits for ZEB

85 Table 1 Basic information of ZEB

Project name	Zero Energy Building
Location	200 Braddell Road campus, Singapore
Completion date	October 2009
Gross floor area	4500 m ² (48,438 sq.ft)
Number of Floors	3
Year of operation	2010 to now
Cost	SG\$11 million (approximately US\$7.86 million)
Program	Government office and academic facilities
Owner	Building and construction Authority of Singapore
Award/certification	Singapore Green Mark Platinum

Figure 2 Floor plans of ZEB (From left to right: first floor, second floor and third floor)

Zero energy building is energy self-sufficient and produces as much energy as it uses (U.S. DOE, 2015). Both passive and active design strategies have been applied to reduce energy consumption in ZEB while renewable energy strategies (mainly solar panels) have been applied to provide the demanded energy after the reduction. Three key passive design strategies were adopted at ZEB: reducing heat transmission from building envelope, daylight utilization and improving natural ventilation. In addition, active solutions were applied to reduce the energy consumption as well. Active design strategies include energy efficient facilities and equipment, building management system with sensors and solar panels to generate electricity. The energy efficient systems include lighting system, air-conditioning system and ventilation system, which is essential to reduce the energy consumption. Solar panels were installed on the roof and façade with about 1,540 m² areas. It could generate about 207,000 kWh/ year electricity to supply ZEB. Table 2 lists out main retrofitting strategies used in ZEB.

Table 2 Energy efficient retrofitting strategies of ZEB

Design Strategies		Retrofitting
Passive design solutions	Reduce heat gains	Green walls and green roofs

		Low-emissivity glass
		Solar film coating
		Sunshade devices
	Enhance daylight	Mirror ducts
		Light shelves
		Light pipes
Energy-efficient building services	Increase natural ventilation	Solar assisted natural ventilation (Solar Chimney)
	Energy-efficient Air conditioning and mechanical ventilation	Single Coil Twin Fan system
		Variable Speed Drive
		Displacement ventilation system
		Under-floor cooling
		Personal ventilation system
	Energy-efficient Lighting	LED
		Task lights
		Dimmers
	Intelligent BMS	Sensors
		Building Management system
Renewable Energy system	Solar energy system	Solar panels

102

103 The building's performance was carefully monitored after the retrofit. The actual annual

104 electricity consumption was 183 MWh, about 23 MWh less than the predicted result. A

105 megawatt hour (MWh) is equal to 1,000 Kilowatt hours (kWh). This building saved

SG\$84,000 a year in energy and resources costs. The annual renewable energy production was 207 MWh, higher than the actual annual consumption which is 183 MWh. More details about the renewable energy and production could be found in Table 3 and in another research (Wittkopf et al., 2012). The present research focuses on energy efficiency strategies used to reduce energy demand.

Table 3 Energy saving details

	Estimated saving	Remarks
Energy saving	46.8	% saving compared to code compliance building
	388.72 MWh	MWh energy saving per year
	\$ 77,744	\$ Saving per year (assume 20 Singapore cents/kWh)
Renewable Energy	207 MWh	MWh collected per year
Water Saving	70%	% saving compared to code compliance building (operation phase)
	3620 m ³	Cubic meter savings per year (operation phase)
	\$ 5,502	\$ Saving per year (assume \$1.52/m ³)
Expected overall annual savings	\$ 83246	Energy + water savings

3 Data Collection

Case study method is used in this study. Rather than studying a large sample, this study concentrated on the ZEB project for an in-depth study in order to understand the phenomenon being investigated. The energy data mainly came from building simulation and real-time energy metering. The energy saving estimation for lighting and daylighting was based on the calculation of lighting power density and hours of switching off lights, which are specified, respectively in 4.1 and 4.2. The energy savings for windows, HVAC and solar chimney strategies were based on building simulation and the simulation details are specified in 3.1. The energy saving for greenery was based on the measurement and comparison of heat flux

of green and non-green surfaces.

