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Method to assess the potential of photovoltaic panel based on roof design

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ABSTRACT

The photovoltaic (PV) panel makes it possible for everyone to produce electricity in their own house. However, the panel is quite a costly investment and requires much consideration to maximize its potential. The roof has variables that would impact electricity generation. The roofs of houses in Indonesia were generally built in a complex shape, a combination of gable and hip roofs. This research was conducted to break down factors affecting PV productivity with regard to the roof's aspects. A computer simulation using the Ladybug plugin in Rhinoceros software has been done to achieve the target. Initially, the performance of PV panels on the gable and hip roof is analyzed separately. It is found that the roof's slope and orientation contribute more to the amount of electricity produced than the shape itself. These factors were used to assess the PV potential in several housing models employing simple and complex roof (more than 2 surfaces) construction in the city of Gorontalo. Eventually, a comparison between the estimation of real PV production on housing and the estimation provided by the simulation is conducted to verify the assessment method. The difference is about 4%, which is proof that the simulation result is reliable.

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1. INTRODUCTION

Photovoltaic (PV) is a promising investment to save electricity expenditure. PV will dominate renewable energy capacity expansion by 2020 [1]. But in Indonesia, the capital cost of PV installation ranges from 700 to 1200 USD/kW. The price is higher compared to the capital costs in countries in Europe, China, and India, which are mostly below 1000 USD/kW [2]. Compared to developed countries, Indonesia, as a developing country, still has low PV capacity installed. Yet, from 2018 to late 2020, PV adoption in Indonesia increased by more than 700% [3]. One of the driving forces behind the rise of PV sales is the Indonesian government's campaign on using renewable energy resources.

The household sector, especially housing, consumes relatively low electricity per house. A simple house with an area of 36 to 45 m^2 is provided with a 900-to-1300-volt ampere (VA) electricity supply by the utility company. PV should be able to cover the electricity usage of such a household. Research reports that the household and commercial sector in Indonesia have a high potential solar energy application [4]. To convince people to invest in PV panels, it is important to assure them of the benefit they will gain in the future. A better understanding of how PV works and the region's PV potential is essential in promoting the use of PV panels. In the case of PV potential in the area, there is a lot of research on the method to assess PV panel potential on buildings. Yuan *et al.* [5] employed aerial photos of an area to acquire the roof planes for PV mounting and also objects which would shade and diminish the PV performance. However, this method necessitates high accuracy in both retrieving samples and detecting roof planes and obstacles. Lingfors *et al.* compared both low and high-resolution light detection and ranging (LiDAR) data to calculate the PV potentials, detect the roof types, and analyze the shadow on the roof [6]. The results show that in an area whose buildings are homogenously distributed, the low-resolution data has a 78–86% accuracy level. Lukač *et al.* [7] developed a method based on LiDAR data to determine potential PV locations and then ranked them from roof with high potential to roof unsuitable for installation.

Huang *et al.* [8] used Geographic Information System (GIS) to forecast the PV potential of all Chinese administrative areas. Aboushal *et al.* [9] use a probabilistic approach to find the optimum PV module which will then be installed at the best position previously determined by GIS. Karoline *et al.* [10] develop a method to predict the economic potential of PV on integrated buildings using hourly radiation simulation of an urban area where the facade area of high-rise buildings is almost triple the roof area, and installing PV on them would give an economic potential of 13%. Ko *et al.* [11] show how the performance of PV on low-elevation roofs is affected by the shadow created by adjacent tall buildings using the HillShade module method in ArcGIS. Li *et al.* [12] describe the effect of building inter-shadowing, which would reduce the PV yield by as much as 47.5% in a high-density building area. Mohajeri *et al.* [13] also proves the effect of building compactness in reducing the PV potential. A 15% reduction in energy yield for PV on the roof and a 17% reduction in energy yield for PV on the facade. Machete *et al.* [14] explain that neighboring properties and topographical relief have quite an impact on the PV performance. These factors could affect the energy yield by an average of 30%, compared to excluding them in the simulation. Garni *et al.* [15] emphasize the significance of tilt and orientation to increase the PV electricity yield. León *et al.* [16] take consideration of the roof tilt and the effect of orientation and report that a large area of roof could fit five times more panels than a roof with the smallest area and irregular shapes. Research about the PV potential in residential areas (both low and high-rise buildings) revealed the 3 factors influencing the electricity yield are the total area of roof and facade, the facade orientation, and the position of a building relative to the other buildings [17].

Previous studies have focused on the energy production of buildings and plants on an urban scale and even on the size of a country. This research, however, tries to investigate the PV yield on a smaller scale, namely landed housing. This type of residential property is preferred by Indonesian people, which enables them to have a bigger space to gather their family members in one house and also to own both the land and the house [18]. The property has quite a variety of roof shapes as the focal point. The roof itself also adds aesthetic value to the whole design of a house. The upper structure of a building increases the complexity of estimating PV potential on residential buildings, from a simple gable to a complex hip-roof construction.

By conducting study cases on roof geometry, it is discovered that roofs that receive more solar irradiance are i) flat, ii) shed, iii) gable, and iv) hip, in that order [19]. Mohajeri *et al.* [20] concluded that flat roofs receive the highest irradiation. A flat roof, on the other hand, is unsuitable for construction in a tropical country [21] because it is prone to water leakage. Flat and shed roofs are not a choice in the construction of landed housing in Indonesia. Meanwhile, gable, hip, and many complex roof shapes resulting from the combination of both of them are the common structures in housing construction.

