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Sizing of Grid-Connected Photovoltaic System with Roof Space Constraint

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ABSTRACT

Keywords:
System sizing; Preliminary design tool; Grid-connected; Photovoltaic; Renewable energy

The installation of building-integrated photovoltaic systems has increased over the past years. This paper presents the sizing method of photovoltaic systems with rooftop space as a constraint. A sizing tool is developed to assist the design of PV systems with roof space constraints by using Visual Basic for Application. This new sizing tool is developed by implementing an iterative technique and is able to optimize the quantity of PV panels while overcoming the problem of space constraints on the rooftop. A roof dimension from Google Maps is used for the case study. This tool minimizes the design process time for an integrated PV system with minimum information on a rooftop.

1. Introduction

Nowadays, fossil-fuel resources such as oil, coal, and natural gas on a worldwide basis is decreasing rapidly. These sources are carbon-rich fossilized remnants from millions of years ago, that can only be obtained from beneath the surface of the earth and turned into molecules rich in energy. Due to having limited resource reserves, environmental and global warming phenomena, and oil prices increment, renewable energy (RE) has been selected as one of the alternative energy supplies in the future [1,2].

Due to having a relatively high irradiance level throughout the year, Malaysia is potentially enough to set-up a photovoltaic (PV) system [3], with an average daily solar insolation of 5.5 kW/m^2 or 15 MJ/m^2. Besides, a published study proves that solar score the highest overall priority matrix among other RE resources and most likely a good fit for Malaysia [4]. A grid-connected PV system (GCPV) generates electricity through energy from sun irradiation, and then the electricity is converted into grid-compliant AC by an inverter. PV is one of the RE that is pollution-free but has high

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investment and environmental cost when setup the PV array system [5]. However, to design a GCPV system, sizing constraints such as space constraints, energy demand constraint, and budget constraint must be considered [6].

Energy constraint demand is applied in the process of optimize a limitation where a specific load demand is referred. When consider about energy demand constraint in PV system design, firstly need to identify the annual energy requirement and select the appropriate system configuration to match the demand of load [7]. Two past studies in GCPV system design used the electrical load profile of a specific building as a sizing constraint [8,9]. Since renewable sources' output power is non-linear and unpredictable, battery or energy storage is necessary to store excess energy generated by RE and supplies power to the load when needed especially during the night, cloudy days, and periods with high load demand [10,11].

Budget constraints are happened when having fund limits for installing PV system by investor. This limitation always happed in real life because PV set up cost is high. Besides, it is not practical for every house and building owner to invest in installing PV system. Meantime, the chance to invest on a GCPV system is mostly inclines on support from government and feed-in tariff, since different countries have different market [12-14].

The application space constraints are applied either on a pre-defined area or available spatial area as the sizing limitation when optimize the sizing system process. A PV system can be installed either on an open land or building space. For a limited area of roofs [4,14], walls, land, or canopies to install the PV modules, PV modules quantities was calculated using standard formula, while the shading effects should be considered [5,15-17]. Several past works presented user interface development software for GCPV system sizing [18-20]. However, it is observed that there is no study to design a PV system specifically for rooftop applications while considering both PV arrangement, PV array size, and walkway. These factors are crucial in PV layout design, because if PV array size is too big, it will cause future problem such as difficulty during maintenance, replacement of damaged PV panel, and for cleaning without stepping on PV panels [21]. Bigger size of PV layout that may maximize solar output, this cause maintenance of both the roof and PV systems nearly impossible [22]. Providing proper pathways is also crucial to ensure firefighters get access to the roof for firefighting operations [23-25]. Malaysian Standard [26] provides standardisation, accreditation, and set general installation requirements for GCPV, focusing on the general requirements of GCPV, protection requirements, wiring requirements, etc. However, standard for layout design while considering the maximum area of PV island, to allows maintenance and provide pathway for firefighters are not defined.

Therefore, this project is about the design of PV system layout with space as a constraint. In this paper, the published Pre-Installation Design for GCPV (PIDGCPV V2) [18] is revamped to be able find the optimum arrangement of PV system on rooftop, while considering the PV arrangement, PV array size, and walkway for future maintenance. This supportive tool is now implementing iterative to optimize the quantity of PV panels while overcome the problem of space constraints on rooftop.

