An Adaptive Photovoltaic Performance Study with a Biomimetic Approach for Energy Saving

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ABSTRACT

The facade has a function to improve the energy performance of the building by controlling the acquisition of sunlight and natural lighting. The biomimetic architecture approach is one form of architecture that imitates the principles of nature—integrating photovoltaics with facades to utilize solar lighting and generate electricity for building needs. The novelty of this study aims to examine the effectiveness of adaptive facade forms with a biomimetic approach integrated with photovoltaic on heat transfer and energy saving and determine the factors that influence it. This study uses the parametric modeling simulation method. In addition, this study compares aspects of heat transfer and energy generated by photovoltaics on adaptive facades with a biomimetic approach. The study's results using a flower petal-shaped adaptive biomimetic facade showed that OTTV 35 watt/m^2 (standard) obtained all grid configurations with an opening angle of 10-20 degrees, and the average electrical energy produced by integrated Photovoltaic was around 1,757.7 kWh. This result provides energy savings of 20.03% on a building.

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1. INTRODUCTION

Global energy consumption is forecast to increase 48% in the next 20 years (2020–2040) [1]. In the 2010s, the building sector dominated global energy consumption with a percentage of 40%, mainly used for HVAC (Heating, Ventilation, and Air-conditioning) purposes because modern humans spend 90% of their time indoors [2]. The increasing energy demand, while its availability is decreasing [3], encourages the emergence of sustainable development. In the field of architecture, this is applied to the concept of green architecture [4]. One application of the idea of green architecture is environmentally friendly using renewable energy is BIPV (Building Integrated Photovoltaic). Therefore, integrating photovoltaic modules into dynamic facade systems allows for different fine-tuning functions, generates electricity, and balances energetic performance with architectural expression. Based on these conditions, Loonen released the Climate Adaptive Building Shell (CABS) planning approach in 2013 [5]. This approach focuses on designing smart building envelopes, which adapt to outdoor conditions and user needs, to reduce HVAC energy consumption [6].

Governor Regulation No. 38/2012 concerning Guidelines for the use of green buildings in Jakarta states the facades of office buildings in Indonesia are glass curtain walls so that sunlight can maximally enter the building and impact the energy load received by the building [7]. It also makes it nearly impossible for the building to have an overall thermal transfer value of fewer than 35 watts/m2. However, several studies have stated that facades that take the analogy of natural formations (biomimetics) and adaptive building facades whose mechanism is connected to photovoltaics can be an option because they can save energy by controlling direct and indirect radiation into the building [8].

This study tries to answer how to make an adaptive biomimetic facade integrated with photovoltaic that can reduce heat energy consumption and has good building performance and comfort. It also presents an excellent external image comparable to the curtain wall facade so that the facade formed can work optimally per the essence of its function and application.

1.1. Overall Thermal Transfer Value (OTTV)

Overall Thermal Transfer Value, generally abbreviated as OTTV, is the average value of heat transfer per square meter (watt/m^2) through the building envelope. ASHRAE (American Society of Heating, Refrigerating, and Air Conditioning Engineers) 1975 first proposed this measurement value, and until now, it has been adopted as a standard and regulation by various countries [9]. If translated from the formulation, OTTV is the total amount of multiple types of heat transfer, which in this case are: heat conduction through the external wall (Qw), heat conduction through the opening (Qf), and heat radiation through the opening (Qs); per square meter of traversed envelope area (A) [9].

$$OTTV = \frac{\mathrm{Qw + Qs + Qf}}{\mathrm{A}}$$

$$OTTV = \frac{\alpha[\mathrm{UW}\ x\ (1 - \mathrm{WWR})\ x\ TDEk] + (Uf\ x\ WWR\ x\ \Delta T) + (SC\ x\ WWR\ x\ SF)}{\mathrm{A}}$$

OTTV : The overall thermal transfer value on the outer wall, which has a specific direction or orientation (W/m^2)
α : Absorbance of solar radiation
UW : Thermal transit of opaque walls (W/m^2.K)
WWR : The ratio of the window area to the area of the entire outer wall at the specified orientation
TDEk : Equivalent temperature difference (K)
SF : Solar radiation factor (W/m^2)
SC : Shading coefficient of the fenestration system
Uf : Penetration thermal transit (W/m^2.K)
ΔT : The design temperature difference between the outside and the inside
A : Surface area (m^2)

In Indonesia, standardization related to OTTV values is regulated in SNI 6389:2011 concerning Energy Conservation of Building Envelopes in Buildings. The SNI is the standard OTTV value at a value not exceeding 35 watts/m^2 [10].

1.2. Building Facade

The advantage of building facade design is that it can reduce heat due to sun exposure[11]. Conventional building facades aim to provide shade and protection against the outside world [5]. The design generally makes the inside of the building insensitive to the surrounding environment. Hence, using HVAC and artificial lighting is an option to fulfill comfort in the building [12].

Adaptive building facades have gained interest in recent years because they can save energy by controlling direct and indirect radiation into buildings while still responding to user preferences. Interestingly, photovoltaic integration is integrated with the facade as a sun-tracking mechanism mounted on the facade driving mechanism. Therefore, incorporating photovoltaic modules into dynamic facade systems allows for different fine-tuning functions, generating electricity, and balancing energetic performance with architectural expression. Under this strategy, photovoltaic-integrated buildings have the potential to provide a substantial segment of the building's energy needs. As a result, even the photovoltaic (PV) industry has identified BIPV (Building Integrated Photovoltaic) as one of the four key success factors of photovoltaic in the future [3].

