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COST OPTIMUM DESIGN OF A TROPICAL NEAR ZERO ENERGY HOUSE (nZEH)

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ABSTRACT

Housing development, as part of economic development, must be supported by energy availability in order to achieve sustainable growth. One of the approaches to supporting renewable energy promotion is to design and build energy efficient housing. However, the optimal design of such buildings faces two conflicting requirements, namely the consideration of cost effectiveness and minimum environmental impact. The high costs of energy efficient buildings, such as the near Zero Energy House (nZEH), are due to the high price of the materials and equipment used, such as photovoltaic (PV) panels, insulation and other supporting materials. Indonesia is situated on the equator and benefits from sunlight throughout the year. Nonetheless, this potential has not been fully realized, as the solar-generated energy technology for housing comes at a high price. Therefore, the objective of this study is to find the cost optimum combination of validated design variables for an nZEH which suit the tropical climate conditions of Indonesia. Experiments and a case study are employed in the study to validate the design variables for an optimum nZEH design, which include building orientation, PV panels, fenestration, and passive design. The study finds that the cost optimum nZEH design achieved 72 percent site-energy savings and 21 percent savings in the total Net Present Value (NPV) of life cycle costs, with insignificant incremental initial construction costs in enhancing the design.

Keywords: Design optimization; Near Zero Energy House; Sequential search

1. INTRODUCTION

As its population continues to grow, Indonesia is currently facing increasing demand for housing and electricity production. A by-product of such rapid development is greenhouse gas emissions. The Centre of Energy Studies at the University of Indonesia has projected that these emissions will grow continuously to an alarming level by 2025 (PEUI, 2006) if Indonesia continues to develop a business-as-usual (BAU) scheme. In the Paris Accord 2015, Indonesia signed a commitment to reduce its greenhouse gas emissions by up to 29% by 2030 (United Nations Framework Convention on Climate Change, 2016); however, to date it has only been able to achieve a 1.49% reduction (INDC, 2015). To maintain social welfare by meeting the basic needs of adequate housing and energy and continuing to keep the environmental impact at a minimum level, the development of the housing and energy sectors

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needs innovation.

The energy performance of a building is the key element in reducing greenhouse gas emissions and making energy savings. Improving such performance is a cost-effective solution to overcoming climate change and improving energy security. Energy conservation in the building sector has attracted the interest and concern of the world community with respect to environmental conservation (Koesalamwardi, 2014).

In practice, it is very difficult to achieve zero energy consumption in a building. Buildings that consume just a little more energy than that generated are called near zero energy buildings (nZEBs), while an nZEH is a residential building that consumes a little more energy than it produces. Buildings that can generate energy usually use solar panels on their roofs and facades. By collecting energy from the sun, an nZEH can use its own generated energy and minimize energy consumption from outside sources (Marszal et al., 2011). Indonesia's tropical climate provides the potential for the development of nZEHs integrated with photovoltaic (PV) panels. However, this potential has not been fully explored due to the expensive technology of solar power generation systems (Dhany, 2013).

Reducing energy consumption without compromising living standards, e.g. indoor room temperature and comfort, is an important issue in the building construction industry. In addition, this problem also creates a contradiction for energy-efficient building design, which typically uses expensive materials and technology, and which directly affects the overall cost of construction (Milajic et al., 2013). This requires optimal use of green technology and attention to construction costs, so that energy-efficient building technologies will be economically feasible.

Buildings with high energy performance, such as the nZEH, should also be economically viable. Strategies and solutions are needed to reduce energy consumption for such buildings and to continually provide energy from renewable sources (Milan et al., 2012). In recent years, many energy conservation technologies have been developed, but the use of these tools does not guarantee optimal energy savings. This is because energy consumption is highly dependent on the combination and use of these tools, so these factors should be planned and optimized in order to obtain the best levels of energy saving (Ooka & Komamura, 2009). The purpose of this research is to develop an nZEH design with optimal costs using a sequential search optimization algorithm.