3.1 Building Simulation

Building simulation was conducted for the ZEB to determine the energy savings due to different active and passive strategies compared to typical settings. A 19-zone thermal model was created for the building energy simulation of the ZEB. Detailed inputs of each zone were entered into the computer model for energy prediction of ZEB. Staircase and corridors were not modelled as thermal zones, however they were modelled as obstruction objects, which had only shading effects to the building. The software used for the building energy simulation of the ZEB is DesignBuilder and EnergyPlus. The climate data were based on ASHRAE's International Weather for Energy Calculation for Singapore. All simulating details can be found in the Appendix, which includes thermal zones, occupancy loads, air-conditioned and non-air-conditioned space, and HVAC settings. The occupancy loads for General Office ranged from 11.0 to 61.7 m² per person and the loads for Research Office ranged from 12.8 to 56.5 m² per person. Averagely, the ETTV for the referenced model was 49.71 W/m² and 43.79 W/m² for the proposed model, based on the design strategies specified in 4.3. The LPD was dramatically decreased due to the use of LED; therefore the LPD for the referenced model was 15 W/m² in the general offices while for the proposed model it was 5 – 7 W/m². The lighting and HVAC strategies used for the ZEB are specified in 4.1 and 4.4 respectively. The occupancy hours for lighting and HVAC operations were 8am-7pm, Monday – Friday.

3.2 Real-time Energy Metering

Besides building simulation, data were also collected from real-time energy metering and sub-metering. In the ZEB building, separate electrical and water sub-meters are installed on the various systems and services to facilitate monitoring of utility. The electricity

consumption is measured by terminal uses in four major categories: lighting, power & plug load, chillers & components, air distribution system and other auxiliary systems (including system losses). Electricity meters record the consumption separately in different areas of the ZEB building, covering first floor offices, visitor center, multi-purpose room, second floor classroom, library, third floor offices, experimental office, school hall, and common area. The consumption on usage are trended and compared for various months or periods of time by the BMS.

4. Energy Savings

In response to the two objectives, this chapter firstly discloses the energy efficiency improvement through individual strategy and secondly compares cost-effectiveness of key strategies used in this retrofitting project, especially active and passive strategies.

4.1 Lighting

The lighting system for indoor and outdoor areas of the original building consisted of mainly T5 fluorescent tubes. The energy consumption of the T5 lights is approximately 28 watts excluding electronic ballasts loss. Although T5 lighting was considered a relatively energy efficient solution during the last decades, advances in lighting technology have further pushed the frontiers especially with the introduction of LED (light-emitting diode) lighting. At ZEB, the T5 lights were replaced with energy saving LEDs along with a control system as a test-bed to study the impact on energy performance (Figure 3). Each LED panel was equipped with an intelligent sensor grid that could determine lighting levels according to occupancy conditions (Figure 4 left). Task lights were installed in workstations to provide personal control on lighting (Figure 4 right).

The installation and commissioning of the LED lighting system took place in February 2013. The lighting end use electricity bills from Sep 2012 to Jan 2013 were collected. The average consumption was 176kWh, and it dropped to 105 kWh from March 2013 to Nov

2013 after installing LED lights in Feb 2013. This indicated a 40% energy reduction based on typical office usage. Prior to the retrofit, the average monthly lighting energy used in that office was 176kWh, and it dropped to 105 kWh after installing LED lights. After testing LED lighting in this small-scale test-bed, a large scale LED lighting retrofit was conducted in the year 2014 for the common areas, classrooms and other offices. Table 4 shows that light power density significantly dropped due to the introduction of LED lighting. Compared with pre-retrofit settings, the lighting retrofitting saved 71,264 kWh energy in a year and the lighting control saved 2990 kWh annual energy at ZEB.

Figure 3 Original T5 lights (Left) and new LED lights (right)

Figure 4 Motion sensors (left) and task lights (right)

Table 4 Lighting Power Density (LPD) in ZEB

LPD (W/m^2)	ZEB
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	Pre-retrofit	Post-retrofit
Office	15	6.8
Library	15	5.9
Classroom/lecture room	15	9.5
Corridor	2.9	2.9
Staircase	6.0	2.0
Toilet	10.1	10.1
Average	10	5.3