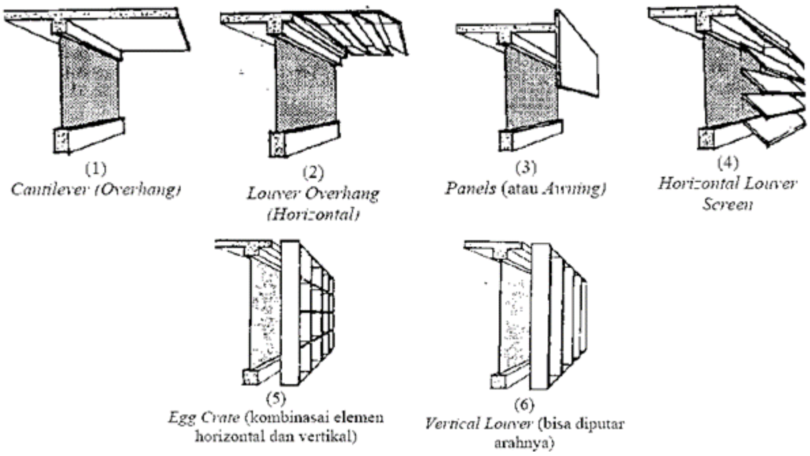

Figure 1. Building Façade.
Source: [12]

1.3. Photovoltaics in Buildings

BIPV (Building Integrated Photovoltaic) describes buildings that use photovoltaic circuits integrated on the roof or in the building envelope system. Lechner said BIPV systems could replace roof layers, curtain walls, glass, or particular elements such as walkways or canopies [13]. In green architecture, BIPV is the application of energy-saving strategies by utilizing solar radiation as an environmentally friendly renewable energy source [14]. In addition to power plants, building envelopes have the potential to be integrated with photovoltaic modules because they can protect buildings from weather influences. Photovoltaic modules in vertical envelopes of buildings can be applied as vertical cladding, windows for natural lighting, and shading devices to reduce solar radiation received by buildings [3].

Figure 2. Photovoltaic Applications in Building Envelopes Tobias Grau Production, Germany
Source: [3]

Two ways can achieve energy savings by applying BIPV to the building envelope. The first way is through the energy generated by photovoltaic panels. Calculate the energy produced by photovoltaic panels to reduce building energy consumption by replacing the energy supply from the State Electricity Company (*Perusahaan Listrik Negara*, PLN). The second way is by designing a building envelope that is responsive to the tropical climate to reduce the internal load of the building. For example, applying photovoltaic panels as shading devices minimizes the entry of solar heat into the room and saves cooling loads [15].

1.4. Photovoltaic Adaptive Facade

The context of CABS (Climate Adaptive Building Shell) includes Photovoltaics adaptive facade. Loonen describes CABS as a building facade that can change some function or behavior over time in response to changing performance requirements and conditions of various variables, aiming to improve the overall performance of the building. So, the building envelope elements in CABS emphasize supporting good quality interior spaces [16].

Loonen also explained that dividing two classes can happen by a mechanism that drives adaptation to the facade. For example, changes in nature or behavior on the macro or micro-scale can divide. The macro-scale, or the kinetic envelope, generally results in a difference in the scale of the building envelope through moving components. While the micro-scale, as the name implies, is a change to smaller and lighter parts, one example is the movable window.

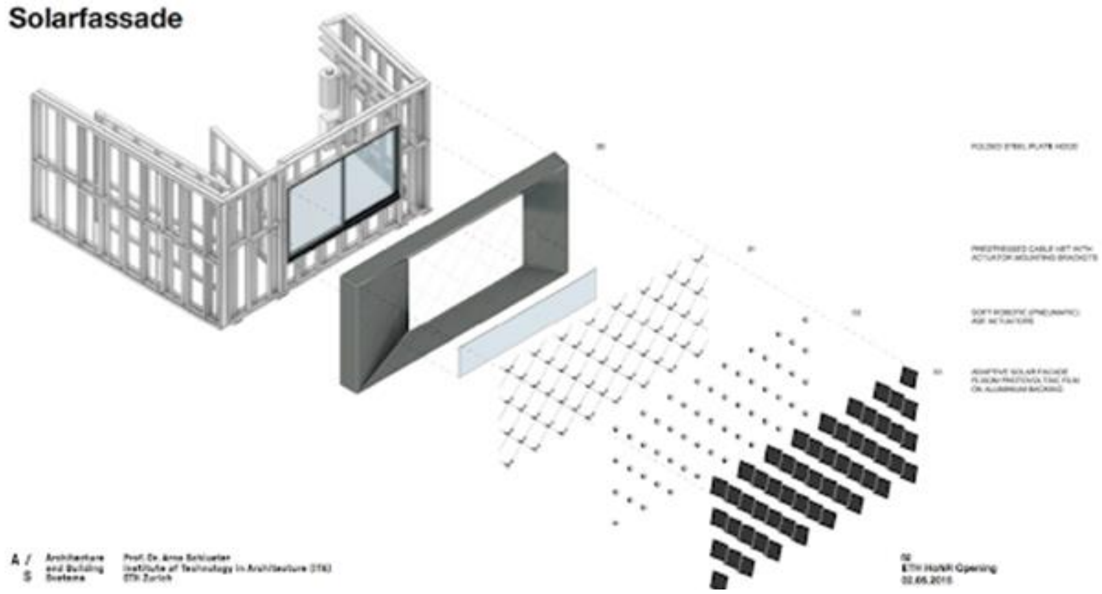

Figure 3. Photovoltaic Applications in Building Envelopes
Source: [17]

The adaptive photovoltaic facade is a lightweight, modular shading system consisting of CIGS (Cu (In, Ga) Se_2) panels. The panels have a flexible shape and light structure compared to traditional photovoltaic modules. Based on the results of previous studies, thin-film photovoltaic modules (CIGS) could also achieve the same efficiency as conventional modules [18]. Also, from an economic point of view, the price per watt peak of the two systems is comparable. Therefore, thin film photovoltaic systems have become a powerful technology for BIPV [18]. Furthermore, the photovoltaic module is driven independently in altitude and azimuth orientation, allowing the system to react to internal user requirements and external weather conditions.