2. THEORETICAL REVIEW

The basic concept of a Zero Energy Building (ZEB) is one that can meet its energy needs from cheap sources, is clean, easy to produce, and renewable. A more precise definition states that a ZEB produces in-place renewables that are sufficient to meet or even exceed annual energy consumption (Torcellini et al., 2006).

Net Zero Energy Buildings have grown in developed countries such as ones in the EU, and the USA and Canada. The EU has stipulated a collective agreement so that all new buildings must embrace the nZEH concept by 2020; the agreement is known as the Energy Performance Building Directive (EPBD) - Recast 2010 (Hamdy et al., 2013).

Some of design parameters for nZEHs used in previous studies are as follows (Boeck et al., 2013; Bucking et al., 2013a; Bucking et al., 2013b): (1) renewable energy technologies, namely the use of PV, including (a) the ratio of the panel area to the roof area and (b) the azimuth direction (orientation) of the PV panels; (2) the shape of the building, together with (a) building orientation and (b) the slope of the roof; (3) the building envelope, which affects insulation; (4) fenestration (windows and doors), including the components of the window, the glazing type, window-to-wall ratio, type of window sills, window direction, and internal and external shading; (5) Heating-Ventilating-Air Conditioning (HVAC), which affects natural ventilation and mechanical cooling/heating; (6) lighting; and (7) renewable energy generators e.g. PV panels.

To further validate nZEH design parameters for the tropical climate, studies by Wimmer (2013), Herubowo (2017), and Kemal (2017) have been used as benchmarks. Development of building design with an nZEH approach in a tropical climate such as that of Indonesia is influenced by several variables. Based on the studies these include building orientation, PV panels, and fenestration (windows and doors), with type of window glazing and window-to-wall ratio subvariables. Geographically, Indonesia lies at a latitude of 6o North and 11^o South, and a longitude of 95^o East and 141^o East, which consequently means the country has a tropical climate. Prominent features in such regions are high average daily temperatures, high humidity and relatively slow air flow for achieving thermal comfort. The use of energy in Indonesia has focused on air cooling and dehumidification (reduction of humidity), which are commonly achieved using passive design to obtain suitable thermal comfort inside buildings (Wimmer, 2013).

The passive design concept in the case study by Kemal (2017) analyzed a building in the Jakarta area, using natural ventilation with the description of building is facing south, which also facing the road, in which all the doors and windows are intended as openings for natural ventilation. Also, it was designed from the early stage using sky lighting to create natural ventilation to induce an air speed of > 0.5 m/s in each floor system, and day lighting systems for non-air-conditioned and air-conditioned areas. Another aspect of the design is the utilization of LED lights, which comprise 98% of lighting. Using this particular design produces big savings by having day lighting generated from the sky lighting and two other voids in the building, meaning the light load in such buildings is only 3.4 watts per square meter. As part of green technology, solar PV panels contribute 25.7% of the total electrical energy from the grid, so it is very important to monitor and maintain the performance of these panels. Consequently, wifi plugs are installed in the solar inverters to monitor and record the total electricity generated in the solar PV panels in order to keep the electricity generated at above 8 kWH/day, with an average of 12 kWH/day (Kemal, 2017).

From the experiments and case study, there are four design variables for nZEHs which closely suit the tropical climate and support energy efficiency, namely building orientation (building azimuth), PV panels, fenestration and passive design. First, because of its tropical climate with high average temperatures caused by the vertical positioning of the sun, buildings in Indonesia are usually oriented towards the north (0^o) or south (180^o) in order to achieve comfortable indoor temperatures and to reduce expenditure on electricity costs for air cooling systems and lighting. Second, in tropical countries such as Indonesia, where the sun shines all year round, renewable energy sources derived from sunlight are seen as a potential form of energy. Solar radiation can be used to generate electricity (photovoltaically) for building utilities and heating water (photovoltaic-thermal systems). Third, fenestration, materials and installation also contribute to the energy channelled through windows, doors or skylights, together with the airflow in the window ventilation to the means of increased energy efficiency. Finally, passive design tends to be applied in tropical countries, since passive cooling systems produce comfortable temperatures (thermal comfort) in buildings (Torcellini et al., 2006; Wimmer, 2013; Kemal, 2017; Herubowo, 2017).

nZEH technology is usually more expensive than that of conventional buildings; it includes natural lighting, solar PV, wind turbines, light emitting diode (LED) lamps, and automatic HVAC systems. However, such technology can preserve more energy, as well as involving lower operational and maintenance costs. Therefore, it is important to make appropriate analysis to measure cost reductions during the building life cycle (Hartungi & Pye, 2009).