This research takes place in Gorontalo city, which lies around 0.50 north of the equator. According to the global solar atlas (GSA), the province has an average PV potential of 4.2 kWh per day. The city is the capital of Gorontalo province, a developing province in the northern part of Sulawesi. The province itself already has a 2 MWp solar powerplant installed in 2016. The fact that Gorontalo received funds for PV installation exhibits the potential of solar power in the region. The potential of residential PV panels on the roof, especially on the houses, needs to be studied. The research will be useful for the people living in houses to estimate how much electricity will be provided to fulfill their own electricity consumption. This study proposes a simple method to roughly assess the PV panel potential of a house based on the roof design with the following parameters: roof shape, slope, and orientation.

2. METHOD

In compiling the assessment method, an exploration of roof's thermal and energy performance on different design is conducted. The three roof parameters' such as shape, orientation or the direction it's facing, and slope, are the variables which taken into account. The orientation referred to 2 types, the 1st is the azimuth, and the 2nd is the roof orientation associated with the axis of the roof's ridge. The roof is modelled on a rectangular plan in a parametric 3-dimensional design program namely Rhinoceros 3D. The program is capable in running environmental and renewable energy simulation.

Some researchers are utilizing the grasshopper, a 3D parametric program to conduct a form finding method to get the most suitable roof shape for PV which produce minimum shading on its own plane [22]. The program is also used to assess the performance of building integrated photovoltaics (BIPV) envelopes in Brazil [23]. To closely match the simulation result with the real condition, it requires local weather file data containing the values of sun radiation, air temperature, wind speed, and so on. The Gorontalo's weather file data used in this simulation is acquired from climate one building, which is the repository of climate data for Building Performance Analysis.

The simulation mainly using the Ladybug's photovoltaic surface component. The component calculates the energy production based on national renewable energy laboratory (NREL) PV watts v1 fixed tilt calculator for crystalline silicon (c-Si) and thin-film photovoltaics. PV watts model simulates energy production hourly [24]. The output of the simulation is the values of AC (alternating current) energy production per hour. Ladybug's radiation analysis component is also used as analysis tool to explain the result. Descriptive analysis method is applied in describing the findings. In calculation of the energy efficiency, the resulting electricity production of the roof's simulation will be compared to the region's PV potential issued by GSA.

There will be 2 stages of simulation distinguished by the objects. The first stage simulates the PV energy yield on simple conceptual objects. In this stage, a comparison of the PV performance on different designs of the roof is conducted. Furthermore, variables affecting the PV production are sorted according to the impact scale and employed to assess PV potential on roof designs. While in the second stage, the simulation is run on the model resembling the actual building, housing found in the city of Gorontalo. Several housings in the region of Gorontalo are selected and measured as the simulation objects. Prior to the simulation, the PV potentials of the housing roof is assessed using the variables mentioned above, then a prediction of the highest energy producing roof is made. The later simulation result is used to verify the impact of the variables in PV yield. The aim of this simulation is to verify the assessment method by comparing the energy produced by PV on all the models with the prediction. Finally, a comparison of the simulation result and PV potential by the GSA is carried out to find out the potential of PV production in given roof's shape, slope, and surface orientation.

2.1. Roof design

As a start, some simple roof shapes are selected to be analyzed in this research. Even though there are many roof shapes on the landed housing in Indonesia, the popular one is gable roof, for it is simple, and cheaper to build. Hence, many housing developers prefer this type of construction. The gable roof shape has 2 surfaces facing opposite way. On both square and rectangle floorplan, its ridge can be directed along the short or the long axis of the plan. The ridge will influence the direction the roof is facing and also the height of the roof. Roof with its ridge parallel to the short axis is higher than the roof with its ridge parallel to the long axis. However, despite the height difference, the roof surface area in both of them remains the same.

Hip roof shape has 4 surfaces and has one ridge's direction only which is on the long axis. On a square floorplan, the ridge will not exist. Consequently, floorplan modelled in this stage of simulation will take the shape of rectangle. For the simulation, the model's roof slope is tested on 10°, 15°, 20°, 25°, 30°, 35°, 40°, and 45°. Asbestos roof can be mounted on 10° slope roofs, the minimum angle a roof can be constructed to prevent water leakage. While most of the house roof is constructed in approximately 30° slope roofs, 45° is a maximum inclination for a conventional pitched roof.

As for the orientation, roof planes of the housings could be facing many directions such as the north, east, and so on. Gable roof faces 2 directions, and hip roof faces 4 directions. The simulation result on a roof model will cover more than one direction. The direction is measured using azimuth. North is azimuth 0°, south 180°, east 90° and west -90°. To cut the simulation process time, a step of 15° angle is taken, and there will only be 12 models for each type of roof.

2.2. PV specifications

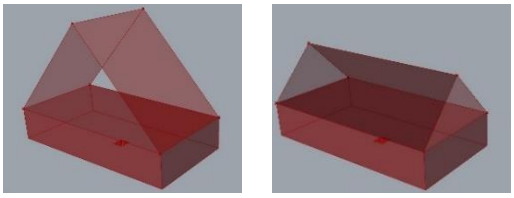
The PV employed in the simulation is specified as follows. Module material: crystal silicon, which is the popular PV material used in Indonesia. Module type: close (flush) roof mount, a gap between the roof and the panel is provided to allow air circulation to cool down both the roof and the panel. Module active area: 90%, which means the PV panel cover almost all over the roof, because there are some parts on the roof such as the ridge, hip, and valley where the pv is unmountable. Module efficiency: 15%. Temperature coefficient-0.5%/C. DC to AC derate factor: 0.85, which means the conversion factor from DC to AC is 0.85. The value of produced electricity written in this paper is in AC. The PV system size is determined by the formula:

$$SS = RA \times MAA \times ME \tag{1}$$

Where: SS is the PV system size in kW, RA is the roof area, MAA is the module active area, and ME is the module efficiency.