1.5. Biomimetics in Architecture

The understanding of the term Biomimicry comes from the words "bios," which means life, and "mimesis," which means imitate. Hence, the meaning is as a new science that studies the best ideas of nature and then imitates these designs and processes to solve human problems [19]. The main idea is that the imaginative nature by necessity has succeeded in solving many of the issues we struggle with, where we find that animals, plants, and microbes take on the roles of skilled architects and engineers. They have discovered what works and what doesn't, what is appropriate and what doesn't, and, most importantly, what continues and is happening on Earth. Nature utilized strategies in its evolution, including the maximum economy, structural and behavioral adaptation, and integration of functions. The key word is nature:

- Nature as a “Model”
  “Biomimicry studies natural models and then imitates or draws inspiration from these designs and processes to solve human problems.”
- Nature as “Measure”
  "Biomimicry uses ecological standards to judge the veracity of our innovations. After 3.8 billion years of evolution, nature has learned: what works; what is appropriate; what lasts."
- Nature as “Mentor”
  “Biomimicry introduces an era that is not based on what we can extract from nature, but on what we can learn from it.”

Figure 4. Example of an Architectural Biomimetic Approach.
Source: [20]

2. RESEARCH METHOD

The method used in this study is the Simulation Modeling method. This method aims to create a copy of reality and represent model operations using parametric-based software, namely Rhinoceros 6, Grasshopper 0.9, Ladybug 0.0.69, and Honeybee 0.0.66. This system facilitates simulations carried out on adaptive facades with various motion configurations. However, this condition differs from a static facade, with one simulation on adaptive facades with different motion configurations. However, this condition varies from a static facade with one configuration [21]. There are several stages in this research. The first stage of this research is to collect data and create a model of the test room and facade. The second stage is to simulate OTTV and Cooling Load in the test room within one year. The third stage is to conduct photovoltaic energy simulations in the test room to obtain information on the performance of building facades with a biomimetic approach integrated with photovoltaics to save energy in buildings in Indonesia.

2.1 Test Room Model

The test room model used in this study is 8 m long, 8 m wide, and 2.8 m high, which on the side with high sun exposure potential, has an opening with a Window Wall Ratio (WWR) of 99%. The placement of the adaptive building facade is modeled at a distance of 0.1 m (10 cm) from the side of the room opening. The standard minimum area of office space listed in the Decree of the Minister of Law and Human Rights of the Republic of Indonesia in 2016 concerning the Standardization of Office Space and Office Facilities in the Ministry of Law and Human Rights produces the size of this room [22]. The standard stated in the Ministerial Regulation is that the minimum workspace area is $60m^2$. Therefore, calculating the area of the Data Architect's room becomes a reference for the preparation of standardization of office space with the standard of comfort of a workspace of 1 person being $3m^2$. In this case, a small workspace with a capacity of 20 people is 60m2 due to the same [23].

In this study, the test room model is a description of a room that has openings that are directly adjacent to the outside space and the floor of the room is directly adjacent to the ground, as well as part of the ceiling of the room and the other side besides openings bordering other spaces. It can be defined as an adiabatic plane model or without heat and mass transfer between the system and its surroundings except the opening and the floor.

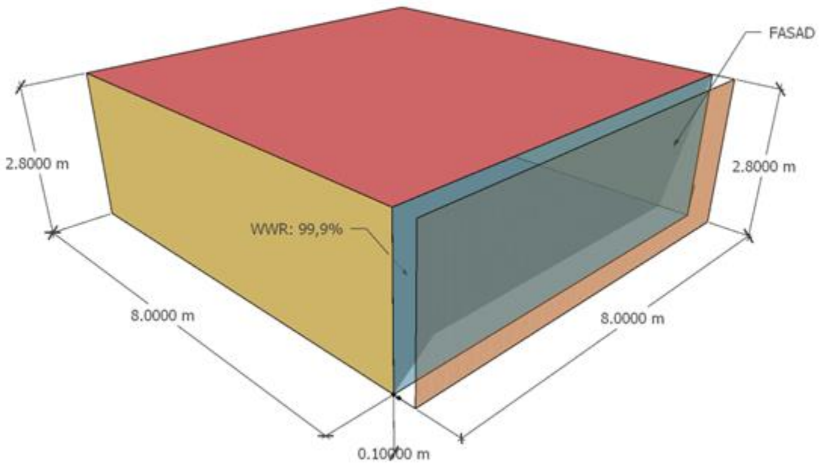

Figure 5. Test Room Model
Source: Authors

Table 1. Test Room Model Properties

Parameter	EP Construction	EPBC
Main Wall (North)	ID. Exterior Wall	-
Wall (South, West, & East)	ID. Interior Wall	Adiabatic
Roof	ID Interior Ceiling	Adiabatic
Floor	ID Interior Floor	Adiabatic
Window Parameter	**EP Construction**	**WWR**
Main Wall Window	ID SHGC 0.705 NFRC 4230	99.99%