2. System Configuration

This section describes the configuration architecture and system components in GCPV. The GCPV system is a PV system that feeds PV generated electricity to the utility grid. It is the simplest PV application with the least capital expense. The configuration consists of a PV generator, inverter, PV meter, main distribution board, net energy metering (NEM), the Alternating Current (AC) load, and the utility grid. The energy produced from the generator is provided to the load first, and the balance will be exported and sold to distribution licensees. Figure 1 shows the typical configuration of a GCPV system [27].

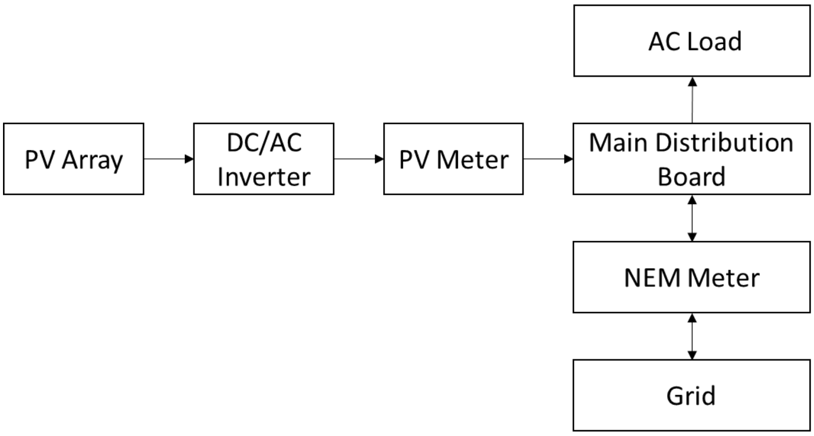


Fig. 1. Configuration architecture and energy flows diagram for GCPV

3. Methodology

This section explains the proposed optimization tool for automated PV sizing by implementing iterative method in VBA. The PV sizing is performed while considering the walkway distance from the top edge of the roof (top gap), the walkway distance from the side and lower edge of the roof (side and below gap), walkway distance between PV array, and maximum width for PV array, as shown in Figure 2.

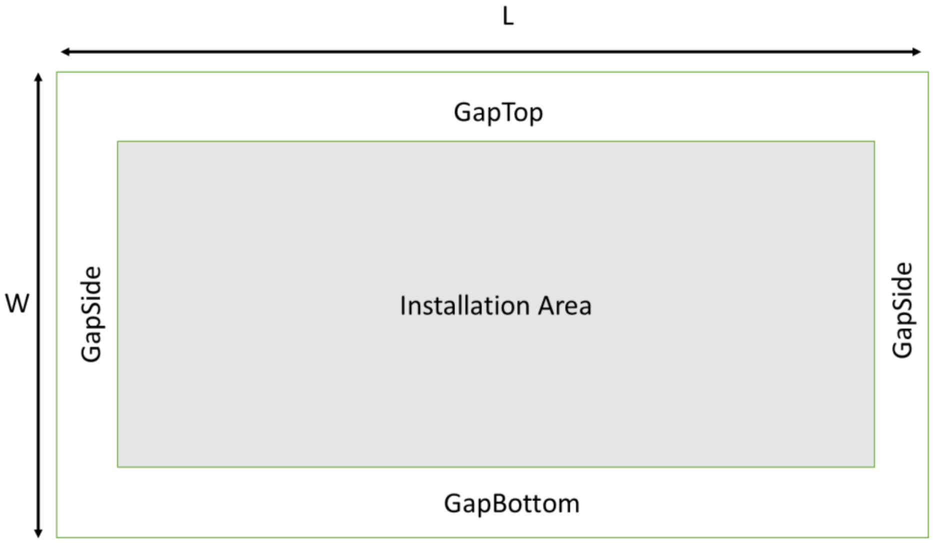


Fig. 2. Gap between PV panel area and edge of roof

This tool will automatically propose four possible maximum PV layout, based on the following four type of PV panel arrangement, as shown in Figure 3:

i. Panel arrangement: lengthwise across; walkway vertical
ii. Panel arrangement: lengthwise across; walkway horizontal
iii. Panel arrangement: lengthwise up; walkway vertical
iv. Panel arrangement: lengthwise up; walkway horizontal

The white colour area is representing the area at top gap, side gap, and below gap, and blue colour represents PV panel installation area. Then, to obtain the optimize PV system on the rooftop with limited area, this tool will select the PV layout with maximum PV area among these four PV panel arrangements.