4.2 Daylighting

Daylighting is a challenge at ZEB due to the deep floor plan which is 18 m for ZEB. Tinted glazing, shading devices and vertical green walls exacerbated the daylighting challenge. In response to the challenge, mirror ducts (Figure 5), light shelves (Figure 6), and light pipes (Figure 7) systems were integrated in the façade and roof system. An innovative design concept was to collect the zenithal light from the roof and façade and to redirect it to the deep space in ZEB. Mirror ducts were installed on the roof and east façade. Mirror ducts were a simple yet effective system that did not require any mechanical parts of electrical power to light up a space (BCA, 2014). Mirror ducts captured zenith daylight which was brighter than lateral daylight through external collectors. The light was channeled into horizontal reflective ducts installed in the false ceiling. The duct and collector both were equipped with a highly reflective material to reflect light. Light shelves were equipped with highly reflective materials, which could reflect daylight deeper into the building. As an external device on the façade, they also provided shading against direct sunlight. The work principle of the light shelves was similar to the mirror ducts. The efficiency of the light shelves at ZEB was improved via ceiling material that had a highly reflective coating (BCA,

202 2014). However, this was at the expense of color rendition, as the light appeared slightly
 203 yellowish at the exit opening (Stephen, 2015). Light pipes were installed on building's roof
 204 and direct sunlight into interior rooms. They were more energy efficient than skylights. There
 205 were two types of light pipes adopted at ZEB—one was equipped with rotating mirror
 206 installed on the roof and the other one without installed on the walls. The angles of the mirror
 207 could change according to the sun's trajectory in a day. The other type of light pipe had
 208 operable blades which could be controlled by the occupants inside the building. The users
 209 could open or shut it to adjust the amount of light entering the room (BCA, 2014).

210 The savings through light pipes were estimated by assuming that light pipes provided
 211 sufficient daylight for three hours per day on average; namely, the lights near the light pipes
 212 were switched off for three hours per day from 11am to 13:00pm. With the remaining lights
 213 controlled by dimmers, the lighting power was calculated as above and shown in Figure 8.
 214 The total daily energy consumption for artificial lighting for the zones was 80.2 kWh taking
 215 into account the power saved through dimming when daylight was available. If dimmers were
 216 not provided and the lights were turned on from 8:00 am to 19:00 pm in the above zones, the
 217 energy consumption would be 92.04 kWh. Thus there was saving of 12% through the use of
 218 dimmers. The energy saving due to light pipes was 550 kWh per year; the energy saving due
 219 to light shelves was 180 kWh per year; and the energy saving due to mirror ducts was 50
 220 kWh per year.

222 Figure 5 Mirror ducts installed in the East Façade at ZEB (Left) and openings provided in the

duct and false ceiling for light to come in and light up the space (Right)

Figure 6 Internal and external light shelves at ZEB

Figure 7 Light pipes with rotating mirror installed on the roof at ZEB

Figure 8 Hourly calculated energy consumptions with and without light pipes

4.3 Windows

Heat flow through windows approximately took up 27% of total heat gains for a building

(EIA, 2014). Ultra-violet (UV) film coatings on the glass helped to reduce UV rays and the sun's heat by reflecting them without comprising the visibility. As a result, air-conditioning load decreased with the reduction in heat gains. This translated to a cut in electricity consumption and cost. High resistance to heat flow (high R-value, low U-value) was important in air-conditioned buildings in tropics where energy using services were used to maintain a large temperatures difference between indoors and outdoors. The main direction of ZEB was west and east. The main glazing retrofit in ZEB was in west façade because the east façade had corridors which provided sun shading for the building. The west façade had the largest glazing area (Figure 9). Four different types of glazing were installed in ZEB's west facade (Table 5). The annual energy saving due to the glazing retrofit was 1250 kWh. The window film or solar coat retrofit could reduce the heat transmission through the glazing; however, it should not comprise the daylight. According illuminance measurements conducted by Grobe et al. (2010) and Wittkopf (2015) in the ZEB, there might be a comprise of daylighting due to the coatings.