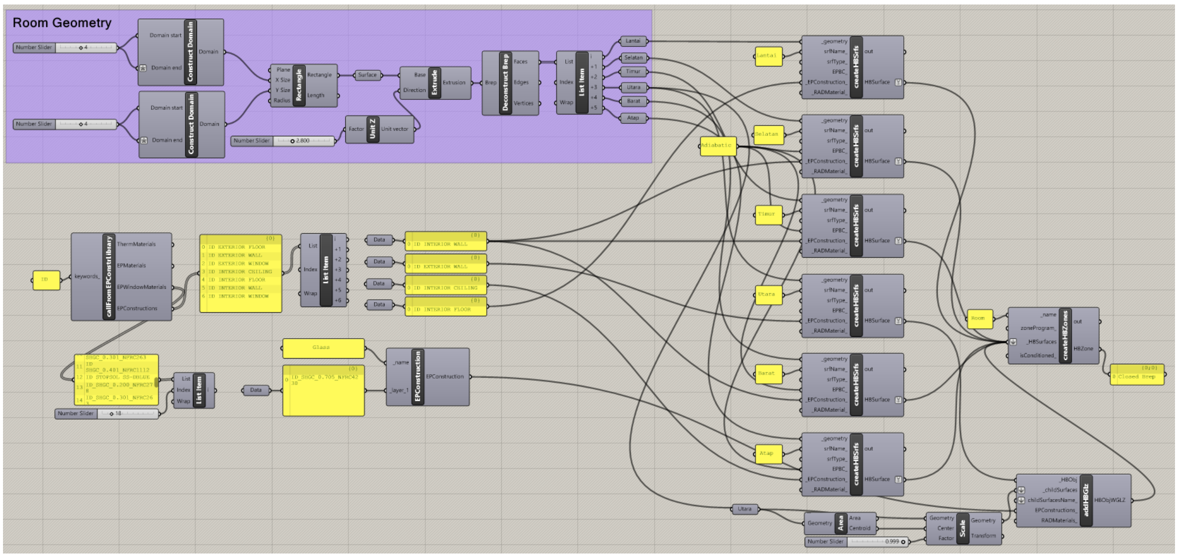

Figure 6. Test Room Model Properties
Source: Authors

2.2 Building Facade Model

2.2.1 Taking Shape Inspiration

The shape of the facade is made a model to move by adapting the movement mechanism and the form adapted from natural formations [24]. The figure will be modeled and simulated to determine the shape's performance on the building's OTTV value. The explanation regarding the form of the facade based on the inspiration of nature is as follows:

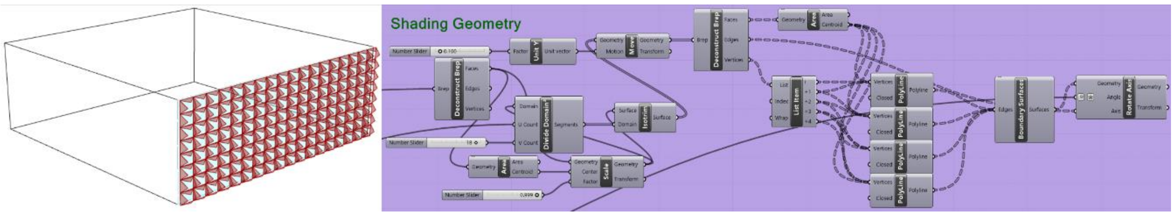

Figure 7. The Process of Making the Facade
Source: Authors

The shape of the facade takes inspiration from the shape of the "purple shamrocks" flower petals. This flower has the scientific name Oxalis Triangularis, or in Indonesia, it is better known as the butterfly flower because it has a triangular leaf shape that resembles a butterfly flower. The leaves are 'photophilic,' i.e., they can open and close themselves in response to light. These butterfly flowers are neatly folded and curled up at night, looking like a swarm of tiny purple butterflies. Then in the morning, the leaves will widen. The facade can adapt from the movement and shape of this flower petal with the same approach, namely the photophilic mechanism of the leaf opening and closing the lid based on an attractor, in this case, sunlight.

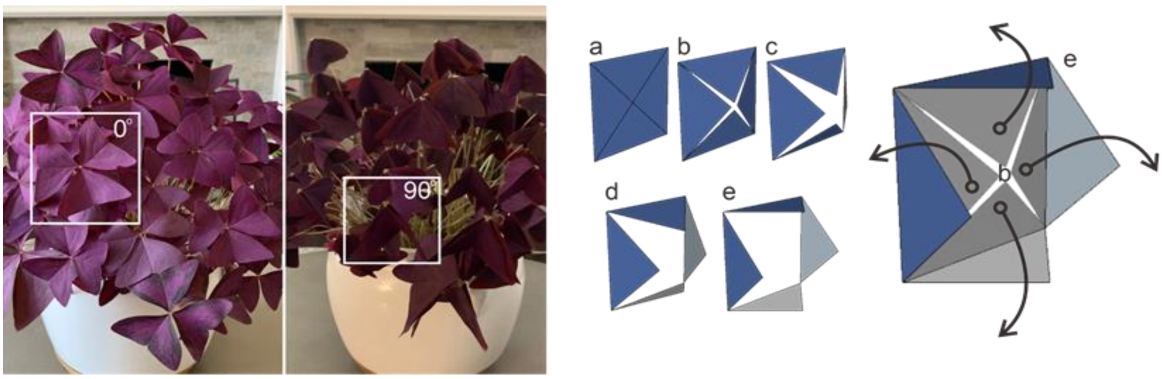

Figure 8. The Process of Taking Inspiration from Nature
Source: Authors

2.2.2 Configure Shapes in Simulation

In the previous modeling of the test space, the shape has undergone a simulation process. The simulation will apply several parameters, such as grid dimensions and the degree of slope of the opening. The simulations will be sorted by the smallest to the largest parameters. The flower petal facade model will be simulated by dividing the sides of the opening into several grids. The smallest grid consists of 4 pieces (2x2), and the largest grid is 64 pieces (8x8). Each grid division has a fin, which will also be simulated based on the degree of slope of the openings. It will also show the percentage of WWR in each of these openings. The figure below will further explain this statement:

