LAPORAN AKHIR

PENELITIAN MANDIRI

Metode Menilai Potensi Panel PV Atap berdasarkan Desain Atap

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RINGKASAN

Indonesia terletak di garis khatulistiwa, memiliki potensi sinar matahari yang berlimpah sebagai sumber energi yang dapat dikonversi menjadi tenaga listrik. Pengubahan tersebut dilakukan menggunakan Pembangkit Listrik Tenaga Surya (PLTS) yang dirangkaikan dengan peralatan listrik lainnya sampai menjadi listrik yang dapat digunakan untuk menyalakan berbagai perangkat elektronik. PLTS dapat dipasang terintegrasi dengan bangunan atau terpisah dengan bangunan. PLTS yang berintegrasi dengan bangunan berupa PLTS di atas atap atau yang dipasang pada fasad bangunan. Pada bangunan tinggi dengan jumlah lantai berpuluh-puluh, PLTS dapat dipasang pada bidang fasad yang memiliki luas bidang dinding yang besar. Namun, pada bangunan rendah seperti rumah tinggal, maka bidang atap sebagai bidang terluasnya menjadi pilihan utama sebagai lokasi PLTS.

PLTS Atap dapat mengurangi tagihan listrik, dengan cara alih-alih menggunakan listrik PLN pada siang hari, listrik yang diproduksi oleh PLTS Ataplah yang digunakan. Makin banyak daya PLTS Atap yang dimiliki akan semakin baik, semakin besar pula penghematan yang didapatkan. Berbagai penelitian dan preseden menjelaskan, secara arsitektural, besar produksi energi listrik oleh PLTS pada atap dipengaruhi oleh beberapa hal seperti kemiringan atap, arah hadap atap, hingga bentuk atap dan luas bidang atapnya. Kesemuanya akan saling berkaitan dengan desain bangunan secara keseluruhan, dan berpengaruh terhadap faktor desain arsitektur seperti estetika tampilan bangunan, jenis konstruksi bangunan, tata letak bangunan pada lahan, dan lain-lain. Perlu adanya kajian-kajian yang diakukan secara bertahap untuk mengatasi baik masalah penyediaan energi listrik melalui PLTS Atap dan masalah arsitektural bangunannya.

Kajian ini akan diawali dengan menentukan variabel-variabel atap dan PLTS yang akan berpengaruh terhadap produksi energi listrik, membuat model bangunan pada program simulasi, kemudian PLTS Atap dimodelkan di atas bangunan. Program simulasi digunakan untuk mendapatkan besar produksi listrik PLTS Atap. Hasil simulasi ini akan digunakan untuk menghitung besar penghematan tagihan listrik, dengan cara membandingkannya dengan data daya listrik terpasang, dan besar tagihan listrik yang telah diperoleh sebelumnya,

Kata Kunci: Atap, Perumahan, PLTS Atap, Energi listrik

BAB I PENDAHULUAN

1.1 Latar Belakang

Indonesia, khususnya Gorontalo memiliki potensi untuk memproduksi listrik melalui PLTS hingga sebesar 4,3kWp per hari[1]. Angka ini setara dengan 4300 Wh yang artinya dapat memenuhi kebutuhan listrik sebuah bangunan bahkan jika penggunaaan daya listriknya sebesar (maksimal) 175 W setiap jam selama 24 jam (1 hari penuh). Potensi sebesar ini tentunya harus dimanfaatkan dengan cara menggunakan PLTS sebagai sumber listrik pada bangunan.

Sebelum menggunakan PLTS perlu mengetahui terlebih dahulu cara menggunakannya, cara merancang pemasangannya agar peralatannya dapat bekerja secara efisien. Pedoman ini dapat ditemukan pada buku Panduan Perencanaan dan Pemanfaatan PLTS Atap di Indonesia[2] yang menjelaskan secara lengkap terkait seluk beluk PLTS Atap. Panduan ini sangat membantu bagi masyarakat awam dalam merencanakan pemasangan PLTS Atap untuk bangunannya.

Penggunaan PLTS Atap diklaim dapat menghemat tagihan listrik PLN hingga enam puluh persen[3]. Media lain melalui perhitungan menyebutkan penghematan bisa mencapai kurang lebih 79%[4]. Bahkan pada kenyataannya, penghematan yang diperoleh melebihi besar perkiraan penghematannya itu sendiri[5]. Berbagai klaim menunjukkan kelebihan penggunaan PLTS Atap yang akan membantu mengurangi biaya operasional bangunan yang tentunya sangat diinginkan oleh semua kalangan masyarakat. Kelebihan PLTS Atap dalam mengurangi tagihan listrik ini perlu ditelusuri, khususnya di Gorontalo dengan pengaruh cuaca lokal sebagai variabel yang mempengaruhi kinerja PLTS Atap.

Berbagai bangunan memiliki atap sebagai penutup struktur atas, melindungi bangunan dari panas Matahari dan basah air hujan. Atap pada bangunan didesain dengan beragam bentuk sesuai tipologi, fungsi, bentuk bangunan, dan selera pemilik bangunan. Beda jenis

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[1] The World Bank, Source: Global Solar Atlas 2.0, Solar resource data: Solargis, 2019
[2] Indonesia Clean Energy Development II, Panduan Perencanaan dan Pemanfaatan PLTS Atap di Indonesia
[3] Janaloka, Benarkah Rumah Menteri ESDM Bisa Hemat Dengan Panel Surya?, Juli 2018
[4] Pvinasia, Penggunaan Sistem Panel Surya Untuk Rumah Dengan Daya 2200 VA, Juni 2020
[5] Fikru, 2019. Estimated electricity bill savings for residential solar photovoltaic system owners: Are they accurate enough?

bangunan, beda pula desain atapnya. Pada jenis bangunan rumah, desain atap biasanya merupakan olahan geometri dari bentuk seperti pelana dan limasan atau perisai. Pada rumah pula, desain atap dibuat berkreasi untuk memberikan nilai estetika, dan ciri khasnya. Perumahan adalah salah satu jenis bangunan yang berfungsi hunian yang dapat dipasangkan PLTS Atap. Perumahan saat ini telah menjadi pilihan bagi masyarakat untuk memiliki hunian permanen yang terjangkau. Bentuk atap pada perumahan umumnya seragam, namun keseragaman ini mempermudah dalam menilai potensi panel PV atap. Dibanding menilai potensi PV atap pada rumah biasa yang sangat bervariasi, menilai potensi PV atap pada perumahan akan lebih mudah dilakukan dan sekaligus dapat memberikan gambaran potensi pada kawasan perumahan tersebut. Namun, pada beberapa perumahan memiliki berbagai desain atap yang sama, dan beberapa perumahan lainnya desain atapnya berbeda. Adanya perbedaan pada desain ini perlu dikaji untuk mencari desain yang optimum untuk PLTS atap. Metode pencarian desain yang optimum menjadi pertanyaan penelitian ini.

Untuk menjawab pertanyaan di atas, penelitian mengenai metode menilai potensi panel PV atap berdasarkan desain atap khususnya bangunan perumahan ini diusulkan. Dengan menggunakan data cuaca lokal (Gorontalo) sebagai input yang menentukan jumlah waktu penyinaran dan intensitas cahaya matahari yang berpengaruh terhadap produksi energi listrik, akan dapat disimulasikan kinerja PLTS Atap dengan hasil yang sesuai dengan kondisi setempat. Analisisnya akan membandingkan hasil simulasi pada berbagai desain atap perumahan sehingga dapat ditemukan desain yang terbaik.

Penelitian ini diharapkan dapat mendukung rencana dan strategi Universitas Negeri Gorontalo khususnya dalam hal intensifikasi energi. Kajian tentang pemaksimalan kinerja PLTS Atap yang akan dilakukan dari sisi arsitektural ini mencoba memberikan gambaran dan pertimbangan dalam menerapkan teknologi energi baru dan terbarukan, khususnya PLTS di Gorontalo.

