Conference Paper

Cost Optimum Design of Zero-Energy Residential Building

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Abstract

The continuous growth of population in sub-urban areas leads to increasing demand for mid-rise housing. Recent studies found that greenhouse gas emission in Indonesia continues to escalate at an alarming rate, and housing development is considered as one of the greenhouse gas contributors. Zero-Energy Residential Building, a highly energy efficient and low carbon housing design concept, is regarded as the answer for this environmental issue. Application of Zero-Energy Residential Building concept can reach almost zero sites electrical consumption and reduce greenhouse gas emission since this concept utilizes clean and renewable energy sources, e.g. solar cell, to generate electricity independently. However, this design concept has not been implemented widely since the utilization of solar panels, and other energy conservation components are still too expensive. This study is proposed to find out an optimum combination of design parameters that contribute to cost optimization housing design using sequential search algorithm. Comprehensive study literature and experiment using software are applied in this research. Hence, using the parameter combination in designing a mid-rise dense housing and Zero-Energy Building concept can generate optimum life cycle cost performance. As a result, the study concludes that the life cycle cost of optimized mid-rise Zero-Energy Building is better than the conventional mid-rise housing with annual electrical cost saving up to 98 percent.

Keywords: Zero-Energy Building, low carbon housing, energy efficient, design optimization, sequential search algorithm.

1. Introduction

Indonesia is currently promoting economic development which transforms the rural economy country to urban economy one. Indonesia cities have the fastest growing rate than in other Asian countries at a rate of 4.1 percent per year. In 2016, the urban population in Indonesia had reached 55 percent. By 2025 Indonesia can expect to have 68 percent of its population living in urban areas. In 2010, the urban area in Indonesia increased to 10,000 square kilometers, making it the third largest metropolitan area in Eastern Asia after China and Japan. The high-density urban area can put more pressure

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on existing infrastructure. From 2010 urban population in Indonesia soared from 7,400 people per square kilometers to 9,400 people per square kilometers, while the newly added urban land per new resident is the smallest amount of the region at 40 square meters [1].

The soaring growth of urban population drives the growth of apartment supply and demand. By the end of 2013 to early 2014, there is a significant increase in demand in dense residential building, e.g. apartment, as shown in **Figure 1** [2]. However, demand growth of dense residential buildings creates another environmental problem.

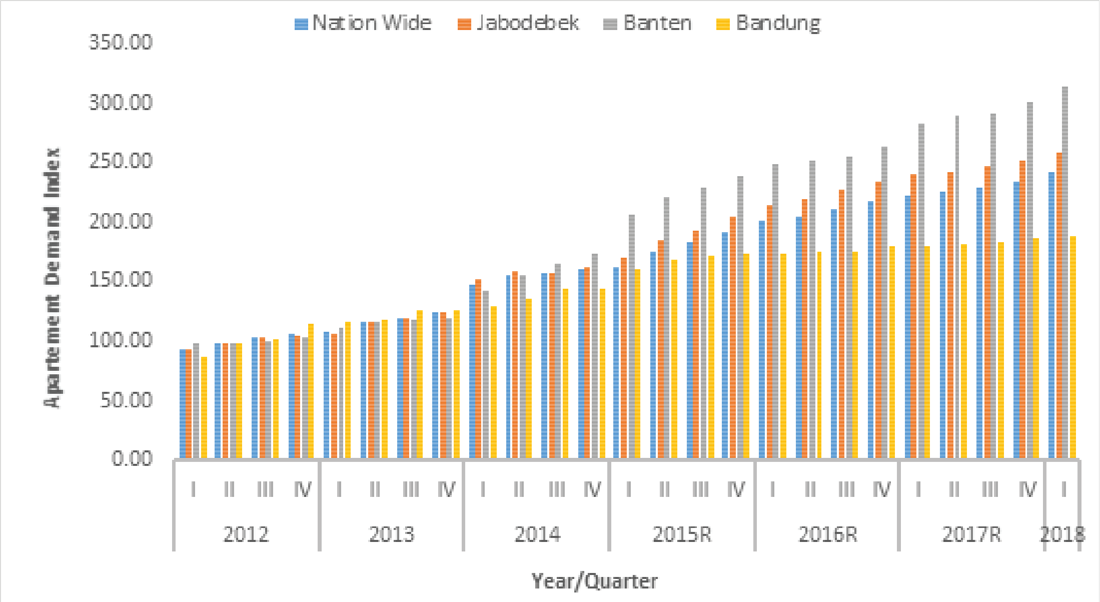

Figure 1: Apartment Demand Index Growth [2].