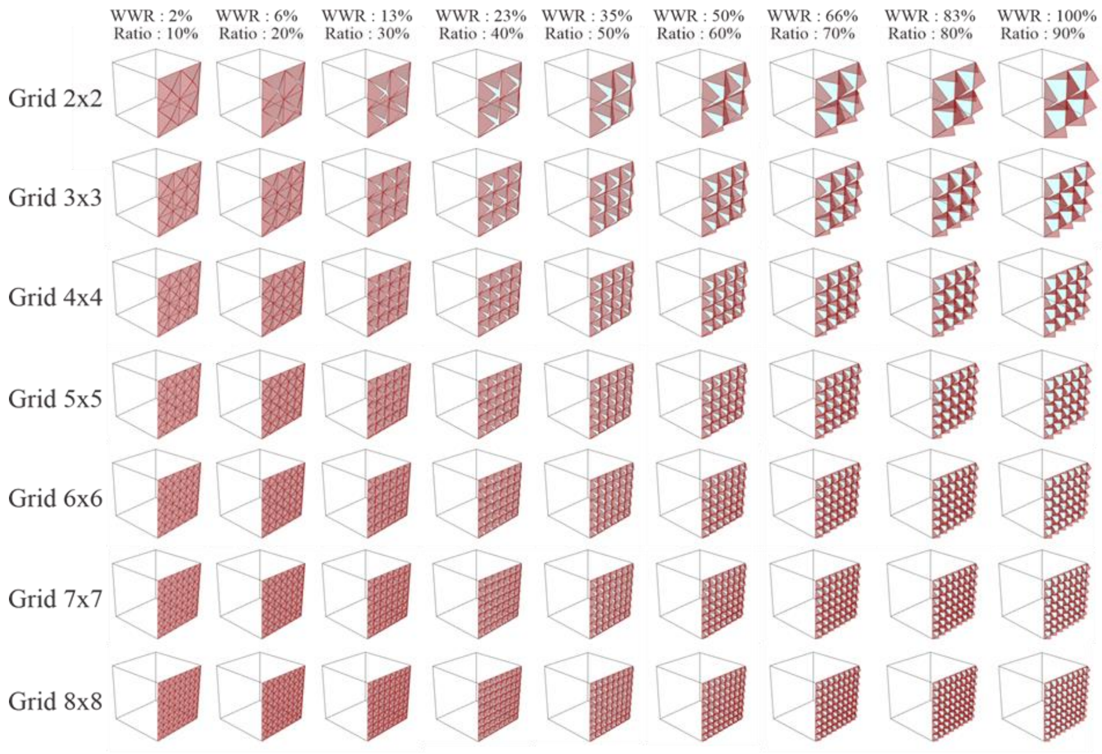

Figure 9. Flower Petals Facade Shape Configuration
Source: Authors

2.2.3 Photovoltaic

This study uses opaque photovoltaic material made of thin film, a type of opaque photovoltaic efficiency generally used as wall and shading elements. The photovoltaic module used is copper indium gallium selenide (CIGS), with an efficiency of 11%. The efficiency of the 11% module means that when the photovoltaic module receives 1000W/m^2 solar radiation and the photovoltaic cell temperature is 25 ^{o}C, the result of the change in electric power from the amount of solar radiation is 11%. The choice of copper indium gallium selenide (CIGS) was because the supplier was the highest-ranked supplier of photovoltaic modules in 2014 [25].

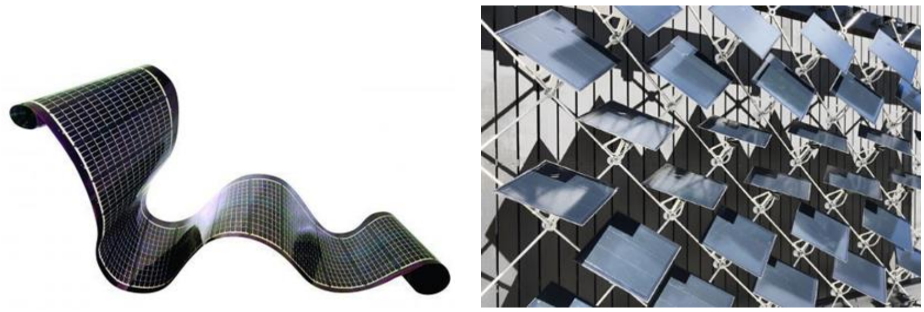

Figure 10. Copper Indium Gallium Selenide (CIGS) Photovoltaic Module
Source: Authors

2.3 Type of Simulation Performed

This research focuses on two types of simulations to see the performance and effectiveness of adaptive facades with an integrated biomimetic approach on photovoltaic panels for energy savings in buildings. This research focuses on two types of simulations to see the performance and effectiveness of adaptive facades with an integrated biomimetic approach on photovoltaic panels for energy savings in buildings. There are two simulations, namely:

2.3.1 OTTV Simulation

This simulation measures the average total value of heat transfer across the building facade per square meter in an entire year [6]. Based on this research, the OTTV standard value is below 35 watts/m^2 according to SNI 6389:2011 [10].