2.3. Building model

The model is 8 m long, 4 m wide, and 3 m height. The dimension is selected to resemble the size of simple housing in Indonesia whose area is around 36 m^2. A ratio of 2:1 between the length and the width of the building is applied. The aim of the 2:1 ratio is to create a distinct shape between gable roofs with its ridge parallel toward the width axis and the length axis of the building. A ridge is the line where the top edges of two roof planes coincide. The depiction of a ridge parallel to the width axis, and a ridge parallel to the length axis is shown in Figure 1.



(a) (b)

Figure 1. Gable roof with its ridge (a) parallel to the width axis and (b) parallel to the length axis

2.4. Simulation steps

Before the simulation is conducted, a series of simulation steps need to be determined. The first step is modeling the simulation object. Then the next step is the simulation process, starting from simulation with the least variables, and proceed to simulation with more variables. To organize the simulation, the steps are put in order as in Table 1.

Table 1. Simulation steps and the explanation of the process to acquire the research aims

Steps	Variables
Modeling the building and the roof	
Finding the best roof shapes	Gable and hip roof shapes are simulated. Roof slope 30° is employed. Objects longest axis oriented to azimuth 90° and -90°.
Finding the best roof slope	The slope of the best roof shape is modified from a low angle (a minimum of 10°), until the high angle (a maximum of 45°)
Finding the best roof orientation	The roof is rotated from azimuth 0° to azimuth 165°. Inside the range, 15° step is employed, so only 12 models are calculated

3. RESULTS AND DISCUSSION

Gable roof has 2 surfaces, and hip roof has 4 surfaces. The PV is mounted on all of the surfaces, and the result on this section is showing the sum of electricity produced on all of the roof planes.

3.1. Result of roof shape simulation

A comparison of PV productivity on the hip and gable roofs is shown in the Table 2. Gable roof is separated in 2 orientations according to the direction of the ridge. Gable with its ridge parallel to the length axis will be named as gable A, and the other one with its ridge parallel to the width axis as gable B. On the same floor plan dimension, the three types of the roof have the same area, which also means all of the PV system size are similar. In comparison, there is not a single superior roof shape in producing electricity. There is less than 1% of difference among the 3 roof shapes. Even though the planes of gable A and B are different in the direction they are facing to, the result is almost similar, which indicate that the orientation is not a matter influencing the PV productivity.

Table 2. PV electricity production on different roof shapes

	Roof Shape		
	Hip	Gable A	Gable B
Total roof area (m^2)	36.95	36.95	36.95
System size (kWp)	4.98	4.98	4.98
Annual Electricity Production (kWh)	6,612	6,621	6,585
Production per roof area (kWh/m^2)	178.95	179.2	178.21

3.2. Result of roof slope simulation

While there is no significant difference in the simulation result of roof shape above, the process is then resumed to the roof slope simulation using all of the roof shapes as the model. A total of 24 models (which consist of 3 roof shape and 8 inclination) facing azimuth 90° and -90° is simulated. The roof slope simulation in Figure 2 explains, as the slope degree increased, the roof's slope length is also increasing. Eventually, the roof area is also expanding, and as a result, the system size increase, so is the electricity production.

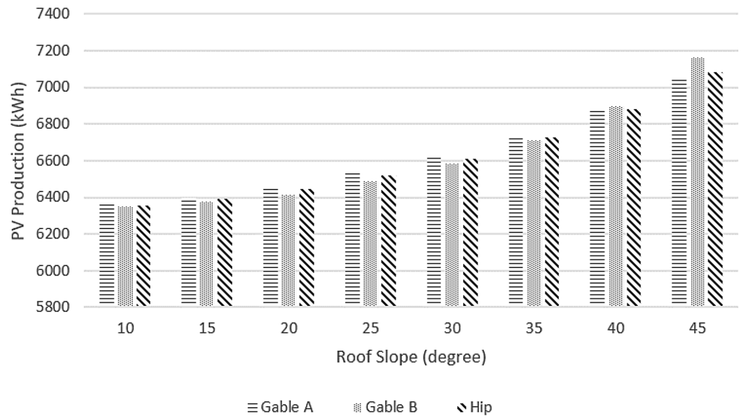


Figure 2. PV electricity production on different roof slopes

PV on roof slope 45°, produce 10% more electricity than 10° roof slope, however, the productivity is not proportional to the roof area and the system size itself. The 45° roof slope's system size is 28% bigger than the 10°'s, and the large system size is expected to yield more energy. The relation among the roof area, system size, annual production, and production per roof area is shown in Table 3.

Table 3. Roof slope and PV productivity

Roof Slope	Roof area (m^2)	System size (kWp)	Production (kWh)	Production per roof area (kWh/m^2)
10°	32.49	4.39	6,350.01	195.4452
15°	33.13	4.47	6,374.82	192.4185
20°	34.05	4.60	6,411.52	188.2973
25°	35.31	4.77	6,485.94	183.6856
30°	36.95	4.99	6,585.71	178.233
35°	39.06	5.27	6,709.71	171.7797
40°	41.77	5.64	6,898.42	165.1525
45°	45.25	6.11	7,161.12	158.2569

It can be seen, as the roof slope increase, PV productivity decreased. A look into the radiation analysis and sunlight hours is conducted to learn more on this finding. Ladybug radiation analysis and sunlight hours analysis component are the tool used to calculate the maximum radiation and the total duration of the roof in receiving the sunlight. Gable B roof shape is employed as the simulation model.