Centre for Energy Studies of University of Indonesia (Pengkajian Energi Universitas Indonesia, PEUI) in 2006 reported that in the last ten years there had been a significant increase in greenhouse gas (GHG) emission from various sectors as from housing and electrical generation (energy) sector, as shown in **Figure 2**. This 2006 report is confirmed by INDC (2015) that by 2017 total GHG emission level has reached 453 Metric Ton. If Indonesia continues to develop its housing and energy sector using the business-as-usual (BAU) scheme, the GHG emission will continue to rise at 6.7% per year, and by 2030 it will reach 1,669 Metric Ton.

Improving the energy performance of the residential buildings using energy saving materials and utilizing on-site renewable energy technology (RET) can be a solution to this issue. A design concept namely Zero-Energy Building (ZEB) is a concept for residential buildings that can minimize the energy consumption while at the same time independently generate on-site electricity from clean and renewable sources, i.e., photovoltaic (PV) panels [4]. Haslam and Farrell (2014) also define the ZEB as a building

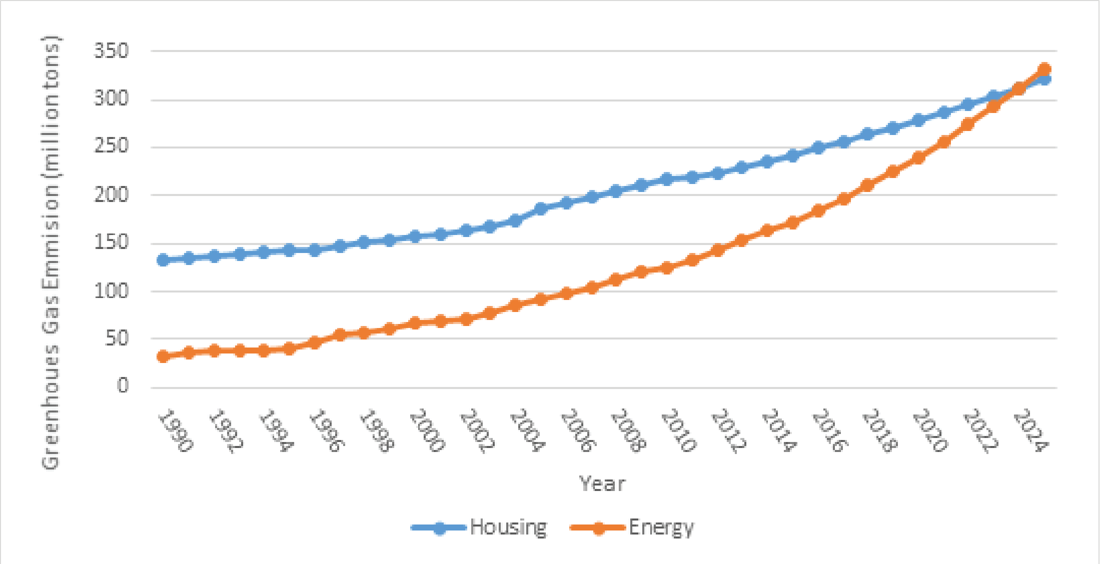

Figure 2: Greenhouse Gas Emission Projection *[3]*.

which consumes less electricity than the electricity it generates on-site. This concept is a realistic solution for the reduction of GHG emission from energy and building sector [5]. The ZEB design concept has been adopted around the world. Canada has Ecoterra, a nearly Zero-Energy House (nZEH) equipped with PV panels. This house consumes 50.8 kWh/m2.y of electricity, while its PV panels generate 16.35 kWh/m2.y. Leaf House, Italy, is a residential building which also utilizes PV panels as the renewable energy source. Leaf House annual electrical consumption is 151.24 kWh/m2.y while its PV panels generate 128 kWh/m2.y. Plus Energy Houses in Austria consumes 129.5 kWh/m2.y of electricity annually while its PV panels generate 150.4 kWh/m2.y. All of these examples come from arid countries, where the sun does not shine throughout the year [6].

Indonesia as a tropical country, where the sun shines throughout the year, have the most significant potential for the development of nZEH that is integrated with PV panels [7]. However, this potential has not been fully explored due to the high cost of energy-saving materials and renewable energy technologies [8]. Most energy-saving and renewable energy technologies are still expensive and will directly affect the entire initial construction cost of a building [9]. Highly efficient energy building should be financially feasible to use widely [10]. The objective of this paper is to find optimum cost design which will create a high energy efficient building by minimizing operational costs without significantly increasing the initial construction cost.