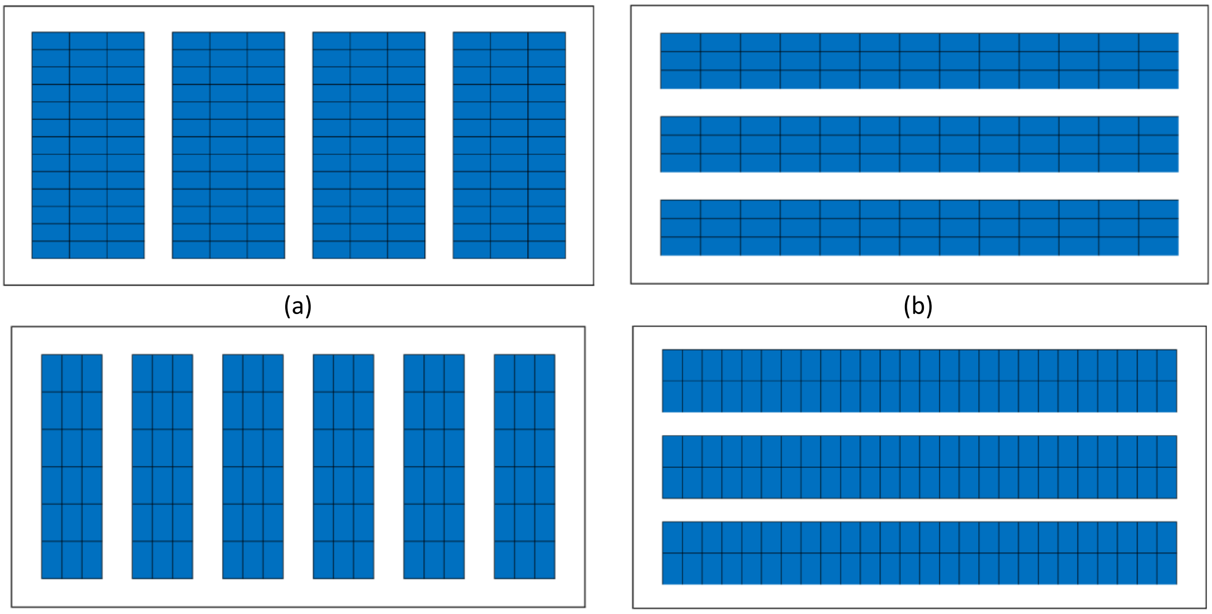


Fig. 3. Panel arrangement (a) Panel lengthwise across; Walkway vertical, (b) Panel lengthwise across; Walkway horizontal, (c) Panel lengthwise up; Walkway Vertical, (d) Panel lengthwise up; Walkway horizontal

The tool's operating procedure is started by obtaining the rooftop area and inserting the roof size into the proposed optimization tool. Then, it follows with obtaining PV size (length and width from datasheet). Next, the user needs to set input information into the optimization tool, such as the gap between panels and the gaps between roof edge, which is simplified in Figure 4.

Fig. 4. Flowchart of implementation plan for the proposed optimization methods

Figure 5 illustrates the subroutine for one of the subroutines, the Panel Lengthwise Across arrangement. The subroutine will automatically estimate size of rooftop to mount PV array area where it represented by blue colour, red as walkway, and yellow area as gaps array. Subsequently, the number of maximum PV panels to be installed can be calculated.

First four steps in the subroutine are to remove walkway area from the total roof area (Length * Width) by changing the walkway areas into yellow colour, and the red area represent the available roof area. Next step is to initial the iterative values, such as maximum pre-set island, maximum roof area, and walkway width. Afterwards, starting from j=1, the roof area is in red colour will be changing to blue colour, which represent the area to install PV panel, and gap between the PV array will remain red. The other three PV arrangements apply similar subroutine, whereby some modification in VBA coding is needed in during initialization of length and width for PV panel and roof area.