Figure 9 Solar path analyses for ZEB

Table 5 Four types of glass uses in the fenestration of ZEB west façade

West façade	3 rd storey	2 nd storey	2 nd and 3 rd storey	2 nd and 3 rd storey	2 nd storey classroom m
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Type of glass	6mm thick tempered d sunergy clear glass	24mm thick tempered d sunergy green DGU glass	24mm thick tempered sunergy green DGU glass	6mm thick double glazed tinted tempered glass	6mm thick clear tempered glass
U-value	4.10	2.19	2.19	2.19	5.74
Shading coefficient of glass with solar control film	0.70	0.38	0.38	0.38	0.96
Method or external shading	Roof canopy	no	Lightshelve s	Lightshelve s	Sunshade/ no
Shading coefficient of external shading	0.76	no	0.50	0.60	0.60
Area in m ²	11.85	8.64	17.55	31.86	7.02/3.61

4.4 Air Conditioning

Three strategies were used to make air-conditioning system more efficient: energy-efficient air-conditioning with Variable Speed Fan (VSF), Single Coil Twin Fan system (SCTF), Displacement Ventilation (DV) System and Personalized ventilation (PV) System. The VSF system detected carbon dioxide levels and lowered fan speed (and thereby ventilation rates) when fewer people were around. It could save energy via monitoring occupants. Conventional drives only had uniform speed even during the periods when less

air-conditioning was required. Variable speed drive could switch to a slower mode when there was sufficient ventilation, and vice versa. Fan speed of the mechanical ventilated fans located at the walls could be adjusted by the controllers which could be easily found near the box next to the light switches. The SCTF was Singapore's invention, patented by the NUS and designed specifically for buildings in the tropics (Maheswaran et al., 2006). Normally, fresh air and re-circulated air were cooled and dispensed together in air conditioning system into the space; however, the cooling fresh air and the re-circulated air were separate in SCTF system, which reduced the energy use and provided ventilation on demand (Figure 10). Another strategy as shown in Figure 11 is displacement ventilation with underfloor cooling. Conventional ventilation systems were designed to supply air from the ceiling. The displacement ventilation system in ZEB supplied air from the floor via the under floor system and at a low velocity. This air which was slightly cooler than the ambient air will settle downstairs and spread out across the floor due to the gravity. Displacement ventilation system was energy efficient because it could supply air at a lower speed compare to the conventional ventilation system (Lin and Lin, 2014). The temperature of the air that was supplied could also be higher than that of a conventional system. Personalized ventilation system involved decided individual supply ducts that delivered cool fresh air to each individual occupant (Figure 12). A set of personalized ventilators was located on each occupant's worktable, allowing for individual adjustment of the air volume. The surrounding air-conditioning could be turned down and temperature of the ambient environment kept slightly higher without affecting the occupant comfort. This directly led to a reduction in the amount of the energy consumed to achieve the same cooling effect. Simulation between the systems used in ZEB and those conventional systems showed VSF leading to annual energy saving of 64,000 kWh, SCTF system leading to annual energy saving of 37,189.6 kWh, and DV and PV leading to annual energy saving of 3,410 kWh. Separate control of

fresh air and recirculated air was more energy efficient at 12% reduction in cooling capacity.

Figure 10 Conventional air-conditioning system and single coil twin fan system at ZEB

Figure 11 Displacement Ventilation System (left) and under floor cooling system (right) at ZEB

Figure 12 Personalized ventilation on each workstation at ZEB

4.5 Solar Chimney Ventilation

Among non-air-conditioned areas, the school hall (one-third of the gross floor area) was cooled by natural ventilation with solar chimney (Figure 13). Four chimneys on the roof were

the most visible part of the system where a series of hidden ducts were installed along the building facade. When the chimney heated up, hot air inside the space became lighter and rised due to the buoyancy effect and sucked warm indoor air through various inlets (Chung et al., 2015). And the outdoor ambient air would be drawn through the façade into the interior. The design of the solar assisted stack effect ventilation system was to enhance natural air movement using buoyancy principle (Khanal and Lei, 2011). The solar stack consisted of solar chimneys installed on the roof of ZEB with vertical ducts that were connected to the indoor air space via louvered openings (Wong and Heryanto, 2004). A 300 mm gap between the solar panels and the metal roof to allowed the air circulation. Extraction fans were installed in each chimney to provide the extraction when stack effect was not functioning. Through simulation comparison between two conditions: 1) natural ventilation assisted by the solar chimney system and 2) air-conditioning, the annual energy saving was 832 kWh due to shorter fan operating time. The simulation was simply based on the assumption of two different conditions. The results should be verified by in-depth investigation via Computer Fluid Dynamics. The relevant studies could be found in the studies by Tong et al. (2016a; 2016b).