2. Theoretical Framework

2.1. Zero-energy building

A building with a Zero-Energy Building concept uses electricity generated independently from clean and renewable sources for its consumption [11]. By that definition, an ideal application of this concept should first prioritize energy efficiency, the utilization of renewable energy sources available on-site [4]. To achieve the zero-energy consumption, the primary approach in designing buildings with a Zero-Energy concept is by following these steps (Fig 3):

Passive strategies by applying passive design are the first and most essential step toward Zero-Energy building. Passive design is a design concept which exploits the climate to sustain indoor temperature at a comfortable level, by minimizes auxiliary heating and cooling [12]. Therefore this concept contributes significantly to the Zero-Energy design by directly reduce energy consumption for mechanical ventilation systems and building electricity [13, 14].

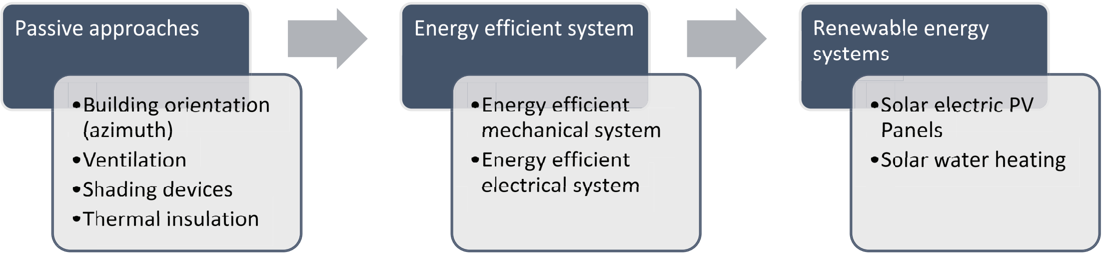

Figure 3: Zero-Energy Design Strategy [30].

Energy efficiency system has a significant contribution to reducing total building energy consumption [15]. The objective is to maximize energy efficiency measures by minimizing the costs of energy, i.e. electric bills utilizing preventing energy wastefulness, and possibly reducing carbon dioxide (CO^2) emissions [16]. The use of energy efficient lighting and electrical equipment are an advanced strategy to achieve zero-energy buildings [17].

Achieving zero-energy consumption is not only accomplished by reducing energy consumption using passive design and utilizing energy efficient appliances but also balancing the consumption and energy production from renewable sources, e.g. solar PV panels [18]. As discussed in [4] and [11], optimizing the energy balance in a zero-energy building can be realized by connecting it to the central electrical grid so that the surplus electrical energy can be exported.

2.2. Design parameters

Latief et al. [19], as shown in Table 1, the suitable design parameters for a tropical zero-energy house (ZEH) are identified. The objective of applying passive design for the tropical residential building is to minimize the amount of heat radiation into the house.

TABLE 1: Tropical ZEH Design Parameters *[19]*.

No.	**Design Parameters**	**Sub-Parameters**
1.	Passive Design	Building orientation (azimuth)
2.	Construction Specification	Roof
		Attic
		External door
		Window
		External wall
3.	Fenestration	External shading
		Glazing
4.	Lighting	Artificial lighting
		Natural lighting
5.	PV Panels	PV Capacity
		PV Azimuth
		PV Tilt

3. Methodology

Thus, to achieve the purpose of this paper, research will apply an experimental method using sequential search algorithm-based software and life-cycle cost analysis. A building energy simulation software then is used to simulate the energy performance of buildings as well as find the optimum cost combination of design parameters with the sequential search algorithm. The generated design combination then will be analyzed using a life cycle analysis to find the whole building Net Present Value (NPV).

3.1. Simulation and optimization approach

The optimization method is used to find the optimum combination of costs in a simulated environment. The sequential search algorithm previously applied has been used in some similar research by Horowitz [20], Christensen et al. [21], and Ihm and Krarti [22].

This simulation runs as the first step is creating a building model that will be simulated. This research simulates a 5-story apartment building with a total building area of 2700 square meters (or 29250 square feet). Each floor consists of 10 units of apartments with corridors, as shown in the following floor plan (**Figure 4**). This apartment consists of 50 residential units, with 40 units of 54 square meters area equipped with two bedrooms and one bathroom; and ten corner units of 60 square meters area with three bedrooms and two bathrooms.