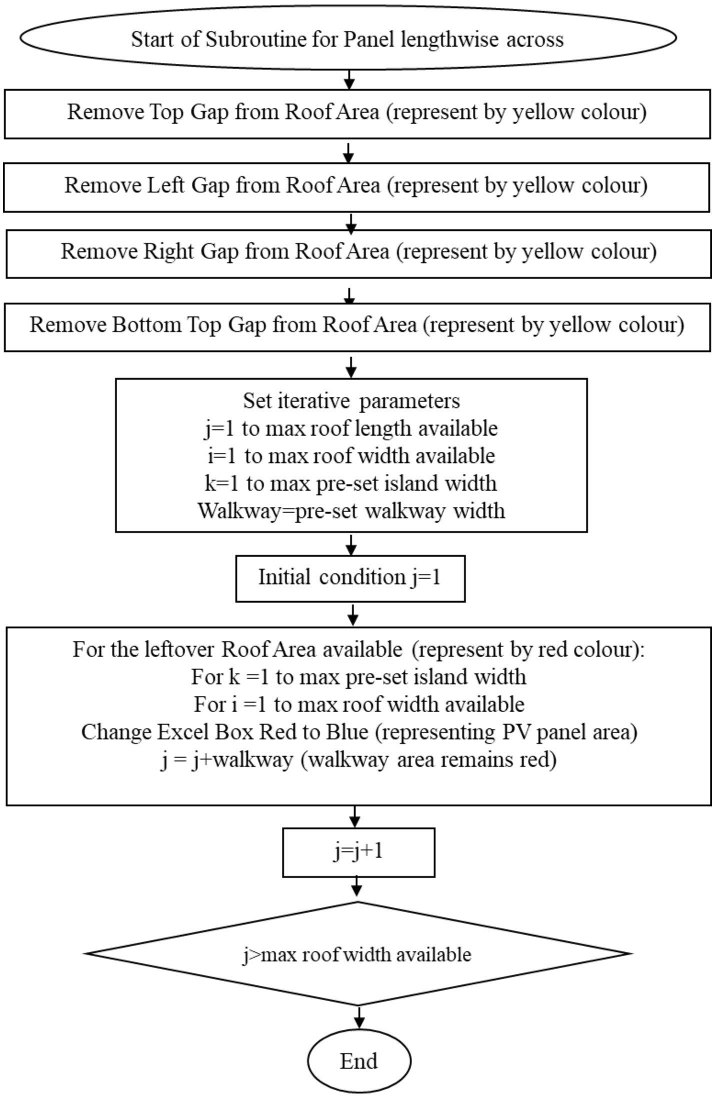


Fig. 5. Subroutine for panel lengthwise across

4. Software Development

The development of PIDGCPV V2 is divided into three parts, which are the sizing, economic analysis, and system performance. Figure 6 shows the flowchart of PIDGCPV V2 [18].