1.2 Rumusan Masalah

Berdasarkan uraian di atas maka dapat dirumuskan masalah sebagai berikut:

- Bagaimana metode menilai potensi panel PLTS Atap berdasarkan desain atap pada bangunan perumahan?.

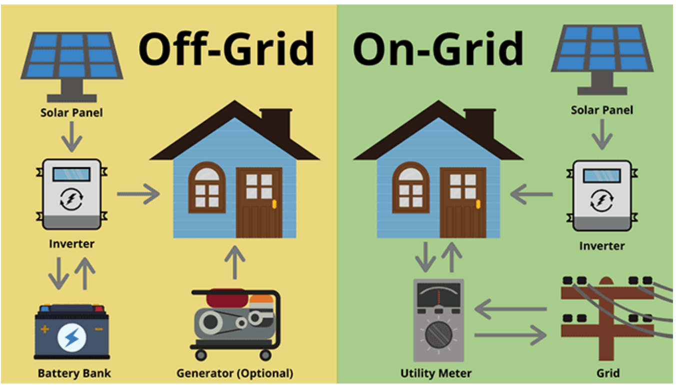
1.3 Batasan Masalah

Penelitian ini hanya akan membahas masalah penilaian potensi panel PV berdasarkan desain atap perumahan. Perumahan berbeda dengan rumah tinggal yang desain atapnya lebih bervariasi dibanding atap perumahan. Objek perumahan yang akan diambil sebagai sampel dan diamati adalah perumahan yang berlokasi di kota Gorontalo. Perumahan dipilih sebagai objek penelitian karena bentuknya yang relatif sederhana serta ukurannya yang lebih kecil dibanding atap rumah tinggal pribadi pada umumnya.

BAB II KAJIAN PUSTAKA

2.1 PLTS Atap

PLTS adalah perangkat sistem pembangkit energi listrik yang sumber tenaganya berasal dari radiasi matahari kemudian dikonversi oleh sel fotovoltaik menjadi listrik[6]. Jika dipasang pada atap, maka disebut PLTS Atap. Untuk bekerja PLTS memerlukan beberapa komponen yang berfungsi antara lain untuk mengatur tegangan yang dihasilkan, mengubah tegangan dari arus searah menjadi arus bolak-balik, serta komponen yang dapat menyimpan energi listrik untuk dapat digunakan di waktu lain. Komponen yang disebutkan terakhir dapat menjadi pilihan untuk digunakan atau tidak. Jika tidak digunakan, maka manfaat PLTS hanya dapat digunakan pagi hingga siang hari saat matahari bersinar. Dan sebaliknya, jika digunakan maka listriknya dapat disimpan dan digunakan pada malam hari.



Gambar 2.1 Sistem PLTS Off-Grid dan On-Grid

Sumber: paradisesolarenergy.com

Dalam penggunaannya, PLTS dapat dipasang secara on grid dan off grid[7]. Perbedaan keduanya bergantung apakah PLTS tersambung dengan jaringan listrik PLN. On grid berarti PLTS tersambung dengan PLN, sehingga saat ada kelebihan daya yang tidak digunakan, daya tersebut akan dikirimkan oleh PLN ke fasilitas lain yang membutuhkannya. Sedangkan Off grid berarti tidak tersambung dengan PLN dan menggunakan baterai untuk menyimpan

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[6] Badan Standardisasi Nasional, SNI 8395:2017
[7] Indonesia Clean Energy Development II, 2018, Buku Panduan Studi Kelayakan PLTS Terpusat Off-Grid

energi listrik yang berlebih. Adapun gabungan keduanya disebut dengan sistem hybrid. Dimana terdapat pengotomasian, jika baterai yang digunakan untuk menyimpan listrik telah penuh, maka energi listrik berikutnya yang tidak digunakan oleh perangkat elektronik akan dikirim ke jaringan PLN.

Untuk memproduksi energi listrik PLTS menggunakan panel fotovoltaik yang memiliki berbagai jenis efisensi dan ukuran daya yang dihasilkan. Jenis panel fotovoltaik ini antara lain:

- Monocrystalline, memiliki efisiensi tertinggi, memiliki dimensi yang relatif lebih kecil (dibanding polycrystalline), cocok untuk area atap terbatas, warna hitam.
- Polycrystalline, memiliki efisiensi sedang, harga relatif lebih terjangkau (dibanding monocrystalline), warna kebiruan.

Dalam bekerja, panel fotovoltaik idealnya mendapatkan radiasi matahari sepanjang hari tanpa terbayangi oleh objek seperti bangunan, bagian dari bangunan, atau pepohonan. Bayangan yang ada dapat mengakibatkan tidak maksimalnya energi listrik yang dihasilkan.

Gambar 2.2 Panel surya terbayangi oleh bagian bangunan

Sumber: cleanenergyreviews.info

Kinerja panel fotovoltaik dipengaruhi pembayangan objek-objek di sekitarnya, Dalam kaitannya dengan arsitektur, seharusnya desain bangunan dibuat sehingga tidak ada bagian bangunan yang lebih tinggi dari bagian atap yang dapat membayangi panel. Demikian halnya bangunan bersebelahan yang jika tingginya melebihi tinggi atap, akan dapat membayangi panel ini. Konfigurasi atap yang melibatkan bentuk atap, kemiringan atap, dan arap hadap atap diperlukan untuk mendapatkan desain atap yang dapat memaksimalkan kinerja PLTS Atap.

2.2 Atap Bangunan Perumahan

Atap pada bangunan perumahan umumnya terdiri atas bentuk-bentuk seperti pelana (sisi miring hanya pada 2 arah), atap perisai (sisi miring di lebih dari 2 arah), atau gabungan keduanya yang menjadikan bentuk atap lebih rumit. Pengembang perumahan cenderung membangun produknya dengan bentuk pelana yang sederhana sehingga pembangunannya juga lebih mudah dan biaya konstruksinya pun lebih rendah pula. Atap dengan bentuk yang sederhana akan lebih mudah untuk dipasangkan PLTS Atap di atasnya. Sedangkan atap dengan bentuk yang tidak beraturan atau rumit akan sulit untuk dipasangkan PLTS Atap, terlebih lagi bila menggunakan panel fotovoltaik dengan kapasitas dan dimensi yang besar[7].

Gambar 2.3 Bentuk atap shed

Sumber: houzz.com

Selain bentuk atap, kemiringan atap mempengaruhi kinerja PLTS Atap. Atap yang relatif datar lebih baik dibanding atap dengan sudut kemiringan yang besar[8]. Sedangkan untuk Indonesia dengan curah hujan yang tinggi, atap perlu dibuat miring agar air hujan segera turun dari atap dan tidak menggenang sehingga tidak menimbulkan kebocoran. Bahan penutup atap seperti seng yang sering digunakan di Gorontalo, perlu dipasang dengan

[8] Mohajeri, N., et al, (2016), Does Roof Shape Matter? Solar PV Integration on Roofs, Sustainable Built Environment (SBE) Regional Conference, Zurich, June 15-17 2016

kemiringan 20^0-25^0 [9]. Namun berdasarkan pengamatan dan pengukuran di lapangan, ditemukan atap dengan kemiringan 35^0, melebihi standar yang ada. Bentuk atap berikutnya yang direkomendasikan adalah atap shed[10] yaitu bentuk atap untuk naungan sederhana yang hanya terdiri atas 1 bidang yang miring. Karena hanya memiliki 1 bidang, maka seluruh panel fotovoltaik akan mendapat radiasi matahari sepanjang hari, berbeda dengan bentuk atap seperti pelana yang terdiri atas 2 bidang miring dan dapat saling meneduhkan satu sama lainnya.

Atap sebagai wadah untuk PLTS Atap perlu dibuat sedemikian sehingga panel fotovoltaik dapat terus mendapatkan radiasi matahari sepanjang hari agar memiliki kinerja yang baik, namun perlu memperhatikan juga bentuk dan kemiringan atap agar keindahan bangunan yang meliputi estetika bentuk dan proporsi atap terhadap bangunan secara keseluruhan.