The Figure 3 is showing the maximum sunlight hours and radiation on a plane. The 10° roof slope received both the highest radiation and the longest duration of sun exposure. Due to the inclination, 45° roof, is so tall, that one plane will prevent the other plane in obtaining the sunlight at the same time. Consequently, receiving lesser sunlight and radiation compared to the lower sloped roof. While on the 10° roof, the planes are almost flat and receiving sunlight simultaneously during the daytime. The 10° roof receives 23% and 16% more sunlight and radiation than the 45° roof, respectively.

The smaller the plane's angle, the longer a surface obtain radiation a day long to produce more electricity. Low angle roof means shorter truss structure and narrower roof area. This construction will benefit in the saving of material and cost construction, thus low budget and affordable. But a low angle roof construction would also provide small volume of the attic and supporting the heat to build up easily inside. However, it is discovered that the coverage of PV on the roof could decrease the heat gain [25], therefore the building's cooling load would also be diminished [26]. Research on the effect of PV to cool down the roof and building in Indonesia is needed in the future to raise the use value of PV panel.

Based on the observation on the field, a house employing 10° slope roof is quite a rare sight. It is found mainly on the shophouse and commercial buildings whose facade deliver the image of a modern building. While the 30° roof slope is a common construction, housing constructed in more than 30° roof angles can be recognized easily due to its bulging shape, protruding the sky.

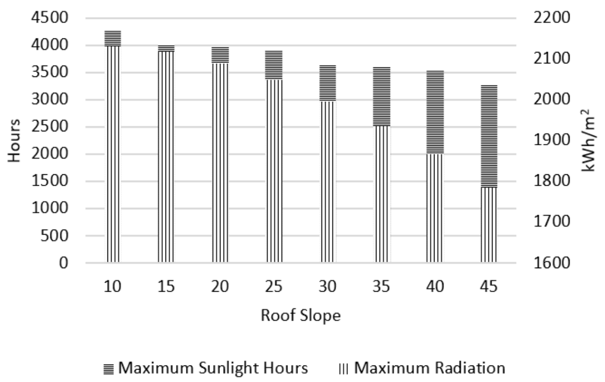


Figure 3. Comparison of maximum radiation and sunlight hours on different roof slopes

3.3. Result of roof orientation simulation

In this stage, the roof is rotated and tested at different azimuth to obtain the energy production. Since there are plentiful of possible angles to include in the simulation, only several of them are calculated. Gable roof has two planes facing opposing way. Since a roof oriented along east-west direction will have two orientations, azimuth 90° and -90°, the need of constructing many models is not necessary. Twelve models (24 azimuths) are used in the simulation (with 15° step). As there is no notable roof shape in the result of first stage simulation, any shape is employable. Gable B, as the sample, with the slope angle of 10°, 15°, 20°, 25°, 30°, 35°, 40°, and 45° is employed in this simulation. The result is given in Table 4.

In all of the roof's inclination, the maximum yield is achieved on the azimuth -90° or the West orientation. The East is the worse orientation the roof should be facing to, as it turns out as the azimuth where the roof planes producing the least. Except for the higher inclination, 40° roof's produce minimum result in azimuth 75°, and 45° roofs in azimuth 60°. There is only a 4% difference of production between the best and worst orientation in 10° roof slope. As the roof inclination increase, the gap escalates, 6% in 15° roof slope, 8% in 20° roof slope, 9% in 25° roof slope, 11% in 30° roof slope, 12% in 35° roof slope, 13% in 40° roof slope and 14% in 45° roof slope. But for a gable roof with its 2 planes oriented toward both east and west simultaneously, the combination is actually a poor one. In fact, the combination of roof facing 0°, and 180°, generates more power than the others. A radiation analysis of the roof models in orientation simulation is conducted to observe the difference of radiation on different orientation of the roof. For both the 90° and -90° azimuth, the contrast in radiation gain is high compared to 0° and 180° azimuth in Figure 4.