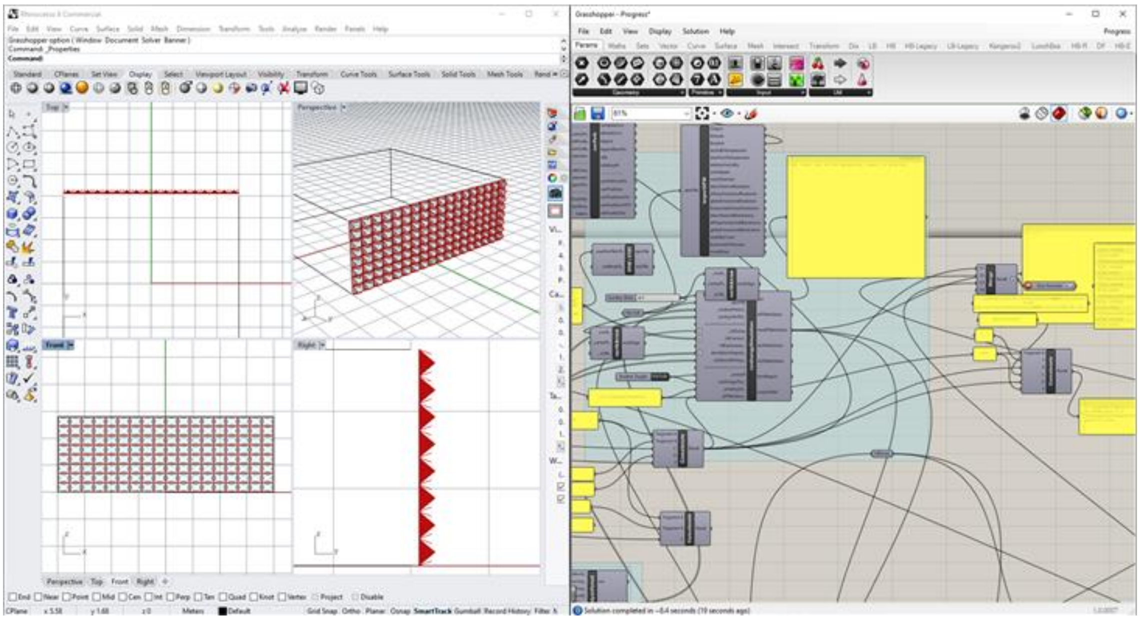

Figure 11. OTTV Simulation
Source: Authors

2.3.2 Photovoltaic Simulation

This study focuses on simulating the energy production of photovoltaic generators to see the amount of energy produced by photovoltaic modules that integrate facade configuration with a biomimetic approach in the test chamber envelope [3].

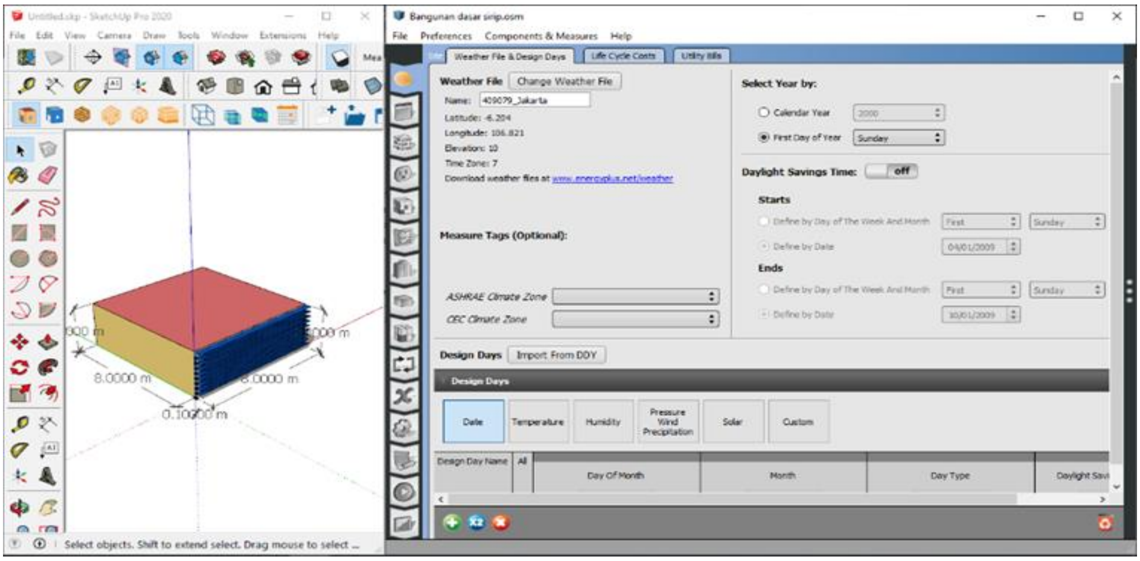

Figure 12. Photovoltaic Simulation
Source: Authors

2.4 Simulation Properties and Limitations

2.4.1 Simulation Properties

The properties in the simulation are needed to get more accurate simulation results according to the research objectives. The table below describes the simulation properties used in the simulation process in this study. Jakarta weather data was chosen as the research area because it is the most appropriate description of the application of facades in high-rise buildings to reduce energy use. The window used is a specification of ID SHGC 0.705 NFRC 4230, commonly known as clear glass. In addition, other specifications have been adapted to the test space and the current state of the simulation, as described in Table 2.

Table 2. Simulation Properties

Properties	Specification
EPW	Jakarta
Glass Type	SHGC 0.705 NFRC 4230
Equipment Load per Area	10 W/m^2
Lighting Density per Area	0.1 Ppl/m
People per Area	3 W/m^2
Ventilation per Area	0.000305 $m^3/s\text{-}m^2$
Recirculated Air per Area	0.00236 $m^3/s\text{-}m^2$

2.4.2 Simulation Limits

The limitation or weakness in this simulation lies in the facade model. The researcher realizes that in a simulation, there must be fewer and many weaknesses. One of them is from the elements of the facade model. The frame that forms the facade is the completeness of the facade model, the thickness of the facade material, the driving mechanism of the facade, and other elements related to the formation of the adaptive facade. If you pay attention to the simulation, then these elements have an impact on the simulation results. However, in this simulation, all these elements are ignored. There is an assumption that they have no effect, so only the shape of the facade that covers the test room model's opening area is considered.