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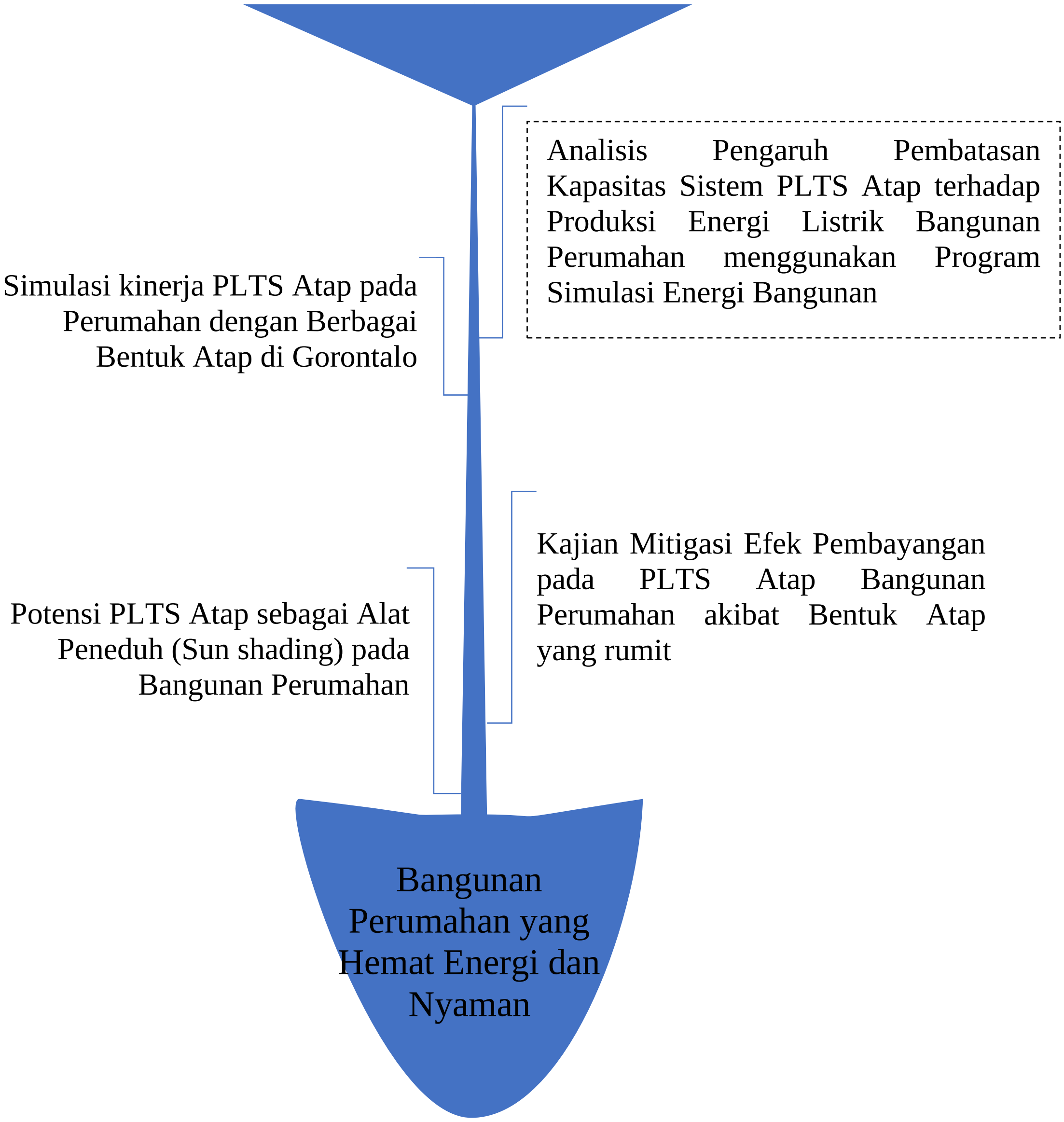
[9] Kementerian Pekerjaan Umum, 2011, Materi Pelatihan Berbasis Kompetensi.
[10] Shapiro, Ian. (2012). The Receptivity of Roofs to Solar Panels. 887. 10.3390/wsf2-00887

2.3 Road Map Penelitian



Gambar 2.4 Roadmap Penelitian

BAB III TUJUAN DAN MANFAAT PENELITIAN

3.1 Tujuan Penelitian

Tujuan penelitian ini adalah untuk mengetahui metode menilai potensi panel PLTS atap berdasarkan desain atap. Selain itu penelitian ini bertujuan untuk memberikan gambaran energi yang dapat dihasilkan pada atap.

3.2 Manfaat Penelitian

Penelitian ini bermanfaat untuk memberikan informasi dan gambaran tentang potensi dan besaran energi yang bisa didapatkan melalui pemasangan panel PLTS atap di atap bangunan perumahan. Hasilnya dapat dimanfaatkan bagi para arsitek, perancang, dan pemilik bangunan yang ingin memasang panel PLTS Atap di bangunan perumahan.

BAB IV METODE PENELITIAN

4.1 Lokasi dan Waktu Penelitian

Penelitian dilakukan di kota Gorontalo dengan mengambil objek yang diteliti yaitu perumahan di kota Gorontalo. Waktu yang dibutuhkan untuk melakukan penelitian kurang lebih 4 bulan yang terdiri atas kegiatan pengambilan data, pembuatan gambar dan model, penyimulasian model, menganalisis hasil simulasi, dan membuat kesimpulan.

4.2 Cara Penelitian dan Analisis

1. Penelusuran Pustaka

   Pada tahap ini peneliti membaca jurnal dan literatur terkait dengan metode penilaian potensi energi terbarukan pada bangunan dan hal-hal yang mempengaruhi kinerja PLTS atap. Tahap ini akan berguna dalam menganalisis hasil yang diperoleh di lapangan dan hasil simulasi.
2. Pengumpulan Data

   Penelitian diawali dengan pengamatan bentuk-bentuk atap perumahan yang ada di kota Gorontalo. Pengamatan dilakukan sambil memilih 4 bentuk atap yang dapat mewakili bentuk-bentuk atap yang ditemukan. Setelah itu dilakukan pengukuran ke 4 atap menggunakan alat laser meter.
3. Pra Simulasi - Pembuatan Gambar dan Model

   Hasil pengamatan dan pengukuran digambar pada komputer dan dibuatkan model 3Dnya untuk digunakan pada tahap simulasi.
4. Simulasi

   Pada tahap ini dilakukan simulasi menggunakan program Grasshopper dan plugin Ladybug. Atap bangunan model dihubungkan dengan komponen PV Surface untuk bisa menyimulasikan besar energi listrik yang dihasilkan pada tiap atap. Simulasi dilakukan untuk setiap atap model yang dibuat. Pada tahapan ini digunakan file data cuaca Gorontalo sebagai faktor yang mempengaruhi hasil produksi energi listrik pada simulasi.
5. Analisis Hasil Simulasi

Hasil simulasi energi listrik yang diproduksi oleh tiap model atap akan dianalisis dengan cara membandingkan nilai terendah, nilai tertinggi, dan rata-rata produksi energi listrik dari tiap model. Kemudian menganalisa faktor yang menyebabkan tingginya hasil yang ada berdasarkan kemiringan atap, arah orientasi bidang atap, hingga bentuk atap. Terakhir menentukan model yang terbaik berdasarkan hasil analisis.