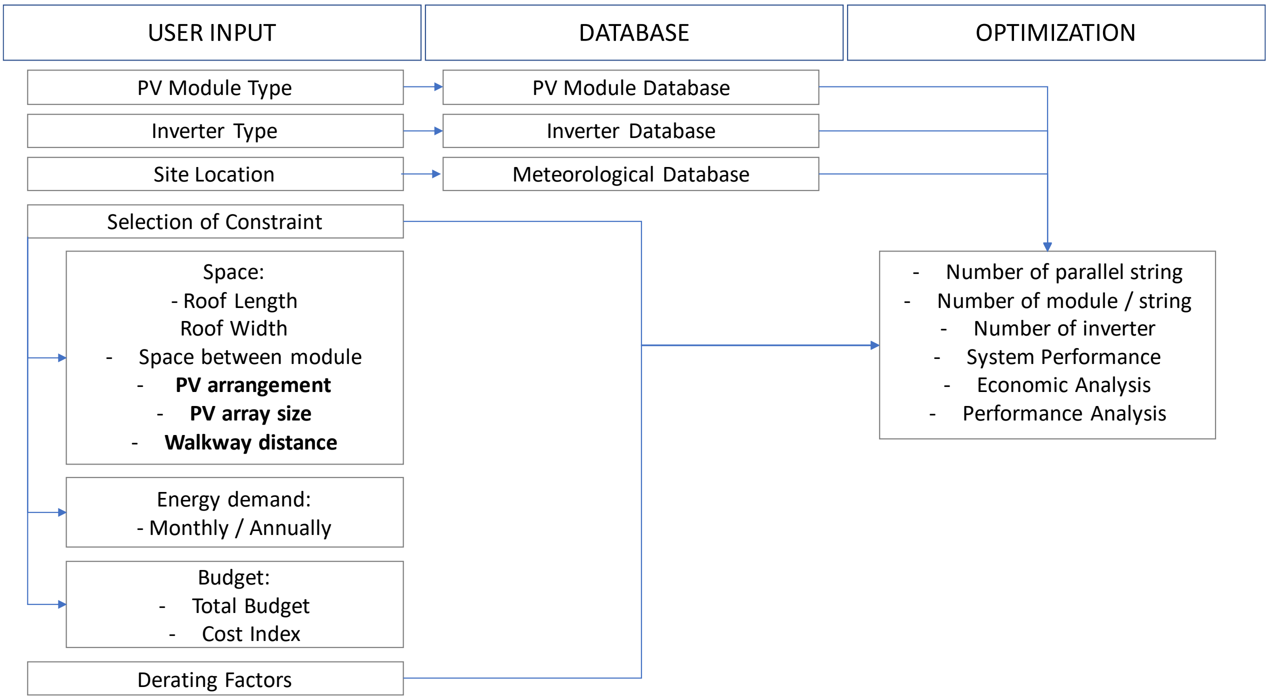


Fig. 6. Flowchart of simulation steps

The user starts by selecting the PV module, inverter, site location and system constraint. PV module, inverter, and site location is chosen based on selection menu generated from database embedded in the tool. The published tool [18] is now revamped by automatically determine the ideal number for modules, while considering four PV arrangements, PV array size, and walkway using iterative techniques. The objectives in developing this software are to:

i. Determine the optimum configuration and preliminary design for GCPV while complying to all space constraints.
ii. Optimize configuration and arrangement for PV module and inverter.
iii. Perform economic analysis and performance analysis.

Vertical menu function and pop-up menu were appended to make the tool user friendly. Figure 7 shows the main page, analysis results, optimum PV arrangement in rooftop space, optimum PV String Configuration, economic analysis, and performance analysis in PIDGCPV V2.

Sizing Constraint = Space

PV MODULE TYPE
BRAND KYCERA
MODEL KC200GH-2P

INVERTER TYPE
PHASE Single Phase
BRAN SMA
MODE SB 5000TL

SPACE CONSTRAINT
Roof Length 23 m
Roof Width 18 m
Gap Between Modules 0.02 m
Gap Between Roof Edge and Modules :
(Top) 0.3 m
(Bottom) 1.2 m
(Side) 1.2 m

BUDGET CONSTRAINT
Budget RM 110200
Cost Index RM 27.55 /Wp

ENERGY REQUIREMENT CONSTRAINT Annual Demand
Energy Supplied by PV system 100 %
Monthly Energy Demand (kWh) :

Jan	511	July	532
Feb	513	Aug	536
Mar	534	Sept	0
Apr	514	Oct	525
May	555	Nov	527
Jun	0	Dis	521

Annual Energy Demand (kWh) : 11213

Derating Factors, Temperature Coefficient and System's Sizing

DERATING FACTORS
fmm 0.95
fdirt 0.97
fpv_inv 0.98

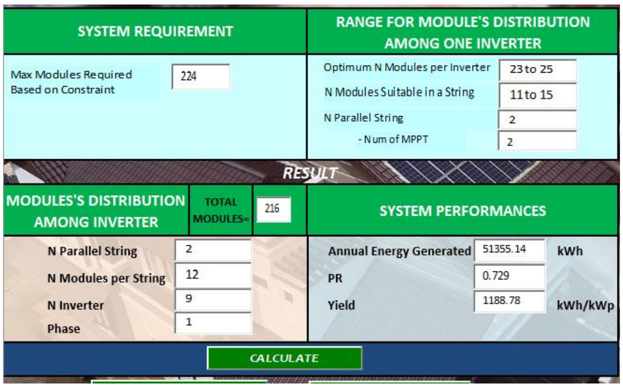
TEMPERATURE DERATING FACTOR
☐ Given Tamb_ave_max 32 °C
☐ Given Gamb_ave_max 850 Wm⁻²
Given NOCT 49 °C
☐ Given Temp Coefficient
Absolute Value (W/°C) -1.194

PEAK SUN HOUR
State: Johor
Region: Johor Bahru
☐ PSH data = 1630.7 h

☐ GIVEN CELL TEMPERATURE
Maximum 60 °C
Minimum 20 °C

☑ Design based on optimum inverter to PV array sizing ratio
Check PV Module & Inverter Compatibility | Suitable | Not Suitable
Npv required (based on condition) 224
Nominal Npv / inverter 23 to 25
N Modules Suitable in a String 11 to 15
N Parallel String 2

(a)