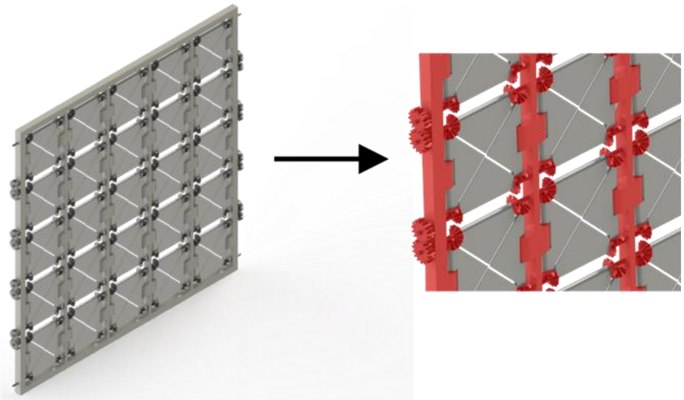

Figure 13. Simulation Limits
Source: Authors

3. RESULTS AND DISCUSSION

3.1 Initial Simulation

The initial stage of this research focuses on identifying the effect of model orientation on the performance of an adaptive facade with a biomimetic approach that is integrated with photovoltaic modules or can be called orientation simulation. Rotating the test room model in eight cardinal directions: North, Northeast, East, South, Southeast, Southwest, West, and Northwest is the way to do this simulation. The simulation activity lasted for one year. Each orientation simulates the values of OTTV, Cooling Load, and Sun Hour as parameters for the best-facing direction and getting maximum sunlight.

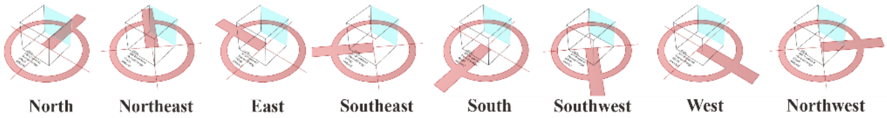

Figure 14. Orientation Simulation
Source: Authors

After the simulation, the conclusion is the north side is the right side for conducting simulations. It aims to evaluate the facade shape's performance with a biomimetic approach. Otherwise, calculate photovoltaic performance because the north side gets the most sunlight exposure for one year with an OTTV value of 206.65 kW/m^2, the value 206.65 kW/m^2. The cooling load can reach the highest level if the room model faces north with a value of 787.36 kWh/m^2, and if the room model faces north, then sun hour can get the highest score. These results align with Anantama and Hariyadi's research (2021) [6], which showed that the annual solar movement affects photovoltaic performance, the north orientation produces the highest radiation, and the average radiation exposure is constant.

Table 3. OTTV Simulation Results

Orientation	Value		
	OTTV	Cooling Load	SunHour
North	23.81	23.66	24.06
Northeast	28.23	28.78	30.50
East	39.59	36.10	36.83
South	53.50	46.76	44.25
Southeast	60.06	54.79	52.65
Southwest	68.47	66.60	66.29
West	76.90	77.56	74.72
Northwest	88.03	85.90	89.70

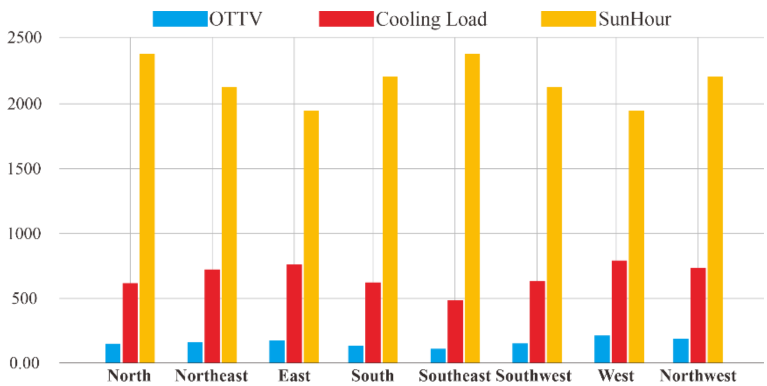

Figure 15. Orientation Simulation Results Chart
Source: Authors

3.2 Final Simulation

This stage describes the manufacture of photovoltaics in the previous step, which integrates it with the facade. Next, the simulation runs using a test model that leads to the orientation specified in the initial simulation. The final simulation period uses a time of one year. The final simulation results are then analyzed as a reference to assess the performance of the integrated photovoltaic facade on the OTTV value and the resulting energy savings.

3.2.1 OTTV Simulation

To carry out this stage with the OTTV simulation, the way to run it is using a test model that leads to the orientation determined in the initial simulation, namely the test room model facing the north side. The final simulation period uses a time of one year. The final result of the simulation then becomes a reference through analysis for conducting photovoltaic simulations.

Table 4. OTTV Simulation Results

Opening Configuration	OTTV Value						
	2x6	3x8	4x10	5x12	6x14	7x16	8x18
10.00	23.81	23.66	24.06	23.95	24.13	26.44	24.51
20.00	28.23	28.78	30.50	28.17	31.35	29.07	28.81
30.00	39.59	36.10	36.83	37.31	37.07	39.71	35.40
40.00	53.50	46.76	44.25	47.14	49.47	48.05	46.15
50.00	60.06	54.79	52.65	53.40	58.72	55.84	53.62
60.00	68.47	66.60	66.29	62.60	65.49	65.84	59.83
70.00	76.90	77.56	74.72	74.55	72.25	73.00	70.81
80.00	88.03	85.90	89.70	81.98	80.81	82.48	82.53
90.00	95.70	96.86	97.18	94.97	91.22	93.31	90.18