6. Analisis Perbandingan Hasil Simulasi dengan Kondisi di Lapangan

   Membandingkan hasil simulasi dengan hasil produksi energi listrik yang ada pada rumah yang menggunakan PLTS Atap di Indonesia. Ini dilakukan untuk menguji metode simulasi yang telah digunakan dengan cara melihat perbedaan hasil keduanya. Selisih antara keduanya diharapkan kecil sebagai tanda keandalan metode simulasi ini,

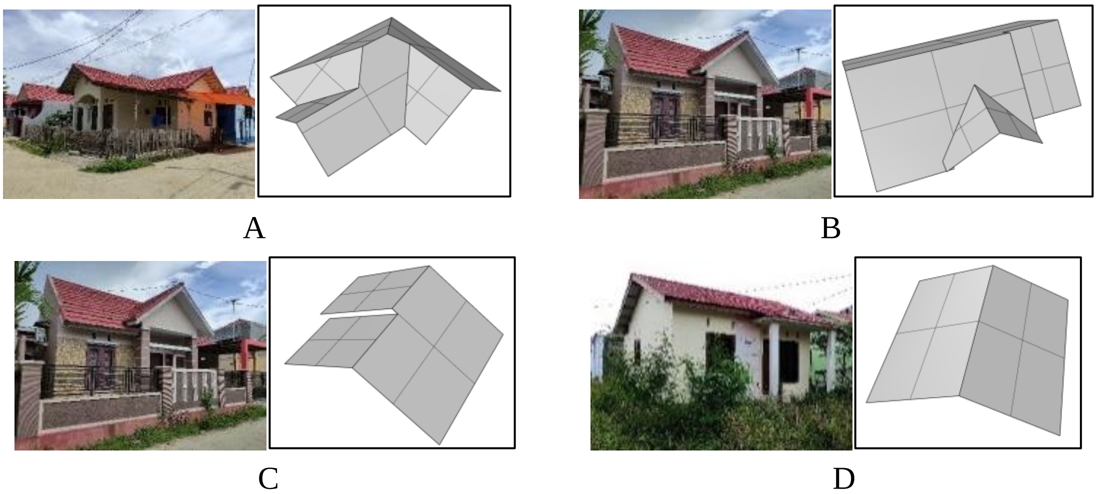
7. Pembuatan Kesimpulan

   Membuat kesimpulan berdasarkan hasil simulasi dan analisis-analisis yang telah dilakukan di atas.

BAB V HASIL DAN PEMBAHASAN

5.1 Hasil Pengamatan Lapangan

Setelah melakukan pengamatan lapangan, didapati beberapa objek perumahan yang menarik untuk diteliti antara lain perumahan A (Anggrindo 2), B (Wongkaditi Permai 3), C (Solaria 3), and D (Griya Dulomo Indah). Kesemua perumahan berlokasi di kota Gorontalo.



Gambar 5.1 Keempat perumahan yang diamati

Spesifikasi perumahan diberikan pada tabel berikut:

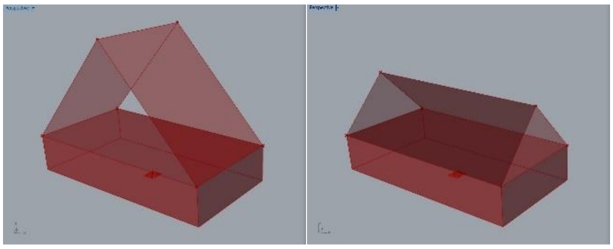
Tabel 5.1. Specifikasi Perumahan

Perumahan	Bentuk Atap	Kemiringan	Jumlah bidang atap	Orientasi bidang (azimuth)	Luas atap (m^2)	Ukuran sistem PV (kW)
A	Complex (Pelana+perisai)	35°	6	65°, 155°, -25°, -25°, -115°, -115°	100	13,5
B	Pelana (2 tegak lurus)	38°	5	0°, 90°, 180°, 180°, -90°	56	7,58
C	Pelana (terpisah tinggi)	30°	3	140°, -40°, -40°	49,61	6,7
D	Gable	22°	2	120°, -60°	52,5	7,1

5.2 Hasil Simulasi

5.2.1 Simulasi Bentuk Atap Sederhana

Sebelum melakukan simulasi terhadap ke 4 atap perumahan di atas, dilakukan simulasi terhadap bidang atap sederhana yang terdiri atas atap pelana A (bubungan sejajar lebar bangunan), pelana B (bubungan sejajar panjang bangunan), dan atap perisai. Simulasi ini dilakukan sebagai pembanding terhadap bidang atap yang rumit seperti pada perumahan A, B, dan C.



Gambar 5.2 Pelana A dan B

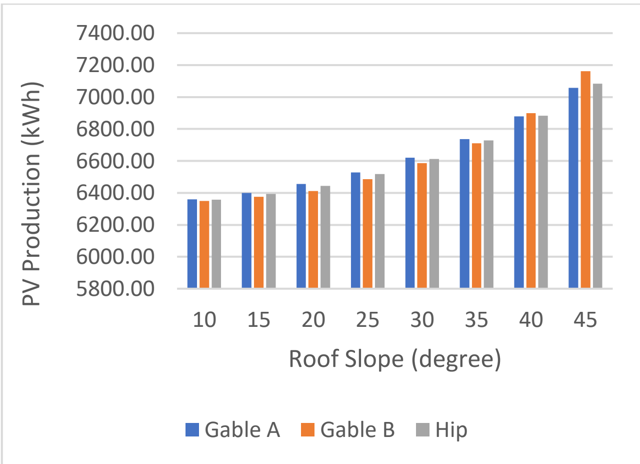
Tabel 5.2. Besar produksi listrik panel PV pada 3 bentuk atap

	Bentuk Atap		
	Perisai	Pelana A	Pelana B
Total luas atap (m^2)	36,95	36,95	36,95
Ukuran sistem (kWp)	4,98	4,98	4,98
Produksi Listrik Tahunan (kWh)	6612	6621	6585
Produksi per luas atap (kWh/m^2)	178,95	179,2	178,21

Hasil simulasi menunjukkan perbedaan produksi yang kecil, tidak signifikan, antara ketiga bentuk atap.

5.2.2 Simulasi Kemiringan Atap Sederhana

Pada simulasi ini, besar sudut kemiringan dari ketiga bentuk atap diubah-ubah menjadi kemiringan 10°, 15°, 20°, 25°, 30°, 35°, 40°, dan 45°, namun ukuran lebar dan panjang bangunan tidak diubah. Hasil simulasi seperti pada gambar 5.3.



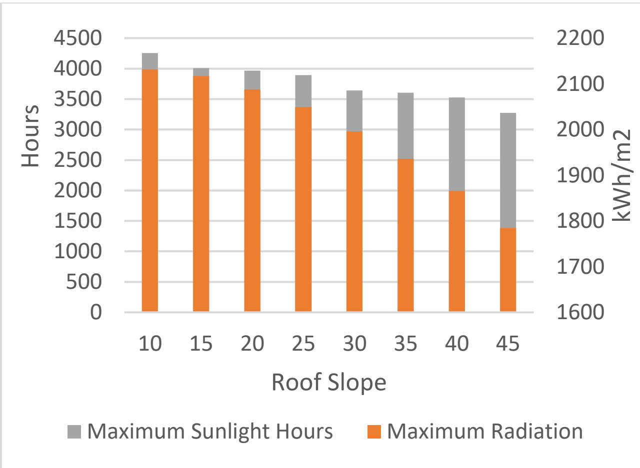
Gambar 5.3 Hasil simulasi produksi energi pada berbagai kemiringan atap.

Hasilnya menunjukkan peningkatan pada pertambahan sudut kemiringan atap. Namun peningkatan ini disebabkan oleh adanya peningkatan luas bidang atap juga. Jika dihitung produktivitas energi yang dihasilkan dengan cara membagi besar produksi listrik dan luas atap, hasilnya justru lebih rendah dibanding atap dengan kemiringan kecil. Produktivitas tertinggi ada pada atap dengan kemiringan 10°. Hasilnya dapat dilihat pada tabel 5.3

Tabel 5.3. Besar Produksi energi PV pada berbagai kemiringan atap

Kemiringan atap	Luas atap (m^2)	Ukuran sistem (kWp)	Besar produksi (kWh)	Produksi per luas atap (kWh/m^2)
10°	32.49	4.39	6350.01	195.4452
15°	33.13	4.47	6374.82	192.4185
20°	34.05	4.60	6411.52	188.2973
25°	35.31	4.77	6485.94	183.6856
30°	36.95	4.99	6585.71	178.233
35°	39.06	5.27	6709.71	171.7797
40°	41.77	5.64	6898.42	165.1525
45°	45.25	6.11	7161.12	158.2569

Untuk menelusuri rendahnya produktivitas atap 45°, dilakukan simulasi yang membandingkan besar radiasi yang jatuh pada atap dan lama penyinaran mataharinya. Hasilnya ditunjukkan pada gambar 5.4.