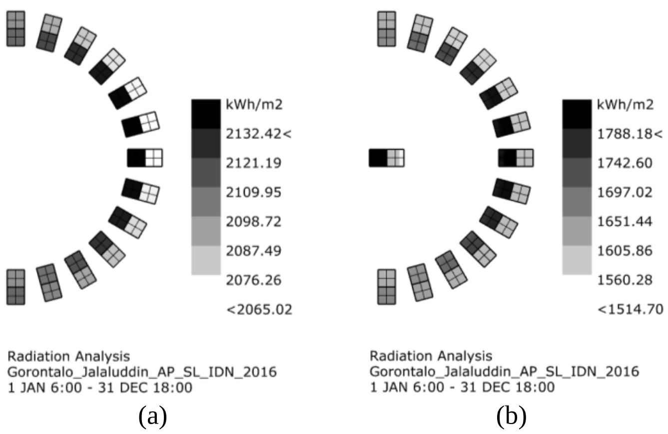


Figure 4. Sun radiation analysis on (a) 10° roof and (b) 45° roof

Table 4. PV electricity production of a roof plane on different azimuths

Azimuth	Electricity Production (kWh)							
	Slope 10°	Slope 15°	Slope 20°	Slope 25°	Slope 30°	Slope 35°	Slope 40°	Slope 45°
0°	3175.68	3193.21	3218.03	3251.18	3294.34	3348.54	3416.38	3501.04
15°	3160.96	3168.79	3184.46	3208.79	3243.38	3289.43	3345.11	3421.12
30°	3146.25	3145.68	3153.23	3170.36	3196.54	3230.48	3283.92	3356.83
45°	3133.49	3125.96	3126.83	3133.90	3150.48	3183.72	3236.84	3312.85
60°	3123.97	3111.00	3102.46	3103.35	3120.97	3159.55	3214.94	3297.01
75°	3118.53	3100.50	3084.43	3091.05	3110.74	3143.44	3202.53	3298.65
90°	3117.76	3096.82	3079.39	3090.56	3109.09	3134.37	3207.16	3305.34
105°	3121.87	3101.32	3087.66	3096.23	3118.34	3144.84	3211.94	3308.69
120°	3130.45	3114.76	3104.24	3114.67	3135.67	3165.86	3229.10	3314.86
135°	3141.93	3136.13	3131.30	3143.21	3170.01	3202.31	3256.62	3338.48
150°	3155.02	3160.10	3169.32	3183.36	3213.39	3256.28	3312.46	3392.89
165°	3169.41	3183.69	3204.47	3232.43	3270.11	3320.48	3385.24	3465.60
180°	3184.04	3206.34	3237.41	3277.38	3326.68	3387.27	3462.12	3555.87
-165°	3197.96	3227.49	3266.25	3315.16	3375.23	3447.68	3537.01	3645.95
-150°	3210.34	3246.06	3291.21	3346.64	3413.50	3495.75	3595.11	3718.28
-135°	3220.43	3261.00	3311.00	3370.48	3443.45	3531.62	3638.99	3779.49
-120°	3227.66	3271.57	3324.56	3386.63	3463.45	3557.10	3672.95	3824.12
-105°	3231.65	3277.28	3331.59	3394.49	3474.90	3572.70	3689.22	3850.71
-90°	3232.25	3278.01	3332.13	3395.38	3476.62	3575.34	3691.26	3855.79
-75°	3229.46	3273.77	3326.48	3389.51	3467.26	3563.08	3682.65	3835.33
-60°	3223.44	3264.84	3314.89	3375.26	3449.35	3538.88	3653.79	3799.01
-45°	3214.53	3251.69	3297.63	3353.24	3422.29	3506.44	3609.38	3742.72
-30°	3203.19	3234.87	3275.37	3325.36	3386.69	3462.46	3554.41	3672.03
-15°	3190.00	3215.15	3248.99	3292.09	3345.40	3410.40	3489.95	3587.62

3.4. Verification of simulation result

Based on the simulations, it is found that the most impactful factors on the production of electricity of the PV roof, is the roof slope. Roof orientation seconds that, while the roof shapes have no influence on PV production. Assessment of PV production on the roof could be done by simply measuring the roof slope and identifying the roof orientation. However, these simulation results need to be verified as a measure to confirm the productivity. To do so, the simulation results will be compared to GSA data, whom collected the PV potential of regions around the globe. According to GSA, the power potential of 1 kWp system in Gorontalo is around 4.2 kWh per day or 1533 kWh annually. The comparison of the energy production on gable in the 8 slopes to the power potential is provided in Table 5. While Figure 5 depicts the comparison of the energy production in the 8 slopes and 24 azimuths all together.

The lower the roof slope, the closer it meets the GSA power potential. PV mounting on all of the examined roof slopes will not meet the expected 100% power potential. Generally, roofs are constructed in around 30° slope, and this comparison state that the efficiency of the system is about 86%. Which means that a 1 kWp PV system bought by a consumer will only produce 3.6 kWh of electricity of the expected 4.2 kWh.

A peak of 96% of electricity production is achievable for the 10° and 15° roof slope in the azimuth of -90°. Meanwhile a maximum of 71% electricity will be produced by the 45° roof slope in the azimuth of 45° to 135°. The more surfaces of the roof facing West, or the larger area of the roof surfaces facing West, the better the roof design is for the purpose of producing electricity by roof PVs.

The conducted simulations however, are employing simple roof shapes as the model, which is rarely found on the field. Housings are commonly constructed on the combination of these simple shapes to create a more aesthetically pleasing design. Therefore, the research proceeds to conduct simulation of the PV production on the more complex roof design. The objective is to find out whether the factor influencing the energy yield on simple roof shape will also work on the complex roof shapes, and if the productivity remains the same.

Table 5. Comparison of gable B simulation result (azimuth 90° and -90°) and GSA PV power potential of Gorontalo

Roof slope	Roof area (m^2)	System size (kWp)	Power potential (kWh)	Simulation Result (kWh)	Comparison of simulation to power potential (%)
10°	32.49	4.39	6,723.97	6,350.01	94%
15°	33.13	4.47	6,856.42	6,374.82	93%
20°	34.05	4.60	7,046.82	6,411.52	91%
25°	35.31	4.77	7,307.58	6,485.94	89%
30°	36.95	4.99	7,646.99	6,585.71	86%
35°	39.06	5.27	8,083.66	6,709.71	83%
40°	41.77	5.64	8,644.51	6,898.42	80%
45°	45.25	6.11	9,364.71	7,161.12	76%