The life cycle cost of an nZEH is influenced by the initial construction cost and annual operational costs (Wang et al., 2005). The initial construction cost is influenced by the renewable energy technology chosen for the nZEH, the choice of building envelope, and the building utilities. Operational costs are affected by the performance and efficiency of the renewable energy technology used and the energy consumption of the utilities (Marszal & Heiselberg, 2011).

3. METHODOLOGY

In order to achieve the objective of determining an nZEH design at the optimum cost, the study included an experiment as the research strategy, using software for building performance simulation (BeOPT), with a sequential search as the main rule of the optimization process (Ihm & Krarti, 2012). The experiment involved two different design samples from conventional houses, based on prior preliminary studies in Indonesia. The designs were designated as business-as-usual (BAU) designs because of their conventionality (Herubowo, 2017). The design variables for the experiment were ones already validated by experts in the previous study (Herubowo, 2017). In this phase, the research used two samples. The simulation process found the optimized design variables that would minimize net site energy consumption from the sample. The energy simulation was based on PV panel energy data and household energy consumption data (daytime and night). The output from the experiment was data on the net energy consumption from the sample of varied design variables and the net present value (NPV) of the samples (PV and non-PV ones), based on the LCC analysis. During the experiment, checklists and BeOpt were used as the research instruments.

4. RESULTS AND DISCUSSION

The results of the simulation using sequential search and BeOpt are the results of the experiment. The main experiment used two different samples of single-family housing, which began with a business-as-usual (BAU) design. The samples were modelled with the building energy simulation software, as shown in Figure 1. Using the default (BAU) design as the benchmark, the optimization used the validated design parameters and sub-parameters from previous research (Latief et al., 2017). The design parameters used in the design optimization process had to be validated by experts. By using sequential search as the optimization algorithm, the objective for the optimization was maximum savings. After running the optimization for 5 minutes, some of the design variables of the benchmark samples (BAU design) were optimized. The selected optimum design parameters are shown in Table 1.

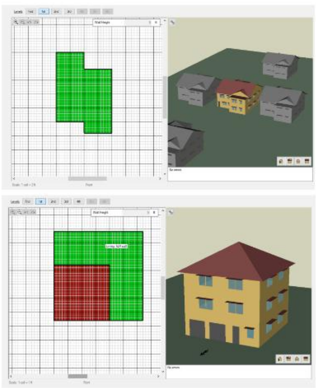

Figure 1 The two schematic model samples used for the experiment

Table 1 Design comparison of business-as-usual (BAU) design and pptimized nZEH design