Gambar 5.3 Hasil simulasi besar radiasi dan penyinaran cahaya Matahari pada berbagai kemiringan atap.

Hasilnya menunjukkan atap dengan kemiringan 10° mendapatkan baik radiasi sinar Matahari dan lama penyinaran yang sama-sama tinggi. Makin besar sudut kemiringan atap, makin menurun perolehannya. Dengan demikian dapat dipahami kenapa produktivitas PV pada atap 45° yang paling kecil.

5.2.3 Simulasi Orientasi Atap

Simulasi ini dilakukan untuk melihat pengaruh orientasi atap dan berbagai kemiringan atap terhadap besar produksi energi listrik panel PV. Atap berkemiringan 10°, 15°, 20°, 25°, 30°, 35°, 40°, dan 45°, diputar pada arah azimuth 0°, 15°, 30°, 45°, 60°, 75°, 90°, -90°,-75°, -60°, -45°, -30°, dan -15°. Dengan 0° menunjukkan arah Utara, 180° menunjukkan arah Selatan, 90° menunjukkan arah Timur, dan -90° menunjukkan arah Barat. Sebuah atap pelana sederhana memiliki 2 bidang atap yang berlawanan arah. Sehingga jika diputar menghadap ke azimuth 0°, maka salah satu bidang atap menghadap ke 0°, dan bidang satunya menghadap ke 180°. Begitupula dengan atap 15°, maka bidang satunya menghadap ke -165°. Hasilnya ditunjukkan pada tabel 5.4.

Tabel 5.4. Besar Produksi energi PV pada berbagai kemiringan atap dan orientasi

Azimuth	Produksi Listrik (kWh)							
	Miring 10°	Miring 15°	Miring 20°	Miring 25°	Miring 30°	Miring 35°	Miring 40°	Miring 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

Jika dianalisa per bidang orientasi, maka dapat dilihat bahwa arah hadap Barat (-90°) memberikan hasil terbesar pada seluruh kemiringan atap. Namun atap pelana tidak bisa dinilai per satu bidang saja, produksi energi pada kedua bidangnya harus dijumlahkan untuk melihat total kinerjanya. Jika melihat total kedua bidang atap pelana, maka dapat dilihat orientasi terbaik ternyata dapat dipengaruhi oleh kemiringan atap. Terlihat untuk atap pada kemiringan 10° hingga 35°, orientasi terbaik adalah pada Utara dan Selatan, namun untuk atap pada kemiringan 40°, dan 45°, orientasi terbaik ada pada arah Barat dan Timur.

5.2.4 Perbandingan Hasil Simulasi dengan Global Solar Atlas

Global Solar Atlas (GSA), adalah sebuah website yang memberikan data radiasi Matahari secara global, termasuk data potensi energi PV. Hasil simulasi pada penelitian ini dibandingkan dengan hasil pada GSA untuk mendapatkan validasi hasil. Menurut GSA potensi daya Gorontalo untuk sebuah 1 kWp sistem adalah 4,2 kWh per hari, atau 1533 kWh per tahun. Perbandingan antara besar simulasi pada beberapa kemiringan atap dan ukuran sistemnya dengan potensi PV oleh GSA sebagai berikut:

Tabel 5.5. Perbandingan Besar Produksi energi PV hasil Simulasi dengan potensi PV GSA

Kemiringan atap	Luas atap (m^2)	Ukuran sistem (kWp)	Potensi (kWh)	Hasil Simulasi (kWh)	Perbandingan simulasi dan potensi (%)
10°	32.49	4.39	6723.97	6350.01	94%
15°	33.13	4.47	6856.42	6374.82	93%
20°	34.05	4.60	7046.82	6411.52	91%
25°	35.31	4.77	7307.58	6485.94	89%
30°	36.95	4.99	7646.99	6585.71	86%
35°	39.06	5.27	8083.66	6709.71	83%
40°	41.77	5.64	8644.51	6898.42	80%
45°	45.25	6.11	9364.71	7161.12	76%

Hasilnya menunjukkan bahwa atap berkemiringan rendah memiliki hasil yang lebih mendekati potensi PV menurut GSA. Dalam kata lain, potensi PV menurut GSA dapat tercapai jika bidang PV lebih rendah dari 10°.

Dari berbagai simulasi yang telah dilakukan pada atap sederhana dapat dilihat bahwa atap berkemiringan rendah memiliki potensi produksi energi PV yang besar. Hasil ini diperkirakan akan berlaku pada bentuk atap rumit yang ditemukan pada atap perumahan..

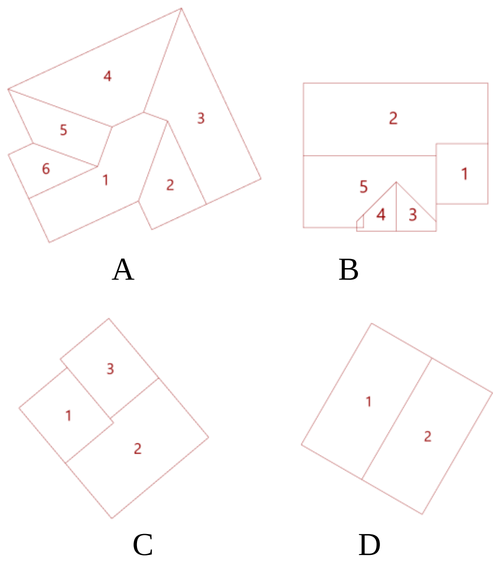
5.3 Menilai Potensi PV pada Atap Perumahan

Simulasi produksi energi listrik pada ke 4 atap perumahan yang telah diukur dan dimodelkan. Hasilnya sebagai berikut:

Tabel 5.5. Hasil simulasi produksi listrik pada 4 perumahan

Perumahan	Ukuran sistem PV (kW)	Produksi tahunan (kWh)	Potensi PV tahunan (kWh)	%
A	13,5	17194	20709	83%
B	7,58	9425	11627	81%
C	6,7	8854	10277	86%
D	7,1	9803	10865	90%

Perumahan A memiliki hasil produksi tahunan yang terbesar disebabkan luasnya bidang atap dan ukuran sistemnya. Namun kemiringan atap menjadi faktor yang mempengaruhi rendahnya persentae perbandingan produksi tahunan terhadap potensi tahunannya. Sedangkan perumahan D yang memiliki kemiringan atap 22° sehingga persentasenya lebih besar dibandingkan perumahan A. Hasil simulasi ini perlu dibreakdown lagi untuk melihat kontribusi setiap bidang atap terhadap total produksi energi. Setiap bidang pada atap diberi nomor untuk menunjukkan produksi masing-masingnya.



Gambar 5.4 Urutan bidang pada atap

Tabel 5.6. Analisis produksi energi PV pada atap perumahan A

Bidang	Azimuth	Ukuran sistem (kWp)	Produksi tahunan (kWh)	Potensi Daya Tahunan (kWh)	%
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%

Tabel 5.7. Analisis produksi energi PV pada atap perumahan B

Bidang	Azimuth	Ukuran sistem (kWp)	Produksi tahunan (kWh)	Potensi Daya Tahunan (kWh)	%
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%

Tabel 5.8. Analisis produksi energi PV pada atap perumahan C

Bidang	Azimuth	Ukuran sistem (kWp)	Produksi tahunan (kWh)	Potensi Daya Tahunan (kWh)	%
1	-40°	1.61	2199	2465	89%
2	140°	3.35	4274	5134	83%
3	-40^0	1.74	2381	2669	89%

Tabel 5.9. Analisis produksi energi PV pada atap perumahan D

Bidang	Azimuth	Ukuran sistem (kWp)	Produksi tahunan (kWh)	Potensi Daya Tahunan (kWh)	%
1	-60°	3.54	5077	5433	93%
2	120°	3.54	4726	5433	87%

Hasil breakdown produksi energi per bidang atap menunjukkan hasil yang beragam. Atap perumahan D memiliki persentase yang paling tinggi dibanding ke 4 atap lainnya. Selisih antara kedua bidang atapnya hanya 6%. Atap perumahan B memiliki rata-rata persentase terendah dengan selisih antara bidang dengan persentase tertinggi dan terendahnya sebesar 12%. Hanya atap perumahan D yang dapat mencapai persentase di atas 90%.