SYSTEM REQUIREMENT
Max Modules Required Based on Constraint 224

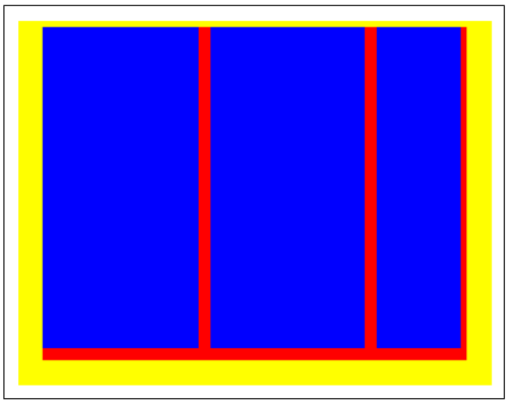
RANGE FOR MODULE'S DISTRIBUTION AMONG ONE INVERTER
Optimum N Modules per Inverter 23 to 25
N Modules Suitable in a String 11 to 15
N Parallel String 2
- Num of MPPT 2

RESULT

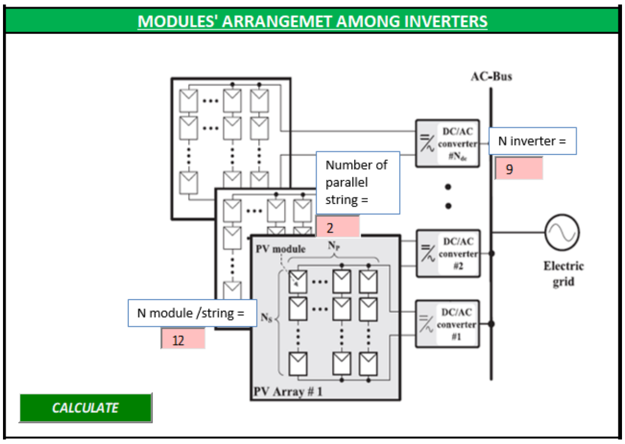
MODULES'S DISTRIBUTION AMONG INVERTER
TOTAL MODULES= 216
N Parallel String 2
N Modules per String 12
N Inverter 9
Phase 1

SYSTEM PERFORMANCES
Annual Energy Generated 51355.14 kWh
PR 0.729
Yield 1188.78 kWh/kWp

(b)



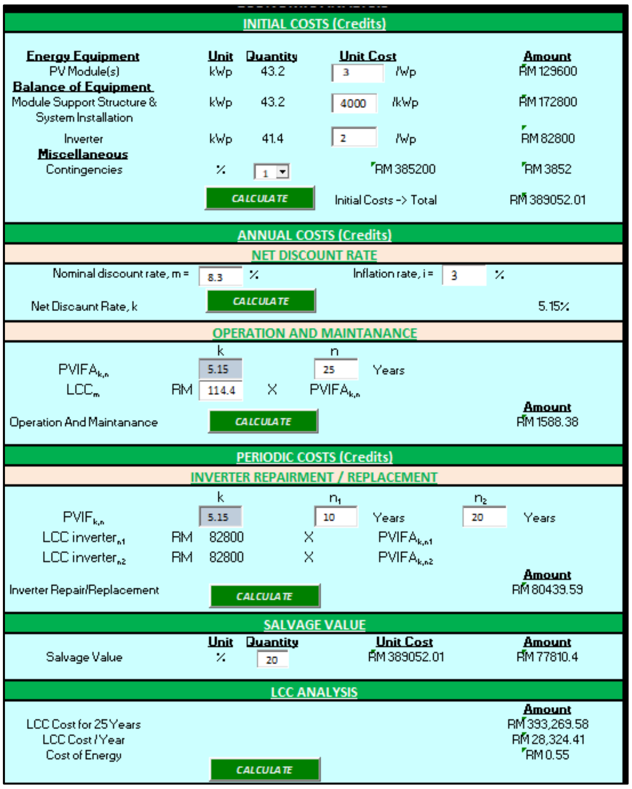
(c)



MODULES' ARRANGEMET AMONG INVERTERS

N inverter = 9
Number of parallel string = 2
N module /string = 12

(d)



INITIAL COSTS (Credits)

	Unit	Quantity	Unit Cost		Amount
Energy Equipment					
PV Module(s)	kWp	43.2	3	/Wp	RM 129600
Balance of Equipment					
Module Support Structure & System Installation	kWp	43.2	4000	/kWp	RM 172800
Inverter	kWp	41.4	2	/Wp	RM 82800
Miscellaneous					
Contingencies	%	1	RM 385200		RM 3852