No.	Design parameter	Sub-parameters	Design Specifications		
			BAU design samples 1 and 2	Optimized nZEH-1	Optimized nZEH-2
1.	Construction specification	a. Roof b. Attic c. External door d. Window e. External wall	a. Asphalt shingles b. Vented R-30 cellulose c. Wood d. Low-E, double pane e. Wood stud with fiberglass	a. Terracotta tiles b. Vented R-30 cellulose c. Wood d. Clear, double pane e. 15 cm hollow CMU, cement finish	a. Terracotta tiles b. Vented R-30 cellulose c. Wood d. Clear, double pane e. 15 cm hollow CMU, cement finish
2.	PV panels	a. PV capacity b. PV azimuth c. PV tilt	a. No PV panels b. N/A c. N/A	a. 4.0 kW b. West-South-West c. 30^0	a. 5.5 kW b. North c. Roof tilt
3.	Passive design	Building azimuth	North	South-South-East	North
4.	Building insulation	a. Roof b. Windows c. Wall	a. Vented R-30 cellulose b. 60 cm eaves, no overhangs c. Wood and 1.3 cm drywall	a. Vented R-30 cellulose b. 60 cm eaves and overhangs c. 5 cm gypsum and 1.3 cm drywall	a. Vented R-30 cellulose b. 60 cm eaves and overhangs c. 5 cm gypsum and 1.3 cm drywall
5.	Fenestration	a. External shading b. Glazing	a. 60 cm eaves, no overhangs b. Low-E double pane	a. 60 cm eaves and overhangs b. Clear, double pane	a. 60 cm eaves and overhangs b. Clear, double pane
6.	Heating and cooling (HVAC)	a. Cooling/ heating b. Water heater	a. Conventional cooling b. Electric water heater	a. Cooling 30% of total area at 24^0C b. None	a. Cooling 30% of total area at 24^0C b. None
7.	Lighting	a. Artificial lighting b. Natural lighting-WWR.	a. CFL hardwired b. 15% on all windows and sides.	a. CFL hardwired b. 15% on all windows and sides.	a. CFL hardwired b. 20% (front, left, right-hand sides) to 40% (back side)

The optimized nZEH design approach to achieving maximum site energy saving while maintaining a comfortable indoor room temperature and adequate lighting was mainly by using passive design; for example, positioning the building so it would not be facing the sun directly by orienting it to the north or slightly to the south. In this way, the heat from the sun would not directly penetrate the building through large openings, i.e. external doors. Hollow concrete brick and gypsum are desirable construction materials for absorbing external heat, so that the indoor temperature can be maintained at a comfortable level of 76^{o}F (24^{o}C). Terracotta roof tiles also can act as heat resistors. The use of artificial lighting can be minimized by optimizing the use of window areas. The window-to-wall area ratio ranged from 15% to 40%, sufficient for creating adequate natural lighting from the sun. A combination of large windows with eaves and overhangs will prevent excessive heat and light from the sun. Using 60 cm eaves and overhangs on all the windows can help to minimize solar heat radiation. Expensive glazing was not used in the design, since eaves and overhangs were already incorporated. The cost optimum selection for the artificial lighting was hardwired CFL lamps, with no need for the use of expensive LED lighting. This first energy saving approach can effectively reduce annual site energy usage by 42% on average.

To achieve near-zero site energy consumption, the use of renewable energy technology should be applied. By applying PV panels, the building can generate enough energy from clean sources to reduce energy consumption further. To harness sunlight effectively, placing such panels facing directly where the sun rises, and sets can generate adequate electrical energy. Adjusting the PV tilt to the roof to 300 can also optimize electrical generation. The figures shown in Figures 2 and 3 show an annual site energy consumption comparison between the BAU design and the optimized nZEH design. After optimization, the BAU design scheme was modified into the optimized nZEH design, resulting in significant electrical energy saving. Applying the energy saving measures mentioned in the previous paragraph together with renewable energy technology can effectively reduce site energy usage by 72% on average, as shown in Table 2.