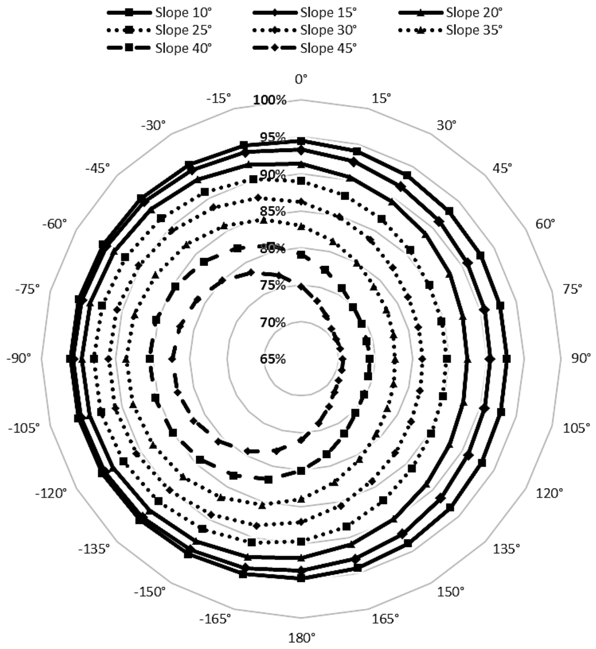


Figure 5. Comparison of the performance of PV on 8 slopes and 24 azimuth

3.5. Verification of simulation result

To test the assessment method on some housing designs in Gorontalo city, 4 selected housings are surveyed, measured using laser meter, modelled, and then simulated. The selection is based on the roof shapes, azimuth, and slope. While the simple gable and hip roof are the object on this study, the roof constructed on the housing are far more complex in shape. Roofs are often combined to create an eye-catching design. The selected housings photos and the roof models are presented in Figure 6. These are the representative of the complex and simple roof housing found in Gorontalo.

Among the 4 housing (Wongkaditi Permai 3, Solaria 3, and Griya Dulomo Indah) have gable roof construction with the planes facing just 2 directions. Wongkaditi 3 is made on the combination of several gable shapes, and the planes face 4 directions. Anggrindo 2 housing is built on a complex roof structure, the combination of gable and hip. The roof has 3 surfaces facing north and south, and 3 surfaces facing east and west. To simplify in writing names, these housings will be shortened as housing: Anggrindo 2 as housing A in Figure 6(a), Wongkaditi Permai 3 as housing B in Figure 6(b), Solaria 3 as housing C in Figure 6(c), and Griya Dulomo Indah as housing D in Figure 6(d). The roofs are facing various azimuths. More information on the buildings can be found in Table 6.

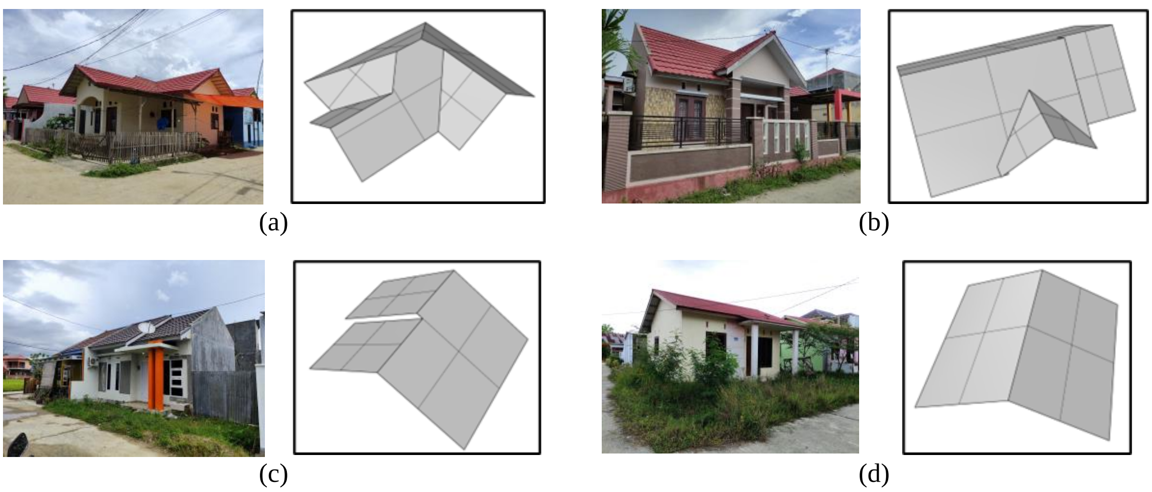


Figure 6. Photos of the housing and the simulation models: (a) housing A, (b) housing B, (c) housing C, and (d) housing D

Table 6. Specifications of the housing

Housing	Roof shape	Slope	Roof surfaces	Surface Orientations (azimuth)	Roof area (m^2)	PV System Size (kW)
A	Complex (Gable + hip)	35°	6	65°, 155°, -25°, -25°, -115°, -115°	100	13.5
B	Gable (2 perpendicular)	38°	5	0°, 90°, 180°, 180°, -90°	56	7.58
C	Gable (split level)	30°	3	140°, -40°, -40°	49.61	6.7
D	Gable	22°	2	120°, -60°	52.5	7.1

Housing B has the steepest slope and is expected to produce the lowest electricity among the housings. Housing D on the otherwise, has the most slope roof among the others, and therefore should be high in production. By examining the roof inclination, the performance of PV production on the housings can be assessed from the highest to the lowest as follows: housing D, C, A, and B. To proof the assessment, the PV energy production of the models are simulated in the program.

The result, as shown in Table 7, puts housing D as the roof with the highest electricity produced. It fits the assessment result because of its low slope (22°). The second is housing D, which has a steeper slope than housing D. Apart from its steep slope, the geometry of roof on housing B creates self-shading effect which could also be the factor affecting this result. Housing A complex roof which has split level construction will have a higher and lower part. The higher roof can shade and reduce the PV productivity of the lower roof. Housing B, C, and D have smaller roof area compared to the housing A, hence the system size is also lower. Nevertheless, the production per roof area on housing A is lower than housing C and D, despite the system size of housing A is almost double the value of both.