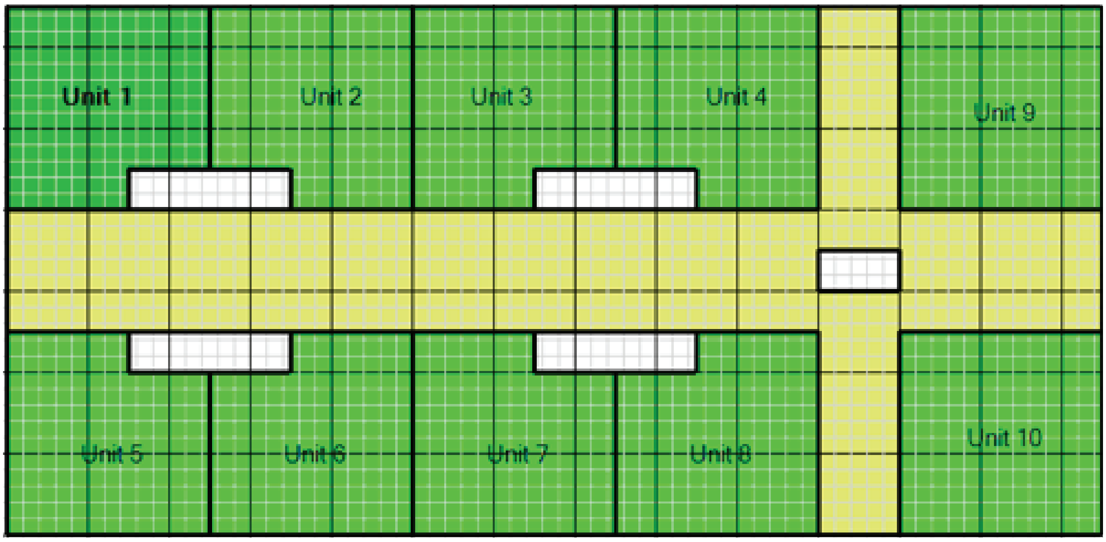

Figure 4: Typical Floor Plan Ground Floor to 5th Floor of the Building Sample.

The reference design for the apartment building is summarized in table below. This reference design is developed from preliminary study on typical apartment building in Indonesia.

Table 2: Sample Building Characteristics.

Number of floors		5 stories
Total built area		2,717.41 m^2
Floor area	Regular units	54 m^2
	Large units	60 m^2
Number of bedrooms	Regular units	2
	Large units	3
Number of bathrooms	Regular units	1.5
	Large units	2
Cooling set point		24°C

In this research, the most influencing design parameter to the energy consumption in a tropical residential building will refer to Latief et al. [19] findings. These design parameters will then be combined with different specifications for each parameter and sub-parameter design. Variants of sub-parameters are described in Table 3 below.

The combination of the design parameters will be simulated using Building Performance Simulation (BPS) software that uses weather data in tropical climates. The

Table 3: Design Parameters and the Variations that will be used in the Experiment.

Design Parameter	**Specification**	**Number of Variations**
Building azimuth	Orientation of the building	16 variations
Roof	Roof material specifications	13 variations
Attic	Attic insulation materials	44 variations
External walls	Wall materials	26 variations
Wall Insulation	Wall insulation material	7 variations
Floor mass	Floor slab material	3 variations
External door	External door materials	3 variations
Window	Sills materials and glazing	26 variations
External shading	Shading structure design	28 variations
Room AC	Air Conditioner specifications	10 variations
Artificial lighting	Lightbulb specifications	25 variations
Natural lighting	Window-to-Wall ratio	11 variations
PV capacity	PV generation capacity	25 variations
PV azimuth	Orientation of the PV Panels	9 variations
PV tilt	Tilt of the PV Panels	14 variations

simulation result will be compiled for later testing with an objective optimization function using a sequential search optimization algorithm. If the result of the parameter design combination is not considered meeting the criteria of the set objective function, then the simulation of the building model will be repeated using BPS.

The objective function of the optimization algorithm used in this paper is the net energy consumption of the building. The objective value that the algorithm must achieve is translated according to equation (1) as follows:

$$E_{netto} = E_{Hot\ water} + E_{HVAC} + E_{Fan} + E_{Lights} + E_{appl} - E_{PV} \tag{1}$$

where E_{netto} is the net annual energy consumption of the whole building; $E_{Hot\ water}$ is the annual electrical consumption for water heater; E_{HVAC} is the annual electrical consumption for mechanical cooling and heating system; E_{Fan} is the annual electrical consumption for ventilation fan; E_{Lights} is the annual electrical consumption for artificial lighting; E_{appl} is the annual electrical consumption for appliances; and E_{PV} is the annual electrical generated from PV panels that will offset the annual building electrical consumption.