Figure 13 Solar Chimney working principle and installation at ZEB

4.6 Greenery

The greenery at ZEB included both vertical and roof green systems. Vertical Green walls were installed in the west façade as a passive solution to reduce energy consumption for

cooling use (Figure 14). Besides producing oxygen, vertical greenery also had the benefits of reducing heat transmission and lessening the effect of the urban heat islands (Lin et al., 2017; Xue et al., 2017; Zhang et al., 2012). Less irrigation was required due to the plenty of rainfall in Singapore. Green roof was a 26.5 m² plot on the roof top of the staircase which was designed to accommodate natural soil and planting (Figure 15). This system could minimize heat entering into the building. The system could be viewed from an observation deck especially designed to showcase innovations of the building. The green wall and green roof in ZEB was a test-bed to see how much energy saving could be achieved through different kinds of green walls. There were three kinds of green walls being tested, which were panel type, planter type and cage type. The results of the measurement and test were concluded in Table 6 (Wong et al., 2011). The study showed that there was significant reduction on the surface temperature of the wall/ roof being shaded by the greenery systems. It could be seen that the planter type of the vertical green wall saved the most energy based on heat flux difference. Totally, the annual energy saving due to the greenery was 82.9 kWh.

Figure 14 Vertical greenery at ZEB

Figure 15 Roof greenery at ZEB

Table 6 Green wall and green roof energy savings at ZEB

Greenery System		Maximum Difference measured compared to a control wall			
		External surface temperature difference (°C)	Heat flux (W/m ²)	Ambient temperature difference (°C)	Energy savings based on heat flux difference (kWh/m ² /year)
Green wall	Panel type	10	4	2	4.16
	Planter type	16	3.5-5	2-3	5.72
	Cage type	6	1.75	2	2.86
Green Roof		24	53	7	70.2

5. Cost-effectiveness

ZEB is an exemplary project. It tried to optimize the retrofit measures. The cost and energy saving for the whole building are disclosed in Table 7. In general, after the retrofit, ZEB saved 46.8% energy compared to the previous setting; its EUI at 55.2 kWh/m²/year was much lower than that of a normal office building which was 243 kWh/m²/year (BCA, 2016).

However, its incremental cost due to green and energy efficiency was not a small number with the payback period over 40 years.

Table 7 Overall cost and energy saving of ZEB

	ZEB
Gross Floor Area	4502 m ²
Cost increase due to green features	2,235,717 USD
Unit construction cost	497 USD/ m ²
Total energy saving	46.8%
	388,720
	(kWh per year)
	Renewable Energy 207,000 kWh
	77,744 SGD (Assume 0.20 SGD /kWh) 54,600 USD (Assume 0.14 USD/kWh)
Energy saving per m ²	86.3 kWh/m ²
Payback Period	40.9 years
EUI after retrofit (kWh/ m ² /year)	55.20

To assess the cost-effectiveness of each strategy used in ZEB, this study applied a factor that is Cost Effectiveness. The equation of the calculation is as below:

$$\text{Cost Effectiveness} = \text{Annual Energy Cost Saving} / \text{Incremental Cost}$$

Cost Effectiveness of each retrofit strategy is disclosed in Table 8. It is obvious that passive strategies were much less cost-effective than active strategies. Among the active strategies, the most cost effective measure was efficient lightings. The second cost effective measure was efficient air conditioning system. Other cost effective measures included SCTF system and personal ventilation with underfloor air distribution system. Comparably, passive

solutions such as high performance glass and façade material with low U-value, mirror ducts, light pipes, light shelves and solar chimney assisted natural ventilation were not cost effective measures which costed too much to reduce one-unit electricity. The energy saving contributed by green roof was too small to be included in this calculation.