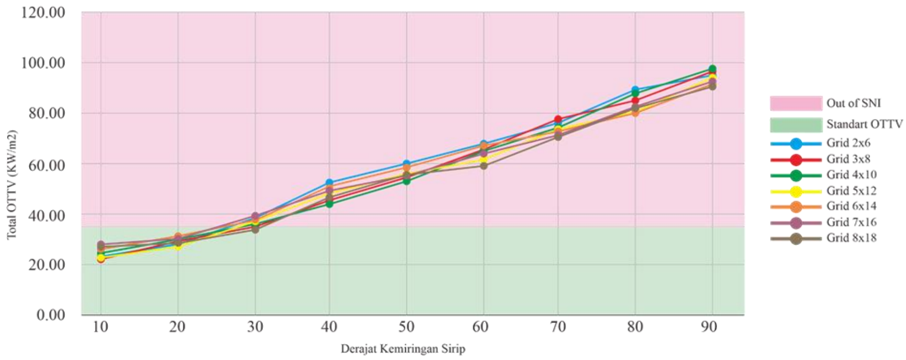

Figure 16. OTTV Simulation Results Charts
Source: Authors

Based on this graph, the lowest value generated is in a 3x8 grid configuration with an opening angle of 10 degrees and a WWR of 2% with an OTTV value of 23.66 kW/m^2, and the highest value obtained is 97.18 kW/m^2 on a 4x10 Grid configuration with an opening angle of 90 degrees and WWR of 100%. All grid configurations with opening angles of 10 to 20 degrees meet the SNI OTTV standard (35 watts/m^2). These results align with research conducted by Hariyadi (2017) [26]; when used as a facade, the position of the shading device can block almost all solar radiation depending on the width of the spacer or WWR. Can also be seen in the trend depicted in the graph, where the greater the WWR value or the degree of opening, the higher the OTTV value tends to be. This graph is also in line with research conducted by Anantama & Hariyadi (2021)[6]. So, the conclusion is the configuration can be used as a reference if the formation of the facade of the building adapts this form. If we only take the maximum OTTV value, we can use the maximum OTTV results in table 5.

Table 5. Maximum OTTV Results According to SNI Standard

Grid	Degrees	WWR	OTTV
2x6	25.40	9%	35 watt/m^2
3x8	28.30	9%	35 watt/m^2
4x10	27.80	9%	35 watt/m^2
5x12	28.15	9%	35 watt/m^2
6x14	28.20	9%	35 watt/m^2
7x16	27.90	9%	35 watt/m^2
8x18	28.50	9%	35 watt/m^2

3.2.2 Photovoltaic Simulation

Table 6 shows the results of measuring the value of energy production from photovoltaic modules placed on the facade in a tilt angle configuration that produces a standard OTTV of 35 watts/m^2. Then the energy production value will be used to calculate the energy efficiency that can be achieved by applying photovoltaic integration to the facade configuration by dividing the energy generated by the thermal energy of the test room.

Table 6. Photovoltaic Simulation Results on Maximum Facade Configuration According to SNI Standard

Facade Condition				Thermal Energy		Energy Output kWh/64m^2	Energy Savings (%)
Grid	Degrees	WWR	OTTV	kWh/m^2	kWh/64m^2		
2x6	25.40	9%	35 watt/m^2	139.31	8915.84	1841.67	20.66
3x8	28.30	9%	35 watt/m^2	137.16	8778.24	1805.56	20.57
4x10	27.80	9%	35 watt/m^2	135.43	8667.52	1775.00	20.48
5x12	28.15	9%	35 watt/m^2	136.68	8747.52	1761.11	20.13
6x14	28.20	9%	35 watt/m^2	137.57	8804.48	1741.67	19.78
7x16	27.90	9%	35 watt/m^2	138.79	8882.56	1719.44	19.36
8x18	28.50	9%	35 watt/m^2	135.80	8691.20	1669.44	19.21

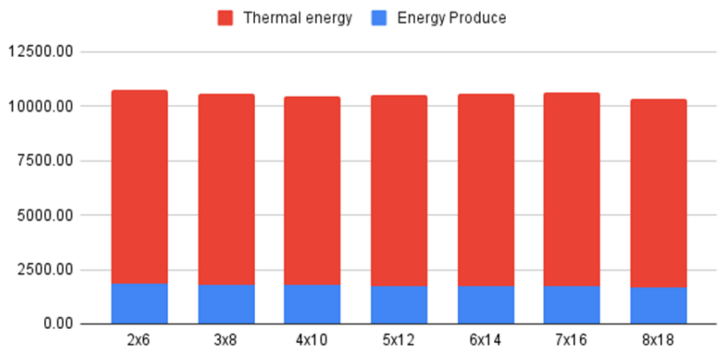

Figure 17. Photovoltaic Simulation Results Charts
Source: Authors

If we look at the table, the trend is that sunlight makes the facade area even more significant; the greater the energy produced, so it will also provide a high percentage of energy savings. The energy produced by the flower petal facade is 1,757.7 kWh on average. The same thing also happens when viewed from the portion of efficiency generated. This efficiency percentage is in line with research conducted by Nagy et al.[18], which found the potential for total energy savings of 25% with their configuration in the European climate and weather. This study found that the "flower petal" facade gave an average efficiency of 20.03% in the test room using simulations of the Indonesian climate, specifically the city of Jakarta.

4. CONCLUSIONS

An adaptive facade with a natural formation approach that takes inspiration from flower petals can be said to have an energy-saving impact. This statement showed the percentage of energy generated in the photovoltaic simulation process with the facade configuration following the maximum standard OTTV value of 35 watts/m^2. In the photovoltaic simulation, the data shows that the shape of the flower petals can provide an average of 1,757.7 kWh, equivalent to 20.03% of the energy requirement of the test room.

Finding the most efficient photovoltaic integrated facade formation can be a recommendation for architects in designing energy-efficient buildings to achieve sustainable buildings. Initial prototypes or other fundamental configuration developments to obtain a more sustainable design can use a flower petal facade shape resulting from energy savings.

Further research is needed using facade formations inspired by other natural formations, the effect of facade formation with the inspiration of natural shapes other than the north orientation, and research with configuration and different test dimensions.

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