3.2. Life cycle cost analysis (LCCA)

Zero-Energy buildings usually have more expensive initial (construction) cost than other conventional buildings. Those situation is due to the utilization of energy saving and renewable energy generator technology, e.g. PV panels, automated HVAC controls, LED lights, etc. This technology, although generally expensive, can reduce energy consumption in a building to reduce the cost of electricity (operational) monthly. These electricity cost savings occur during the operational life of a building, and the benefits are gained during the life of the building. Therefore, to prove the cost performance of this building, it is essential to use a life-cycle cost analysis method that can take into account the cost savings during the operational period of the building [23].

In this paper, the LCCA will calculate the Net-Present Value (NPV) of the incremental life cycle cost which will be defined by Equation (2).

$$\Delta NPV = \Delta IC + \Delta (USPV\,(n,\ i) * EC) \tag{2}$$

where [24],

- ΔNPV is total incremental Net Present Value of the whole life cycle cost. If ΔNPV < 0, then the incremental costs incurred are financially feasible. If ΔNPV > 0, then the incremental cost incurred are not financially feasible;
- ΔIC is incremental initial cost for procuring and constructing the zero-energy building based on design parameters. If ΔIC < 0, then then there is a reduction in the initial cost of construction, while if ΔIC > 0, then then there is an addition to the initial cost of construction;
- EC is annual Electricity Cost to operate the whole building and to maintain comfortable indoor temperature. It is derived from the site energy consumption (kWh) times electricity cost per kWh;
- USPV is Uniform Series Present Value factor which influenced by annual discount rate i and life time n;
- If $\Delta(USPV\,(n,\ i) * EC) < 0$, then there is an annual reduction in electricity costs resulting from energy savings and energy reductions from PV panels. If $\Delta(USPV\,(n,\ i) * EC) > 0$, then there is an additional annual electricity cost resulting from excessive electricity usage.

The analysis is set for n = 25 years and the adjusted with inflation and tax annual discount rate to i=4.8 percent. In order to calculate the annual electricity bill, the electricity rate in Jakarta is established to 1,467.28 IDR/kWh. The simulation applies PV panels in the model building, so the life cycle cost analysis also takes into account the net-metering renewable energy incentives applicable in Indonesia. The net-metering incentive regulation in Indonesia refers to the Rules of Directors of PT. PLN number 0733.K/DIR/2013 on the utilization of electrical energy from photovoltaic by customers.

4. Optimization Result and Discussion

4.1. Optimum design selection

The simulation and optimization process took 1 hour, 27 minutes, and 56 seconds to find the optimum design. The summary of the selected optimum combination of design parameters is shown in table 4.

From the simulation, it is found that orienting the front face of the building, where the large openings, e.g. main doors are arranged should not facing directly towards the sun to minimize the heat penetration. Large openings should avoid facing directly towards the sun to reduce the heat penetration into the building. In addition to sun, wind direction also affects the quality of natural ventilation and thermal comfort in the room of a building. Although the main facade is facing north, it is not necessarily north orientation is the optimum one because there is a wind direction factor. Simulation results conclude south-south-west direction when both factors are considered.

Roof material, attic insulation, external door material, window type and glazing, wall material, wall insulation, and floor slab material are building envelopes structures that have significant influence to the thermal comfort of the building. One way to maintain the comfort of indoor temperature is to choose building materials that are slowing the rate of heat from the outside into the building. An insulating material's resistance to conductive heat flow is measured or rated in terms of its thermal resistance or R-value where the higher the R-value, the greater the insulating effectiveness. The roof cover is the first building material to receive heat from the sun during the day. Terracotta tile has smaller absorptivity than asphalt shingles but slightly larger emissivity. Thus, the terracotta tile reflects more heat than absorb it. Insulating the attic can also restrain the heat penetration rate into the building. The R-30 cellulose has enough R-value to insulate the attic effectively. Ventilation also is necessary to remove the residual heat. For wall material, 20 cm hollow concrete brick is the optimum choice to protect heat from outside the building without having to increase the construction cost significantly. For the simulation of wall material, it was found that the dimensions of the hollow concrete brick affect the resistance value to heat. Fifteen-centimeter hollow concrete brick, which

Table 4: Selected Optimum Combination of Design Parameters.