Table 8 Detailed cost and energy saving of each strategy used for ZEB

Category	List of strategies	Incremental cost (SGD)	Annual savings (SGD)	Cost Effectiveness	Payback (years)
Passive Energy Efficiency	High performance glass with low U-value	103567	275	0.0027	>100
	Mirror Ducts	163900	11	0.0001	>100
	Light Pipes	17365	121	0.0070	>100
	Light Shelves	177548	40	0.0002	>100
	Lighting controls	125000	658	0.0053	>100
	Solar Stack Ventilation	195260	183	0.0009	>100
	Average payback >100 years				
Active Energy efficiency	LEDs and other efficient lightings	27000	15678	0.5807	2
	energy-efficient air-conditioning with Variable Speed Fan (VSF)	150000	14080	0.0939	10
	Single coil twin fan system (SCTF) with ventilation on demand	275000	8182	0.0298	33

	Personal ventilation with underfloor air distribution system	21000	750	0.0357	28
	Average payback 5.4 years				

In total, there was 33% increase in the construction cost due to the green features (including the PV system). Figure 16 summarizes the contributions on incremental costs and energy savings from the two types of design strategies. Passive design costed almost the same as active design. Comparing their contributions to energy saving, only 5% energy saving was attributed to passive design while 40-45% energy saving was due to active design, among which lighting retrofits took up 12-17% and air-conditioning retrofits accounted for 23-28% of energy saving.

Figure 16 Contribution of passive and active strategies to total energy saving and incremental cost

6. Conclusion

As a demonstration project, Zero Energy Building (ZEB) at Singapore completed this

goal with the state-of-art energy-efficient technologies both passively and actively. From the in-depth study of ZEB, the most energy efficient retrofit measures for hot and humid climates were energy efficient lighting and high performance air-conditioning system. Lighting retrofit with LED efficient light was also cost-effective with short payback period. Energy-efficient air conditioning accounted for the largest portion of energy reductions at ZEB. Variable Speed Fan and Single Coil Twin Fan system had been approved to be energy efficient in ZEB. Averagely, passive strategies at ZEB were not cost-effective, which needed a longer payback period. In a real project, the acceptable payback period was usually less than 10 years. Among all passive solutions used in ZEB, window film seemed to be a simple and efficient method to improve the glazing performance for existing buildings, but its payback period was still long. Green roof in ZEB had little influence on energy performance of the building because of the limited area.

No doubt, passive design strategies are of great importance to reduce energy saving and enhancing human comfort. Passive design is also favored by many green architects in their sustainable design practice. However, in hot-humid climates with dense urban contexts, the passive design should be carefully used in existing building retrofits considering their cost and effectiveness because of the climate and density. Active solutions via lighting retrofits and air-conditioning improvements seem to be more cost-effective for retrofitting project under this circumstance.

It should be noted that ZEB is test-bedding project. The cost is caused by three factors which are economic of scale (the scope of work is too small to achieve economic of scale), fabricate products (some of proposed energy conservation measures and products are not available in the market), as well as risks and uncertainties. For example, the rooftop greenery is too small to have significant impact on energy saving. Future studies should select larger scale passive design projects to investigate their cost-effectiveness compared to

active design solutions.

There is some methodological limitation in this study. The method of calculating energy saving for each strategy is differing. For example, the energy saving due to lighting was estimated based on the assumption on lights switches while the energy saving due to air-conditioning was calculated via building performance simulation. The different methods might make the comparison biased. Therefore, the finding is not used to argue which strategy is more cost-effective; instead, the research suggests that active and passive strategies should be used in an integrative way into building design to optimize the energy performance. Particularly, passive design shall be applied in a large scale to have significant energy improvements.

Appendix A: Simulation details

A1. Thermal zones

Zones	Room Name	Floor Area (m ²)	Average Height (m)	Volume (m ³)
1	1st Storey Reception	210.92	3.6	759.31
2	Circulation area	143.73	3.43	493.47
3	1st Storey Testing Chamber	59.04	3.6	212.54
4	1st Storey Multipurpose Room	273.96	3.6	986.26
5	1st Storey Chilled Water Pump Room	85.02	3.6	306.09
6	1st Storey Store Room	46.3	3.6	166.7
7	1st Storey School Open Classroom	166.5	3.6	599.4
8	1st Storey School Class Room1	83.25	3.6	299.7
9	1st Storey School Class Room2	83.25	3.6	299.7
10	2nd Storey AHU Room	28.05	3.6	100.98
11	2nd Storey Library	647.2	3.6	2329.92
12	2nd Storey School Open Classroom	166.5	3.6	599.4