5.4 Perbandingan dengan Produksi Panel PV di Keadaan Nyata

`Beberapa rumah di kota Gorontalo telah memasang panel PV pada bangunannya. Besar produksi energi listrik yang dihasilkan oleh panel ini akan dibandingkan dengan hasil simulasi yang telah dilakukan pada penelitian. Rumah ini dipasangi panel PV dengan total ukuran sistem 1,8 kWp yang dibagi atas 2 bagian, yaitu di atas garasi dan di atas sebuah rak di atap. Kedua bagian ini dipasang pada kemiringan yang rendah, tidak dipasang atau mengikuti kemiringan atap rumah yang cukup tinggi. Hal ini menunjukkan pemahaman para pemasang panel PV akan kemiringan instalasi yang ideal. Kedua bagian PV ini dimodelkan dan disimulasikan pada komputer.

Produksi energi listrik yang dihasilkan PV di rumah ini diperkirakan melalui besar penghematan tagihan listriknya dalam 1 tahun. Diketahui besar penghematannya 2702 kWh per tahun sehingga diasumsikan besar energi yang diproduksi PV untuk rumah ini adalah sebesar 2702 kWh.

Gambar 5.5 Panel surya yang dipasang di atas garasi, dan di atas rak pada atap.

Tabel 5.10. Simulasi energi dari PV yang dipasang pada rumah Gorontalo

Bagian	Azimuth	Kemiringan	Ukuran sistem (kWp)	Produksi tahunan (kWh)	Potensi PV (kWh)	%
1	10^0	6^0	0.6	865	919	94
2	-170^0	2^0	1.2	1741	1840	94

Hasil simulasi menunjukkan total produksi energi listrik untuk ke 2 bagian sebesar 2606 kWh. Tidak terdapat perbedaan yang besar antara estimasi panel PV dan hasil simulasi yang dilakukan dengan program komputer. Hasil ini menunjukkan metode menilai potensi panel PV berdasarkan desain atap menggunakan program simulasi ini dapat diterima.

BAB VI KESIMPULAN DAN SARAN

6.1 Kesimpulan

Panel PV sangat berguna untuk memproduksi energi listrik dan mengurangi tagihan listrik atau ketergantungan terhadap listrik PLN. Namun pemasangannya membutuhkan perencanaan yang matang. Penelitian ini dilakukan untuk menilai potensi panel PV yang akan dipasang di atap, berdasarkan desain atapnya sendiri, khususnya pada bangunan berjenis perumahan. Tujuannya untuk dapat menilai berapa energi yang dapat dihasilkan jika panel diletakkan di atas atap rumah.

Penelitian dilakukan dengan melakukan pengamatan dan pengukuran terhadap beberapa perumahan di kota Gorontalo. Dilanjutkan dengan membuat simulasi produksi energi listrik dari PV baik pada atap sederhana, dan atap perumahan yang telah diamati. Hasil simulasi dibandingkan dengan data potensi energi PV yang diperoleh dari Global Solar Atlas, dan dengan contoh rumah yang telah mengaplikasikan panel PV pada bangunannya. Hasilnya atap dengan kemiringan rendah memiliki besar produksi energi dan produktivitas yang terbaik dibandingkan atap berkemiringan yang lebih tinggi. Selisih antara hasil simulasi dengan potensi dan contoh di lapangan cukup kecil sehingga metode simulasi yang digunakan untuk menilai potensi panel PV berdasarkan desain atap pada penelitian ini dapat diterima.

6.2 Saran

Penelitian terhadap berbagai tipologi atap perumahan lainnya diperlukan untuk melihat secara keseluruhan bagaimana desain atap yang terbaik dalam penerapan teknologi energi terbarukan.

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Method to Assess the Potential of Photovoltaic Panel Based on Roof Design

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ABSTRACT

The photovoltaic 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 which would impact the electricity generation. The roof on housing in Indonesia, were built generally in a complex shape, a combination of gable and hip roof. This research is conducted to breakdown factors affecting PV productivity in regard to the roof's aspects. A computer simulation using Ladybug plugin in Rhinoceros software has been done to achieve the target. Initially, the performance of PV panel on gable, and hip roof, is analyzed respectively. 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 a housing, and the estimation provided by the simulation is conducted to verify the assessment method. The difference is about 4%, as a proof the simulation result is reliable.

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1. INTRODUCTION

Photovoltaic (PV) is a promising investment to save electricity expenditure. In 2020, PV is dominating the renewable energy capacity expansion [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 mostly below 1000 USD/kW [2]. Meanwhile, despite the high cost and the economic problem caused by the covid-19 pandemy, PV installation demand in Indonesia is increasing [3]–[5]. One of the driving forces in the rise of PV sales is the Indonesian government's campaign on using the renewable energy resources.

Household sector especially housings consume relatively low electricity per house. A simple housing with an area of 36 to 45 m2 is provided a 900 to 1300 VA electricity supply by the utility company. PV should be able to cover the electricity usage of such household. A research is reporting that the household and the commercial sector in Indonesia have a high potential solar energy application [6].

To convince people to invest on PV panel, it is important to assure them about the benefit they will gain in the future. Better understanding of how the 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 are many researchs on the method to assess PV panel potential on buildings. Yuan et al. employing aerial photos of an area to acquire the roof planes for PV mounting and also objects which would shade and diminish the PV performance [7]. However, this method requires high accuracy in retrieving the samples and also in detecting the roof planes and obstacles. Lingfors et al. compared both low and high-resolution LiDAR data to calculate the PV potentials, to detect the roof types, and analyze the shadow on roof [8]. The result show that in an area whose building are homogenously distributed, the low-resolution data has 78-86% in accuracy level. Lukac et al. develop a method to determine the potential PV location based on LiDAR data, and then rank them from the roof with high potential to the roof unsuitable for installation [9].

Huang et al. employing GIS to predict the PV potential on all the administration area of China [10]. Aboushal et al. using probabilistic approach to find the optimum PV module which will then be installed on the best position previously determined by GIS [11].

Karoline et al develop a method to predict the economic potential of PV on integrated building using hourly radiation simulation of an urban area, where the façade area of high-rise buildings almost the triple of its roof area and installing PV on them would give economic potential of 13%. [12].

Ko et al show how the performance of PV on low elevation roof is affected by the shadow created by adjacent tall buildings using the HillShade module method in ArcGIS [13]. Li et al describes the effect of building inter-shadowing which would reduce the PV yield as much as 47,5% in a high-density building area. [14].

Mohajeri et al, also prove the effect of compactness of building in reducing the PV potential. A 15% reduce of energy yield for PV on the roof, and 17% for PV on the façade [15]. Machete et al. explains that neighbouring properties and topography reliefs have a quite an impact on the PV performance. These factors could affect the energy yield by an average of 30%, compared to excluding them in simulation [16].

Al Garni et al. emphasize the significance of tilt and orientation to increase the PV electricity yield [17]. Zalamea et al., take considerations of the roof tilt and the effect of orientation and report that large area of roof could fit five times more panels than roof with the smallest area and irregular shapes [18]. On research about the PV potential in residential area (both low and rise building) revealed the 3 factors influencing the electricity yield are the total area of roof and façade, the façade orientation, and position of a building relative to the other buildings [19].

Previous studies are focusing on energy production of buildings and plants in urban scale and even in the size of a country. This research, however, is trying to investigate the PV yield on a smaller scale, landed housing. This type of residential property is preferable by many of Indonesian people, and it is also an important segment market in the country [20]. The property has quite a variety of roof shapes as the focal point. The roof itself also adding aesthetic value to the whole design of a house. From a basic gable into a complex hip roof construction, this upper structure of a building raises the complexity of estimating PV potential on residential building.