Design parameters	**Specifications**	**Design Specifications**	
		Reference Design	**Optimized Design**
Building azimuth	Orientation of the building	North	South-south-west
Roof	Roof material specifications	Dark asphalt shingles	Terracotta tile
Attic	Attic insulation materials	Uninsulated, vented	R-30 cellulose, vented
Walls	Wall materials	15 cm hollow bricks	20 cm hollow bricks
Wall Insulation	Wall insulation material	Double 1.6 cm drywall	Double 1.6 cm drywall
Floor mass	Floor slab material	Wood surface	5 cm gypsum concrete
External door	External door materials	Fiberglass	Wood
Window	Window sills materials and glazing specifications	Double pane, low- E, low gain, non-metal sills	Double pane, low-E, low gain, non-metal sills
External shading	Shading structure design	None	61 cm of eaves and 61 cm of overhang on all windows
Room Air Conditioning	Air Conditioner specifications and settings	Not regulated	Energy Efficiency Rate 10.7, 30% conditioned
Artificial lighting	Lightbulb specifications	100% CFL lightbulbs	40% hardwired LED and 34% plugged in CFL
Natural lighting	Window-to-Wall ratio	15 % on all direction	Front: 20 % Back: 40% Left: 20% Right: 20%
PV Capacity	PV generation capacity	None	5.0 kW
PV azimuth	PV Panels orientation	Not applicable	Left roof
PV Tilt	Tilt of the PV Panels	Not applicable	Roof tilt

is the initial reference of the optimization, is less resistant to heat compared to 20 cm hollow concrete brick. There are several options with higher R-value; however, those options are too expensive. The wall structure needs to add more heat resistance with a double 1.6 cm drywall effectively works as insulation. Heat can also spread from a floor structure. Gypsum concrete is a better material than a wood surface for the floor slab to maintain comfortable indoor room temperature.

Fenestrations design also a critical factor in building energy performance. Installing double paned glazed window will significantly reduce the amount of heat radiation penetrating the building. Adding 61 cm eaves and overhangs on all windows can also considerably reduce the amount of heat from the sun. However, the disadvantage is that installing window glazing and eaves can dim the room so artificial lighting is required which will increase the energy consumption.

The greatest challenge of tropical buildings in terms of energy efficiency is mechanical cooling. The use of a high-efficiency air conditioner is recommended to maintain a comfortable indoor temperature at 240C. The use of air conditioning can be minimized by passive building design as discussed in the previous paragraph. High-efficiency lighting, i.e. Light Emitting Diodes (LED) lamps also recommended as energy consumption reduction. However, to save the initial cost of construction, combining LED lamps with CFL lamps is the optimum cost solution.

Lighting design can be problematic. If the window design is too large, then the heat of the sun can enter the building excessively which later will increase the room temperature. On the other hand, using a narrower window design will reduce natural lighting but increase energy consumption for artificial light. A minimum 20 percent window-to-wall ratio (WWR) and 40 percent WWR at the back side of the building (north facing façade) are sufficient to light the inside of the building with natural lighting. To prevent excessive incoming sunlight, as described in the previous paragraph, the use of glazing and eaves will minimize the heat of the incoming sun through the window openings.

After reducing energy consumption with a passive design approach and the use of high energy efficient AC and lamps, the next step that will bring the energy performance of a building to zero-energy is the application of renewable technology. The simulation and optimization process finds that 5.0 kW PV panels should adequately generate enough electricity to further offset the site electrical consumption to almost zero. It is possible to use a PV with higher production capacity; however, it is not an optimum cost solution.

The combination of all optimum design parameters results in an overall site building energy performance of nearly zero. The summary of the building energy consumption is shown in **Figure 8**.

The reference design employs the business-as-usual (BAU) residential building design with a new water heater, etc. The BAU residential building design consumes 154.23 kWh/m2*year where the most abundant energy consumption comes from mechanical cooling (HVAC) at 59 kWh/m2*year. The energy consumption for cooling is significant due to the building envelope design which lacks the application of thermal resistance materials to the building envelope. The heat that penetrates the building with ease will heat the indoor temperature so that the air conditioning system has to work harder to maintain a comfortable indoor temperature at 240C. When the design applies passive design using thermal resistance materials on the roof, attic, windows, floor mass, and walls; the energy consumption from cooling drops significantly to

18 kWh/m2*year. Using energy efficient air conditioner can also considerably reduce energy consumption.