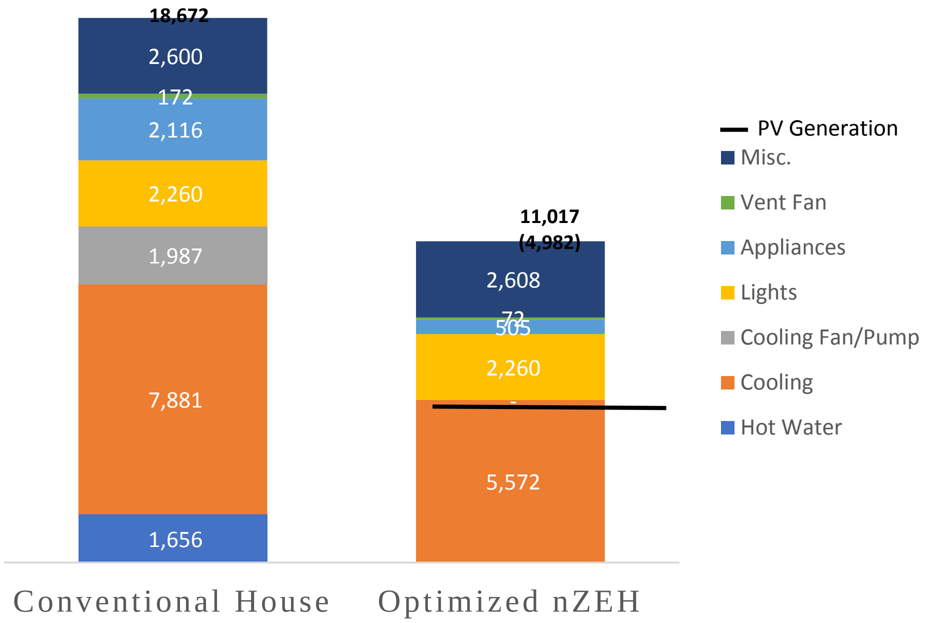

Figure 2 Comparison of annual site electricity use, conventional house and optimized nZEH sample 1

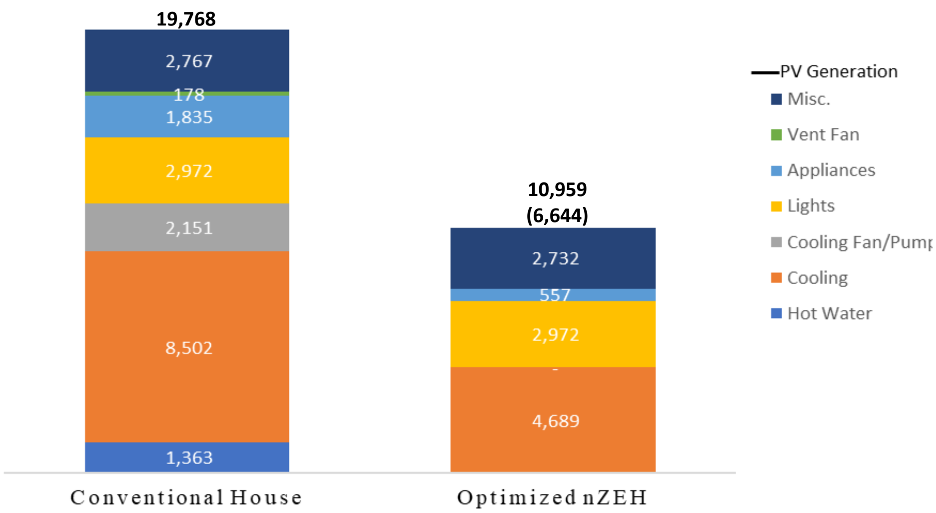

Figure 3 Comparison of annual site electricity use, conventional house and optimized nZEH sample 2

Table 2 Site energy consumption (kWh/m^2 × year) comparison

Sample	Conventional (BAU) design	Passive Design	Optimized nZEH Design
Sample 1	73	43	23
Sample 2	55	31	12

The combination of design parameter specifications will generate optimum life-cycle cost savings for the nZEH. Some sub-design parameters will increase the initial construction cost, while some will reduce the initial and annual electricity (operational) costs. The installation of PV panels will increase the initial construction cost, but at the same time will reduce annual site energy consumption per square meter and reduce electricity bills (operational costs). Therefore, a comprehensive whole life cycle cost calculation is needed to justify economic feasibility by calculating the energy cost savings during the whole life cycle. This analysis assumed that the service period (n) of the overall nZEH system will be 25 years, with a national inflation rate of 5%, and interest rate of 4.8%. The first life cycle cost analysis component that needs to be considered is the initial construction cost. Design improvements to the BAU design in the zero-energy design will increase this initial cost. However, the objective of this optimization process is to minimize the incremental construction costs, while maximizing energy savings toward near zero-energy site consumption. The other cost components in the calculation and analysis of the life cycle costs are the operational costs, one of which is that of electricity. Annual electricity costs are calculated from home electricity usage charges for lighting, household utilities and room cooling. The reduction in annual electricity costs in the optimized nZEH result from the utilization of energy saving design parameters, e.g. passive design and energy efficient lighting, appliances and HVAC. Furthermore, since the nZEH can generate its own electricity from the PV panels, which can be sold to the central power grid (PLN) using the net-metering incentive scheme, there will be a further annual electricity cost reduction. The selling price of electricity from the New Renewable Energy (EBT) is the same as the retail price of electricity, based on the Circular of PLN Directors number 009.E/DIR/2014, which was issued in 2014. The results of the life-cycle-cost analysis (LCCA) are shown in Table 3.