By conducting study cases on the roof geometry, it is found that roofs which receive more solar irradiance are: 1. flat, 2. shed, 3. gable, 4.hip, ordered from the high to low receptivity [21] . Mohajeri seconds this research and concluded that flat roof receives the highest irradiation [22]. But on the other hand, a flat roof is unsuitable to be constructed in the high precipitation rate area of Indonesia [23], because it is susceptive to water leakage. Flat and shed roof is not a choice in the construction of the landed housing in Indonesia. Meanwhile, gable, hip, and many complex roof shapes resulting from the combination of both of them are the common structure in the housing construction.

The research takes place in Gorontalo city, which lies around 0.50 North of equator. According to Global Solar Atlas, 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 fund for PV installation exhibits the potential of solar power in the region.

Potential of residential PV panel on the roof especially on the housing need to be studied. The research will be useful for the people living in housing to estimate how much of electricity will be provided to fulfil their own electricity consumption.

This study proposes a simple method to roughly assess the PV panel potential on housing based on the roof design with the 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 [24]. The program is also used to assess the performance of BIPV envelopes in Brazil [25]. 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.OneBuilding, 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 NREL PVWatts v1 fixed tilt calculator for crystalline silicon (c-Si) and thin-film photovoltaics. PVWatts model simulates energy production hourly [26]. 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 global solar atlas.

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 simulaton objects. Prior to the simulation, the PV potentials of the housing roof is assessed using the variables mention 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 Global Solar Atlas 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. Eventhough 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:

$$SS = RA \times MAA \times ME$$

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 m2. 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.

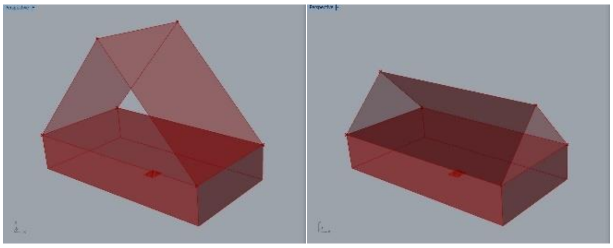


Fig 1. Gable roof with its ridge parallel to the width axis (left), and parallel to the length axis (right)

2.4. Simulation Steps

To organize the simulation, the steps are put in order as follows.

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. 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.

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)	6612	6621	6585
Production per roof area (kWh/m^2)	178,95	179,2	178,21

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.

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.

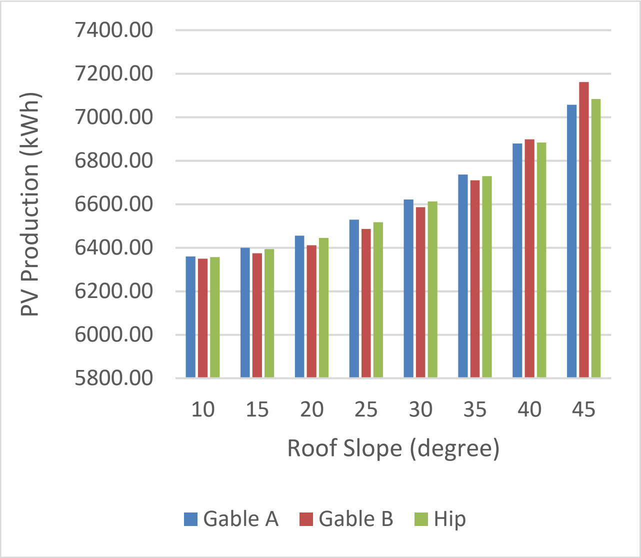


Fig 2. PV Electricity Production on Different Roof Slopes

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. 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 below.

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	6350.01	195.4452
15°	33.13	4.47	6374.82	192.4185
20°	34.05	4.60	6411.52	188.2973
25°	35.31	4.77	6485.94	183.6856
30°	36.95	4.99	6585.71	178.233
35°	39.06	5.27	6709.71	171.7797
40°	41.77	5.64	6898.42	165.1525
45°	45.25	6.11	7161.12	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.

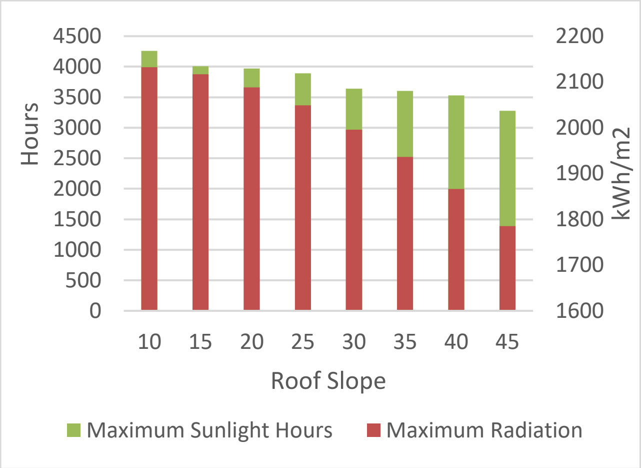


Fig 3. Comparison of Maximum Radiation and Sunlight Hours on Different Roof Slopes

The figure above 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 [27], therefore the building's cooling load would also be diminished [28]. 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 façade 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.

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° roof's 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. See figure 4.

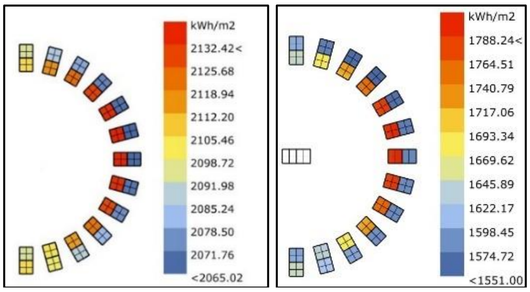


Fig 4. Sun radiation analysis on 10° roof (left), and 45° roof (right)

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

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	6723.97	6350.01	94%
15°	33.13	4.47	6856.42	6374.82	93%
20°	34.05	4.60	7046.82	6411.52	91%
25°	35.31	4.77	7307.58	6485.94	89%
30°	36.95	4.99	7646.99	6585.71	86%
35°	39.06	5.27	8083.66	6709.71	83%
40°	41.77	5.64	8644.51	6898.42	80%
45°	45.25	6.11	9364.71	7161.12	76%

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. Assesment 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 Global Solar Atlas (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 annualy. 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.

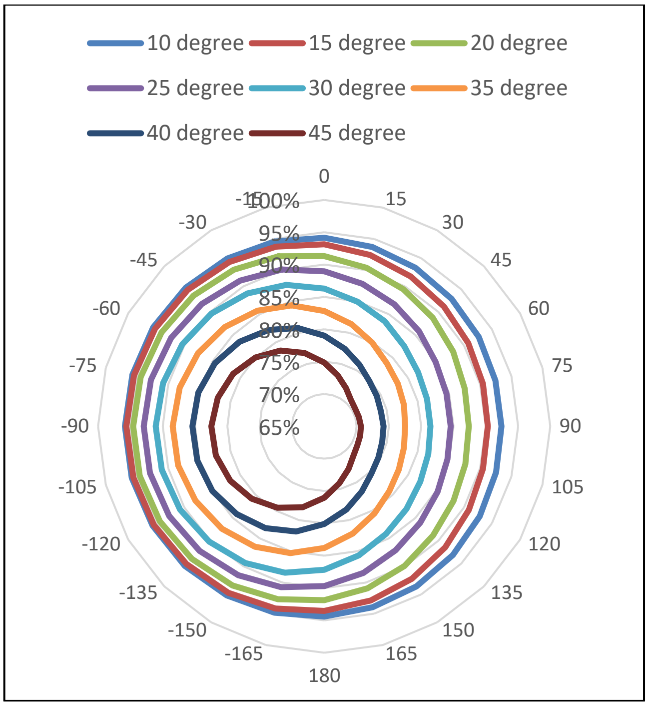


Fig 6. Comparison of the performance of PV on 8 slopes and 24 azimuths

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.