For artificial lighting, the BAU design uses CFL lightbulbs in the whole building area and consumes 29 kWh/m2*year of energy. Although the optimized zero-energy building design uses a combination of CFL and more efficient LED lightbulbs, the energy consumption from artificial lighting is increased to 33 kWh/m2*year of energy in this design. An increase in energy consumption from artificial light needs to prevent in the area of window openings is expanded to reach Window-to-wall ratio (WWR) 20 to 40 percent, from a previous design of only 15 percent. Increasing the WWR can also increase the amount of heat radiation from the sun; therefore, the expansion of the window area shall be offset by the installation of eaves and glazing. In this case, it occurs because the window design that uses glazing and eaves can reduce the amount of natural daylighting from the sun. A design trade-off occurs in this case.

Passive design optimization, the building energy consumption is reduced to 39 percent without PV panels installment. The zero-energy consumption achieved by optimized a design use a 5.00 kW PV panels, which placed on east facing roof to maximize energy generation from the sun. The on-site generated energy from the PV panels is enough to significantly reduce site energy consumption to 2.00 kWh/m2*year.

To summarize, the improvement of energy performance of the building can be seen in **Figure 5** below.

4.2. Incremental life cycle cost analysis

Some parameter designs applied to the zero-energy building model increase the initial cost of construction while others reduce the cost. Design parameters that add the initial cost of construction include 20 cm hollow brick, attic insulation R-30 cellulose, terracotta roof tile, gypsum concrete for floor mass, drywall, window glazing, 60 cm overhangs, and PV panels. Heat pump and water heater are eliminated design parameters to reduce the initial cost of construction.

Although adding some parameter designs increase initial construction costs, the application of parameters to the design is proven reducing annual site energy consumption, thereby reducing monthly electricity billing costs. The annual electricity cost is calculated from the annual site consumption (kWh/year) of the building multiplied by the price of electricity per kWh applicable in Indonesia. The net-metering incentive component in the LCC analysis applies as a direct reduction to the annual energy

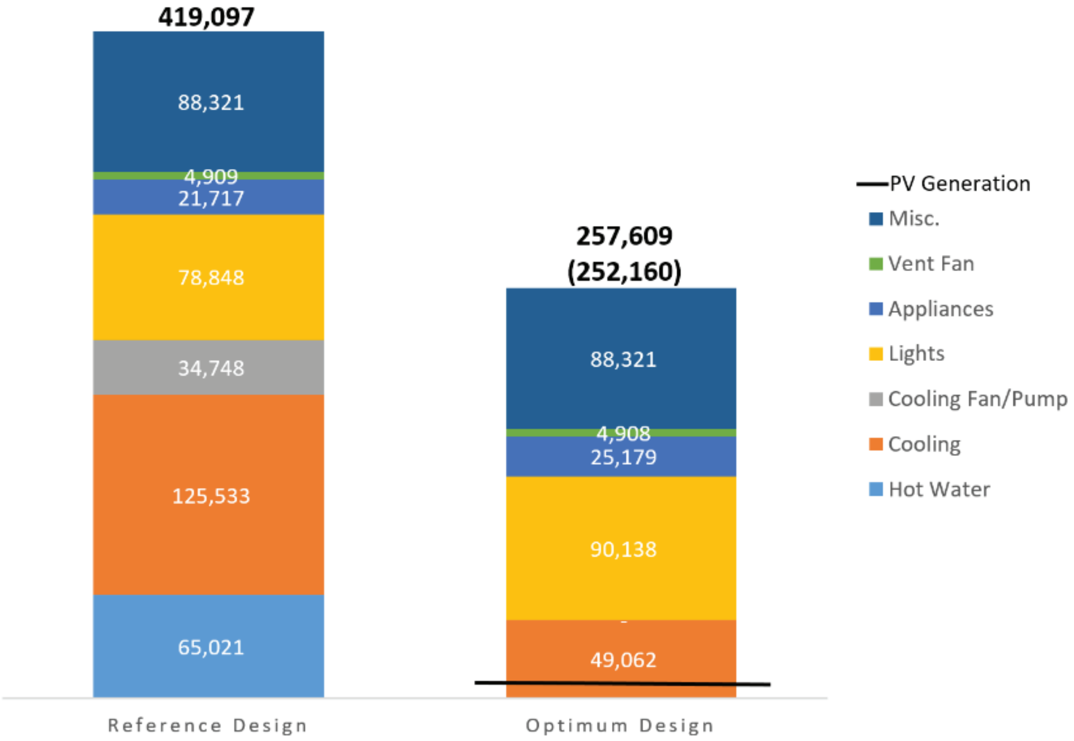

Figure 5: Annual Site Energy Consumption (kWh) of Reference Design vs. Cost Optimum Design.