Comparison to the PV potential map by GSA was also conducted. Simulation result shows housing D produce 9803 kWh annually, which is about 94% of the expected annual PV potential of a 7.1 kW system size in Gorontalo. The rest as shown in Table 7. As in the result of Table 5, a 20° sloped roof has about 91% of energy potential, but then in Figure 5, the influence of azimuth could increase the potential up to 95% and decrease down to 87% (a 8% difference between the maximum and minimum).

Table 7. Comparison of simulation result and PV power potential

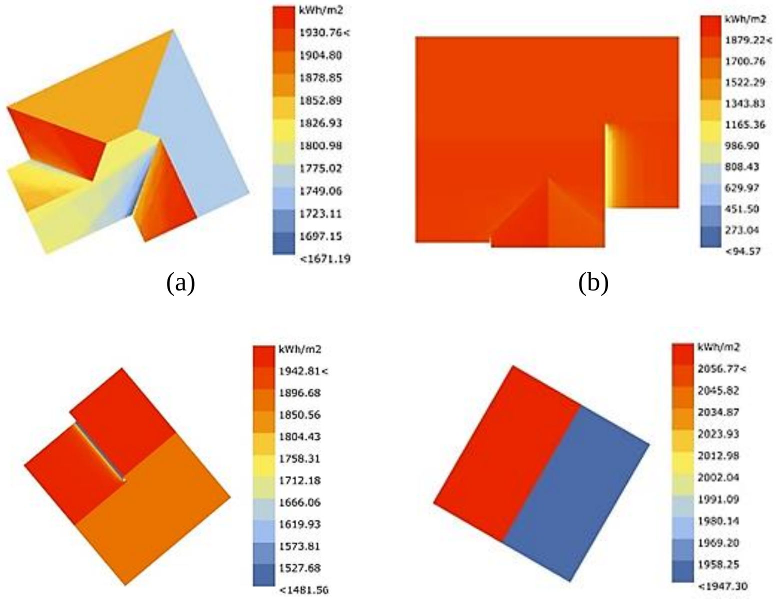
Housing	PV System Size (kW)	Annual Production (kWh)	Annual PV Power Potential (kWh)	Percentage
A	13.5	17,194	20,709	83%
B	7.58	9,425	11,627	81%
C	6.7	8,854	10,277	86%
D	7.1	9,803	10,865	90%

Among the 4 objects, housing D registered the highest and the closest value to meet the annual PV power potential. Radiation analysis simulation on the roof of the housings is then conducted to find out more about the relation between the sun radiation falling on the roof and the PV electricity yield as shown in Figure 7. While on the split-level roof construction of housing B and C, the lower plane is shaded by the upper plane, resulting in the decrease of radiation gain. For most of the roof planes, the maximum radiation is achieved on the West facing surfaces. Having most areas facing north and south, roof on housing B gaining almost the equal radiation on all of the surfaces.

Comparison of the result of radiation analysis simulation is given on Table 7. As a total, housing A receives more radiation than the other housing since it has broader roof plane. But in terms of maximum and minimum radiation, housing D receives the highest. The result is similar to Table 6 where housing A has the biggest annual energy yield but it turns out the effectivity is actually lower compared to housing D. The result of PV energy production simulation on complex roof shapes is showing similar outcome as the simpler roof shapes.

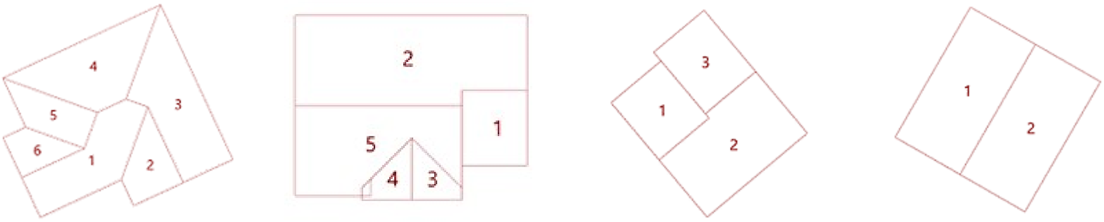
For each housing's roof, a separation of the surfaces is necessary to analyze the energy production on each of them. The number of the roof planes is illustrated in Figure 8. Electricity production for each roof planes of roof on housing A, B, C, and D are given in Table 8-11 respectively. The west facing surfaces (number 2, 4, 5, and 6) producing more electricity than the east facing surfaces (number 1 and 3) in housing A. Among the West facing surfaces, planes number 2 and 5 have the highest potential (88%) since its azimuth is closer to -90°. Overall, the average potential of electricity production in housing A is 83%. The average is quite lower than the highest PV potential since the sum of surface 1, and 3, (81% and 78% potential) are making up 48% of the roof areas.

The major roofs of housing B are facing north-south direction, therefore there is only 1% of potential difference between both orientations. However, due to the high slope, the PV produce less electricity. The average potential is just 81%, the least from all the housings. Roof of housing C is divided in 2 orientations with equal areas. The roof is leaning slightly toward the north-south direction and the slope is 30°. The potential difference of both orientation is 6%, but the resulting potential is quite high. Having the lowest slope, roof D faces west-east direction. Despite the orientation, the average potential is still the highest among all the compared roofs.