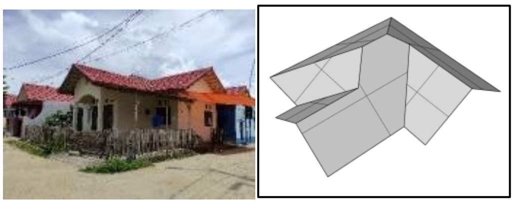
The conducted simulations however, are employing simple roof shapes as the model, which is rarely found on the field. Housings are commonly constructed on the combination of these simple shapes to create a more aesthetically pleasing design. Therefore, the research proceeds to conduct simulation of the 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.

3.5. Assesing PV Potential on Housing

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 5. These are the representative of the complex and simple roof housing found in Gorontalo.

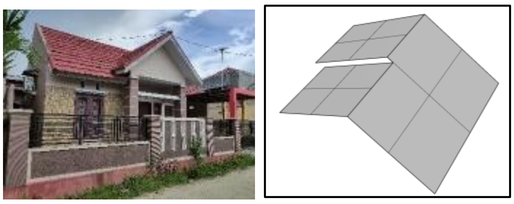
Among the 4 housing, Wongkaditi Permai 3, Solaria 3, and Griya Dulomo Indah have gable roof construction with the planes facing just 2 directions. Wongkaditi 3 is made on the combination of several gable shapes, and the planes face 4 directions. Anggrindo 2 housing is built on a complex roof structure, 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 A (Anggrindo 2), B (Wongkaditi Permai 3), C (Solaria 3), and D (Griya Dulomo Indah). The roofs are facing various azimuths. More information on the buildings can be found in table 6.

Housing B has the steepest slope, and is expected to produce the lowest electricity among the housings. Housing D on the otherwise, has the slopest 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.

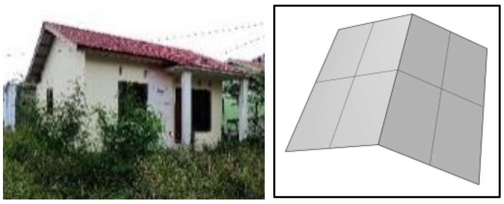


A

B



C



D

Fig 7. Photos of the housing and the simulation models

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

The result, as shown in table 7, puts housing D as the roof with the highest electrity produced. It fits the assessment result because of its low slope (22°). The second is housing C, which has a steeper slope than D. Apart from its steep slope, the geometry of roof on B creates self-shading effect which could also be the factor affecting this result. 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 C and D, despite the system size of housing A is almost double the value of both of them.

Comparison to the PV potential map by Global Solar Atlas is 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 is shown below in table 7. As in the result of table 5, a 20° sloped roof has about 91% of energy potential, but then in figure 6, the influence of azimuth could increase the potential up to 95% and decrease down to 87% (a 8% difference between the maximum and minimum).

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. See figure 8. 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.

Table 7. Comparison of simulation result and PV power potential

Housing	PV System Size (kW)	Annual Production (kWh)	Annual PV Power Potential (kWh)	%
A	13,5	17194	20709	83%
B	7,58	9425	11627	81%
C	6,7	8854	10277	86%
D	7,1	9803	10865	90%

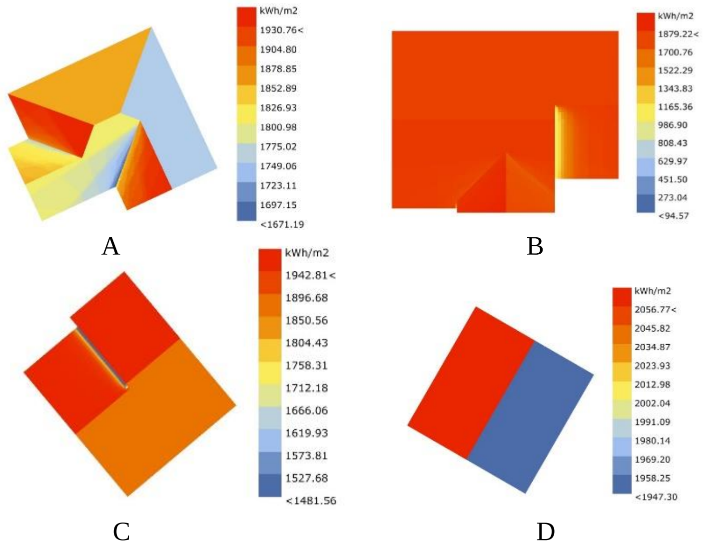


Fig 8. Radiation analysis result

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. Electriticy 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.

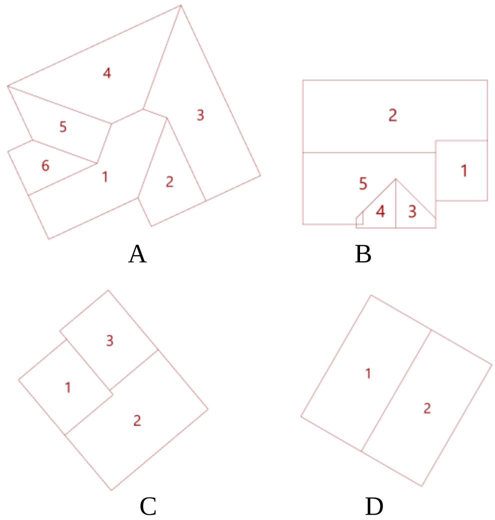


Fig 9. The Surface's order of housing

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)	%
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)	%
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)	%
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)	%
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 buiding, 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 consisted of two parts, 0,6 kWp (3x200Wp) panels to power the house in daylight, and 1,2 kWp (4x300 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.

Fig 10. PV installed on the carport's roof (left), and on a rack (right)

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 sloper 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)	%
1	10^0	6^0	0.6	865	919	94%
2	-170^0	2^0	1.2	1741	1840	94%

4. CONCLUSION

Method to assess the potential of PV panel based on roof design has been proposed in this research by conducting simulation experiments with the parameters of roof shape, slope, and orientation. The purpose is to assess the productivity of PV on a roof construction, especially the landed housing's roof. 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 second factor affecting the PV productivity is the orientation. In the case of Gorontalo which lies on the equator, a North-South orientation is better for the relatively sloper roof. Otherwise, for a 450 roof, East-West orientation would benefit more electricity production. For a single surface roof, the research advises to face the roof to the West as the radiation is higher on this direction. For two surfaces roof, a North-South orientation is recommended hence the potential difference between both surfaces is small. Complex roof construction, or roof with more than two surfaces should be planned thoroughly as the surfaces could be facing many directions and influencing the 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 the 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's 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 Global Solar Atlas.

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 choosing the best roof''s section in producing electricity.

Constructing low inclination roof's housing for PV mounting would be worthwhile, but it would also impair the building's proportion as the height of the wall and the roof would be unbalanced (big body, small head). Some housing adopting the modern look, indicated by the absence of roof on the façade. It is actually a low slope roof with the aid of a tall front wall hiding the upper structure. The client's preference over the architectural style would determine the productivity of PV on the roof.

This study investigates the performance of PV panel on a single building, the effect of neighbouring building which create shadows and hindering the PV to reach the peak potential is not taken into account. The housing plots are usually arranged in 2 adjacent rows, the housing share the same back line and facing opposing direction. A house in the center could be shaded by 3 buildings in the back and 2 buildings in the side. While a house in the corner of the row will just be covered by 2 buildings in the back, and 1 building in the side. The position of the building in the housing row should be a matter to be concerned in the next research.

Housing will also encounter the problem of expanding the house horizontally and vertically. Especially in Indonesia, the growing house concept allowed the house primarily built in the small size, and the owner can enlarge it in the future. This type of housing is popular for the low to middle income society since it is affordable. The house expansion will influence the housing in 2 ways. The PV panels mounted initially before the expansion might need to be removed and reinstalled. The second is when the next-door housing having their building enlarge, the taller constructed structure might cover the PV on one's roof, reducing or even eliminating the electricity production. The issue could be used to evaluate the feasibility of the growing-house housing in regard to renewable energy production on roof.

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

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