13	2nd Storey School Class Room2	83.25	3.6	299.7
14	2nd Storey School Class Room1	83.25	3.6	299.7
15	3rd Storey Research Office	282.66	3.1	876.23
16	3rd Storey General Office	308.7	3.1	956.97
17	3rd Storey School Hall	333	3.15	2096.24
18	3rd Storey AHU Room	59.62	3.21	382.14
19	Roof Space	615.63	3.18	1960.03

408

409 A2. Summary of air-conditioned and non-air-conditioned space

Uses	Air-conditioned (m ²)	Non-air-conditioned (m ²)
Office	591	0
School Hall	0	999
Toilets	0	50
Storage	0	111
Corridor	0	916
Atrium	199	0
Mechanical and Electrical	0	284
Staircase	0	360
Conference (Multipurpose Classroom)	274	0
Control room	12	0
Library	647	0
Testing Chamber	0	59
Classroom	377	0
Total	2100	2779

410

411 A3. Heat transfer of building envelope

Elements	Heat Transfer Coefficient	
	Reference Model	Proposed Model
Wall Construction	East Façade	East Façade

	<p>W4: U-value = 2.14 W/m²*K</p> <p>South Façade</p> <p>W3: U-value = 4.05W/m²*K</p> <p>West Façade</p> <p>W1: U-value = 0.29 W/m²*K</p> <p>W2: U-value = 0.51 W/m²*K</p>	<p>W1: U-value = 0.29 W/m²*K</p> <p>South Façade</p> <p>W3: U-value = 4.05W/m²*K</p> <p>West Façade</p> <p>W1: U-value = 0.29 W/m²*K</p> <p>W2: U-value = 0.51 W/m²*K</p>
Windows	<p>East Façade</p> <p>F1: U-value = 4.10 W/m²*K, SC=0.48</p> <p>F4: U-value = 5.50 W/m²*K, SC=0.85</p> <p>South Façade</p> <p>F2: U-value = 2.19 W/m²*K SC=0.38</p> <p>F4: U-value = 5.50 W/m²*K, SC=0.85</p> <p>West Façade</p> <p>F2: U-value = 2.19 W/m²*K SC=0.38</p> <p>F3: U-value = 4.10 W/m²*K SC=0.70</p>	<p>East Façade</p> <p>F1: U-value = 4.10 W/m²*K, SC=0.48</p> <p>F4: U-value = 5.50 W/m²*K, SC=0.85</p> <p>South Façade</p> <p>F2: U-value = 2.19 W/m²*K SC=0.38</p> <p>D1: U-value = 5.50 W/m²*K, SC=0.85</p> <p>West Façade</p> <p>F2: U-value = 2.19 W/m²*K SC=0.38</p> <p>F3: U-value = 4.10 W/m²*K SC=0.70</p>
Roof	U-value=0.22 W/m ² *K	U-value=0.22 W/m ² *K
WWR	0.41	0.41

412

413 A4. Main HVAC parameters

Elements	Reference Model	Proposed Model
HVAC System Type	Central Air-conditioning	Central Air-conditioning
AHU Fan Properties	<p>AHU Efficiency (VAV) = 0.74</p> <p>W/CMH</p> <p>FCU Efficiency (VAV) = 0.74</p>	<p>SCTF AHU Efficiency (VAV) =0.44</p> <p>W/CMH</p> <p>SCTF FCU Efficiency (VAV) =0.51</p>

	W/CMH FCU Efficiency (CAV) = 0.47 W/CMH	W/CMH Conventional FCU Efficiency (CAV) =0.19 W/CMH
Central Plant Efficiency	Plant Efficiency: 1.054 kW/RT Chiller Efficiency: 0.790 kW/ton Chilled Water Pumps: 0.117 kW/ton Condenser Water Pumps: 0.088 kW/ton Cooling Tower Fans: 0.31 kW/L/S	Plant Efficiency: 0.826 kW/RT Chiller Efficiency: 0.693 kW/ton Chilled Water Pumps: 0.056 kW/ton Condenser Water Pumps: 0.036 kW/ton Cooling Tower Fans: 0.208 kW/L/S

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