(a) (b) (c) (d)

Figure 7. Radiation analysis results: (a) housing A, (b) housing B, (c) housing C, and (d) housing D



(a) (b) (c) (d)

Figure 8. The Housing's surfaces' order: (a) housing A, (b) housing B, (c) housing C, and (d) housing D

Table 8. Analysis of PV electricity production on the roof of housing A

Surface	Azimuth	System Size (kWp)	Annual Production (kWh)	Annual PV Power Potential (kWh)	Percentage
1	155°	2.87	3562	4395	81%
2	-115°	1.38	1864	2114	88%
3	65°	3.65	4369	5600	78%
4	-25°	3.28	4291	5034	85%
5	-115°	1.40	1894	2149	88%
6	-25°	0.93	1214	1424	85%

Table 9. Analysis of PV electricity production on the roof of housing B

Surface	Azimuth	System Size (kWp)	Annual Production (kWh)	Annual PV Power Potential (kWh)	Percentage
1	180°	0.92	1150	1408	82%
2	0°	3.74	4622	5734	81%
3	90°	0.35	401	531	75%
4	-90°	0.35	460	531	87%
5	180°	2.23	2792	3420	82%

Table 10. Analysis of PV electricity production on the roof of housing C

Surface	Azimuth	System Size (kWp)	Annual Production (kWh)	Annual PV Power Potential (kWh)	Percentage
1	-40°	1.61	2199	2465	89%
2	140°	3.35	4274	5134	83%
3	-40^0	1.74	2381	2669	89%

Table 11. Analysis of PV electricity production on the roof of housing D

Surface	Azimuth	System Size (kWp)	Annual Production (kWh)	Annual PV Power Potential (kWh)	Percentage
1	-60°	3.54	5077	5433	93%
2	120°	3.54	4726	5433	87%

3.6. Comparison to the PV electricity production in a Gorontalo housing

Some houses in Gorontalo are incorporating PV into their building, applying the Hybrid system which uses both the electricity provided by the utility company and the PV. One of the houses has been harvesting the solar energy since 2017 and gain around 40% saving in electricity bill. Seven PV panels are utilized to generate electricity in the house with a total system capacity of 1.8 kWp. The system, as shown in Figure 9, consisted of two parts, 0.6 kWp (3×200 Wp) panels to power the house in daylight and 1.2 kWp (4×300 Wp) panels connected to the battery as the electricity source during the night. By examining the electricity bill before the utilization of PV, it is found that the house annual energy consumption is about 6927 kWh. The value reduced to 4225 kWh after enjoying the benefit of PV installation for a year. Thus, the 1.8 kWp PV is assumed to produce around 2702 kWh annually. Compared to the PV annual production on housing A, B, C, and D on the previous discussion.

(a) (b)

Figure 9. PV installed (a) on the carport's roof and (b) on a rack

The first part (0.6 kWp) is located on top of the carport roof with an inclination of 6° facing north, while the second part (1.2 kWp) is mounted on a rack, elevated 1 meter above the roof, sloped 2° facing south. The roof of the house itself is inclined 37° above the horizontal plane. Both parts of the PV's slope are unparallel to the main roof's slope. PV installer aware of the potential of the slope angle to boost the productivity of PV, which explain why the system is not mounted on the steeper roof. The installation does not take the complex main roof shape as a possible place to put the PV on.

A simulation on the PV performance of the 1.8 kWp is conducted to compare the real production and the simulation production. The result is shown in Table 12, notice that the sum of both parts is only 2606 kWh, about 96 kWh less than the estimated production in reality (2702 kWh). The difference between the real and simulation production is 4%, depicting the reliability of the simulation method using ladybug and the weather data used in the process.

Table 12. Simulation of PV electricity production on the roof of housing

Part	Azimuth	Slope	System Size (kWp)	Annual Production (kWh)	Annual PV Power Potential (kWh)	Percentage
1	10^0	6^0	0.6	865	919	94%
2	-170^0	2^0	1.2	1741	1840	94%

4. CONCLUSION

A method to assess the potential of PV panels based on roof design has been proposed in this research by conducting simulation experiments with the parameters of roof shape, slope, and orientation. The goal is to figure out how well PV works on a roof, especially on the roof of a house with a yard. The research would be beneficial to housing owners, developers, and engineers in forecasting electricity production by just examining the roof's parameters.

It is found that, in the case of Indonesia, the lower the slope, the more electricity production can be achieved. The orientation is the second factor influencing PV productivity. In the case of Gorontalo, which lies on the equator, a north-south orientation is better for the relatively sloped roof. Otherwise, for a 45° roof, an east-west orientation would benefit more electricity production. For a single-surface roof, the research advises facing the roof to the west as the radiation is higher in this direction. For two-surface roofs, a north-south orientation is recommended. Hence, the potential difference between both surfaces is small. Complex roof construction, or roofs with more than two surfaces, should be thoroughly planned because the surfaces may face multiple directions, influencing PV productivity. Most of the surfaces, or the largest areas of the complex roof, should be directed toward the West in order to maximize the radiation gain and electricity production. A comparison of PV productivity on simple roof shapes show that it has no contribution in influencing the energy yield at all.

By conducting the PV energy production simulation on 8 roof slopes and 24 azimuths, the research is able to generate a chart providing the PV potential on the roof. The two variables are sufficient in assessing the potential. Nevertheless, the maximum potential of the highest productivity roof (the West-facing 100 roof's slope) is only 96%, compared to the PV energy potential of Gorontalo established by GSA. While mounting PV on all of the roof surfaces is costly, people might opt to install the PV on the part where the potential is the highest. The research findings should be able to help choose the best roof section for producing electricity.

The method defined in the research could simplify the energy potential assessment of PV panels on the roofs of buildings, particularly housing. The method is considered low-cost and only requires convenient measuring tools to obtain the inclination and orientation of the roof. Either the measurement or the assessment can be learned and done by anyone. Using common tools means that the method is more executable and eliminates the need to use high-tech equipment such as LiDAR. However, the method is lacking in evaluating the potential of large-scale housing areas or even buildings in an urban region, as the measurement process takes more time and effort.

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