Initial Costs -> Total RM 389052.01

ANNUAL COSTS (Credits)

NET DISCOUNT RATE
Nominal discount rate, m = 8.3 %
Inflation rate, i = 3 %
Net Discount Rate, k 5.15%

OPERATION AND MAINTANANCE
$PVIFA_{k,n}$ k 5.15 n 25 Years
LCC_m RM 114.4 X $PVIFA_{k,n}$
Operation And Maintanance Amount RM 1588.38

PERIODIC COSTS (Credits)

INVERTER REPAIRMENT / REPLACEMENT
$PVIF_{k,n}$ k 5.15 n_1 10 Years n_2 20 Years
LCC $inverter_{n1}$ RM 82800 X $PVIFA_{k,n1}$
LCC $inverter_{n2}$ RM 82800 X $PVIFA_{k,n2}$
Inverter Repair/Replacement Amount RM 80439.59

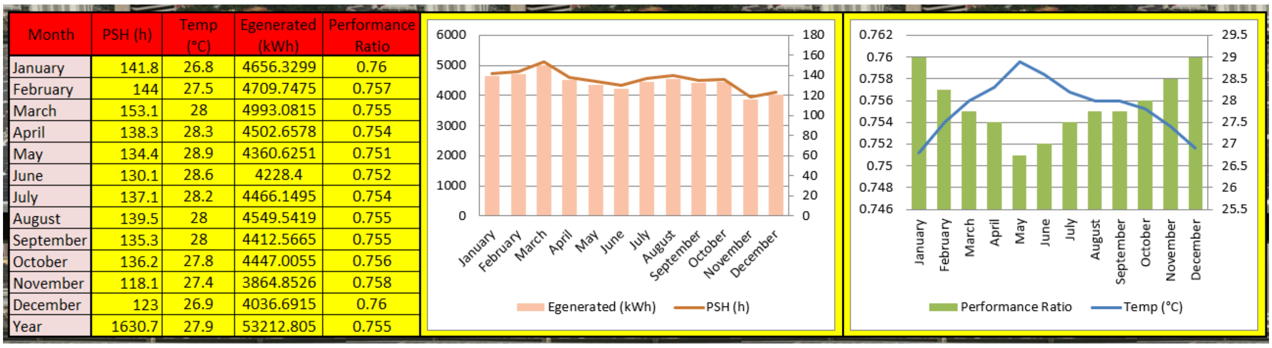
SALVAGE VALUE

	Unit	Quantity	Unit Cost	Amount
Salvage Value	%	20	RM 389052.01	RM 77810.4

LCC ANALYSIS

	Amount
LCC Cost for 25 Years	RM 393,269.58
LCC Cost / Year	RM 28,324.41
Cost of Energy	RM 0.55

(e)



Month	PSH (h)	Temp (°C)	Egenerated (kWh)	Performance Ratio
January	141.8	26.8	4656.3299	0.76
February	144	27.5	4709.7475	0.757
March	153.1	28	4993.0815	0.755
April	138.3	28.3	4502.6578	0.754
May	134.4	28.9	4360.6251	0.751
June	130.1	28.6	4228.4	0.752
July	137.1	28.2	4466.1495	0.754
August	139.5	28	4549.5419	0.755
September	135.3	28	4412.5665	0.755
October	136.2	27.8	4447.0055	0.756
November	118.1	27.4	3864.8526	0.758
December	123	26.9	4036.6915	0.76
Year	1630.7	27.9	53212.805	0.755

(f)

Fig. 7. PIDGCPV V2 UI (a) Main Page, (b) Analysis results based on selected constrain, (c) Optimum PV arrangement in rooftop space, (d) Optimum PV String Configuration, (e) Economic Analysis, (f) Performance Analysis

5. Case Study

The proposed optimization tool for automated PV sizing will show user the total quantity of PV pane to be installed predicated on the available area and the best possible arrangements; lengthwise up or lengthwise across. This section explains the input data used in the case study.

5.1 Site Selection

An industrial building's roof is selected from google maps, where its address is located at Jalan Kempas Lama, Johor Bahru, which is a small industrial area opposite of Southern University College. On Google map's measurement, the rooftop used for the case study is with area of width 23.5 m and length 18.1 m, as shown in Figure 8.