Table 3 Cost comparison between the conventional (BAU scheme) design and the optimized nZEH design

Sample	Construction Cost (× Rp. 1,000)		M-O Cost/yr (× Rp. 1,000)		NPV of Costs (× Rp. 1,000)	
	BAU Design	Opt. nZEH	BAU Design	Opt. nZEH	BAU Design	Opt. nZEH
Sample 1	937,332	940,332	26,613	8,560	1,348,021	1,066,871
Sample 2	877,102	919,230	28,040	6,108	1,282,640	1,008,886

From the experimental results, each of the combinations of design variables and their variants will produce net consumption data on on-site energy consumption and the NPV of overall life cycle costs. The reduction in annual electricity costs (i.e. operational costs) relies on the productivity of the PV panels, and depends on the purchase price of the central grid (PLN, the state-owned electricity company). In some developed countries, the purchase price of electricity from renewable energy sources is higher than the selling price of electricity to consumers, which aims to stimulate the growth and development of renewable energy technologies and energy-efficient buildings (Couture & Gagnon, 2010).

Based on the cost optimum design parameter selection, the incremental construction costs for the design enhancement only add less than 5% to the initial construction costs of the conventional design. Since the optimization objective is cost, the optimization algorithm will generate the design parameter combination which will not add to initial costs significantly, so the design parameters that will reduce site energy consumption to zero are not selected, since they will significantly add the initial construction costs. The cost optimum nZEH design was achieved using a two-step approach: (1) utilization of passive design materials and energy efficient lighting, appliances and HVAC; and (2) utilization of PV panels to further reduce site electrical consumption. Electricity bills would be reduced significantly, but not reach the zero-energy consumption. Since the incremental initial construction cost of design enhancement is not significant, it still manages to greatly reduce annual electrical costs. The total NPV of the nZEH life cycle cost is more feasible than the BAU design, saving 21% of overall life cycle costs.

5. CONCLUSION

To conclude, this study has determined an nZEH design at optimum cost, using nZEH design variables such as PV panels, azimuth (building orientation), fenestration (window-to-wall ratio), and glazing for windows. The design variables were combined and simulated using sequential search numerical rules, with the help of building performance simulation software. The results show that common construction materials, e.g. concrete hollow bricks and terracotta roof tiles, are suitable and represent low-cost heat insulation materials for tropical houses. Comfortable indoor room temperatures can be achieved with minimal usage of air conditioning, by positioning the house so it is not directly facing the sun, and applying 60 cm eaves and overhangs on all windows. The application of these can also reduce the initial construction cost by not having to use expensive glazing. The optimum window-to-wall ratio, which ranged from 15% to 40%, can provide adequate natural lighting, while minimizing heat radiation from the sun. By applying PV panels, electric consumption can also be reduced significantly. The electric power generated by the PV panels can also be exported to the central power grid, thus cutting electricity bills thanks to the net-metering incentive scheme.

The design optimization algorithm will sequentially search for the optimum combinations, thus generating maximum cost savings. Therefore, the optimization process will also eliminate unnecessary, unsuitable, and/or expensive design variables for tropical climates; for example, boilers, asphalt roof shingles, fiberglass wall insulations and LED lighting. Based on the cost optimum design parameter selection, the incremental construction cost for upgrading the design towards nZEH design concept is less than 5% to the initial construction cost of conventional design. The optimized design of the nZEH shows a significant annual maintenance and operational cost reduction, resulting in a lower NPV of cost compared to the conventional house design of up to 21%.

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