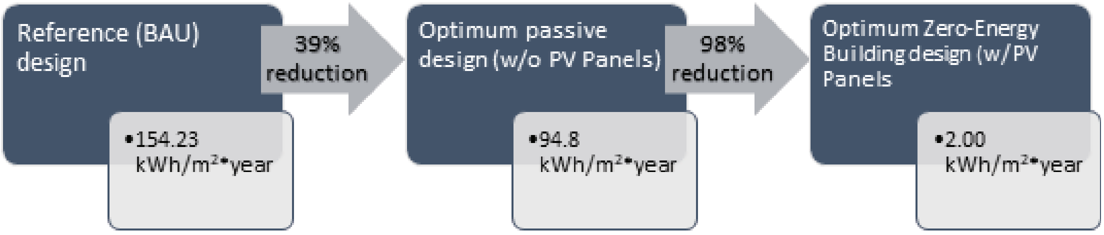

Figure 6: Annual Energy Consumption per Square Meter Reduction for Each Design Scenarios.

consumption of buildings. The study is following the rules stipulated by the Board of Directors of PT. PLN number 0733.K/DIR/2013.

The summary of the incremental life cycle cost analysis can be seen in Table 5 below.

The results of the analysis show that although there is an increase in initial construction costs, the annual incremental value of electricity costs is negative. The additional negative value of annual electricity costs indicates significant yearly electricity cost savings. From those cost components, the incremental NPV of the whole optimized Zero-Energy Building design life cycle cost is negative, shows the additional costs incurred for improving the energy performance of the building is a financially feasible investment.

TABLE 5: Incremental Life Cycle Cost Analysis.

	Reference (BAU) Design	**Optimized ZEB Design**
Initial construction cost (Rp.)	Rp. 11,563,369,402.00	Rp. 12,658,843,924.00
Incremental initial cost (Rp.)	Rp. 0.00	Rp. 1,095,474,522.00
Annual electric bill (Rp./year)	Rp. 634,388,720.21	Rp. 8,246,657.00
Incremental annual electrical Bill (Rp./year)	Rp. 0.00	(Rp. 626,142,063.21)
Incremental NPV of whole LCC with n = 25 years (Rp.)	Rp. 0.00	(Rp. 501,396,306.00)

5. Conclusion

The experiment process concludes that for tropical residential buildings, reducing site energy consumption without compromising indoor thermal comfort, the building design may utilize thermal resistance material for enveloping building design parameters. Building envelope as the outermost layer on a building plays an essential role in retaining the thermal radiation from the sun. Specifications of design parameters that can withstand thermal penetration rates include terracotta roof tile, R-30 cellulose attic insulation, 20 cm concrete hollow bricks insulated by 1.6 cm drywall on both sides, 5 cm gypsum concrete for floor insulation, and glazed low-E and low-gain windows with non-metal sills and 60 cm eaves. The use of these materials will reduce the use of air conditioning and minimize electricity consumption for mechanical cooling. Furthermore, using energy efficient Air Conditioner will significantly reduce energy consumption for maintaining indoor thermal comfort. Besides indoor thermal comfort, one of the challenges in designing zero-energy building is maintaining a healthy and comfortable amount of lighting. Optimum window-to-wall ratio (WWR) of 20 to 40 percent will adequately provide natural light. The use of LED lightbulbs and CFL lighting will further reduce energy consumption from lighting. The zero-energy target is achievable by utilizing 5.0 kW PV panels. By installing the PV panels facing east, this model building can achieve 98% of site energy consumption reduction.

The utilization of energy saving design parameters and renewable energy technology have increased the initial construction cost of the building. However, those design parameters can significantly reduce energy consumption later the operational stage of the building, hence lessen annual electric bill. The incremental life cycle cost analysis has concluded that the additional Net Present Value (NPV) of the optimized zero-energy life cycle cost has a negative value indicating a significant amount of cost saving during the whole optimized zero-energy building life cycle. Therefore, the incremental cost for applying the zero-energy building optimum design parameters is a financially feasible option.

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