(a) (b)

Fig. 8. Rooftop's measurement from Google Map (a) Roof width, (b) Roof length

5.2 PV Panel and Inverter Selection

For PV Module, Kyocera KC200GH-2P was chosen for case study. This PV module is available in the market and the specification is as shown in Table 1.

Table 1
PV module datasheet specification [28]

Parameter	Specifications
Model	Kyocera KC200GH-2P
Maximum power (W)	200W
Maximum power Voltage (V)	26.3V
Open Circuit Voltage (V)	32.9V
Maximum Power Current (A)	7.61A
Short Circuit Current (A)	8.21A
Size W*L*H (mm)	1425*990*36
Product Weight (kg)	17.5Kg

Meanwhile, the details of selected inverter, SMA SB 5000TL, is simplified in Table 2.

Table 2
Inverter specification [29]

Parameter	Specifications
Model	SMA SB 5000TL
Maximum Voltage	550 V
Minimum Window Voltage	175 V
Maximum Window Voltage	440 V
Maximum Current per string (A)	15 A
Nominal Power	46000 W
Efficiency	97 %

5.3 Space Constraint

The optimum design is selected from the maximum possible quantities of PV panel that can fit the rooftop. The list of space constraints applied is simplified in Table 3.

Table 3
List of constraints applied in the case study

Constraint	Value (metre)
Top Gap	0.3
Side and Below Gap	1.2
Walkway	0.6
Maximum width of PV island	8.0

6. Results and Discussion

From the simulation results as summarized in Table 4, maximum quantities of PV panels to be installed is 215 units. The configuration is 12 unit of PV panels connected in each string, with maximum of 2 parallel strings in each inverter. A total of 9-unit inverter is needed for this configuration.

Expected energy generated per year is 53212.805 kWh, the cost of energy is RM 0.55 and performance ratio is 0.755.

Referring to Tenaga Nasional Berhad (TNB) Pricing and Tariffs [30,31], the range of domestic tariff category is RM 0.218 – RM 0.571. For commercial tariff, the range falls into RM 0.224 – RM 0.509 and for industrial category, the range is RM 0.202 – RM 0.441. Any further decline in system cost and hike in TNB tariff in the future making solar energy more competitive with traditional utilities in Malaysia.

Table 4
Result of system sizing

Category	Parameter	No. of PV Panel
Panel Arrangement	Lengthwise across, walkway vertical	200
	Lengthwise across, walkway horizontal	203
	Lengthwise up, walkway vertical	215
	Lengthwise up, walkway horizontal	207
	Optimum Arrangement (Lengthwise up Walkway vertical)	215
Configuration	Max series PV module per string	12
	Max parallel strings per unit inverter	2
	Inverters unit	9
Annual Performance Analysis	Peak Sun Hour	1630.7 h
	Average Temperature	27.9 °C
	Annual Energy generation	53212.805 kWh
	Performance Ratio	0.755
Economic Analysis	Life Cycle Cost for 25 years	RM 393,269.58
	Life Cycle Cost / year	RM 28,324.41
	Cost of Energy	RM 0.55

Besides, additional government incentives and subsidies will contribute to the competitiveness in PV cost of energy. Purchasing PV panels and its balance of equipment could further reduce the initial cost, which affects the system's initial cost. To fulfil the high RE capacity target in Malaysia by 2050, the focus must shift to solar since its tariff is able to compete with natural gas but still not cheap enough to compete with coal [32].

7. Conclusion

This research presented the optimization on space constraint on GCPV system. A new supportive optimization tool is developed by implementing iterative and simulation developed in VBA MS Excel to obtain optimization techniques to overcome the problem of space constraints on rooftop.

The operation of the new sizing tool started by specifying the roof area. From the input roof area, four possible PV panel mounting layouts is proposed by the tool, and the optimum layout is selected based on the highest number of PV panel to be installed on the roof. Annual energy generation, performance ratio, and economic analysis can be simulated by this software.

However, more improvement can be made in the future, since the tool unable to avoid existing obstacle on roof, such as chimney, skylight, exits, and jack roof. Besides, it is recommended that future study to consider not only rectangle roof type, but also irregular roof area for the simulation.

In addition, further study on system design while considering shading analysis and potential source of dust could be beneficial in increasing generated energy system performance. Considering energy demand in sizing is crucial to adequately meet energy needs and avoid grid integration issue, such as low power factor after GCPV integration and reverse power flow.

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