Design Manual
for
Grid-connected Photovoltaic System

June 2009

JICA Study Team

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1 INTRODUCTION

1.1 Background

The Republic of Maldives (hereinafter referred to as "Maldives") is an island nation with an altitude of just one (1) meter above sea level; it is one of the countries most prone to the effects of rising sea level caused by climate change. The Government of Maldives (hereinafter referred to as "the GOM") intends to promote renewable energy in place of petroleum and to increase the share of total energy demand. In doing so, the GOM aims to reduce greenhouse gas emissions from diesel power station and ensure energy security.

Under these circumstances, the GOM issued a request to the Government of Japan (hereinafter referred to as "the GOJ") for implementation of the Feasibility Study for Application of Photovoltaic Power in Male' and Hulhumale' Islands in the Republic of Maldives (hereinafter referred as "the Study"), as a way to improve energy efficiency and mitigate climate change for the purpose of realizing stable power supply in medium to long term.

1.2 Objective of the Manual

This Design Manual has been developed to provide basic knowledge for the engineers who design the grid-connected Photovoltaic (hereinafter referred to as "PV") in the Maldives. It provides procedures and requirements for the design.

1.3 Intended users

The intended users of this design manual are primarily the followings:

- Ministry of Housing, Transport and Environment (MHTE)
- Maldives Energy Authority (MEA)
- State Electric Company Limited (STELCO)

2 EVALUATION OF POTENTIAL SITES

2.1 Requirements for potential sites

In order to introduce the grid-connected PV system, the site must follow the several requirements. The following items are the principle requirements.

The requirements must be checked based on the site survey and the investigation of structural design drawings. As for the capacity of existing power system, SETLCO must examine the power quality of existing grid including the possible impact after the installation.

Table 2-1 Requirements for potential sites

1	Plentiful insolation and less impact of shade by nearby obstructions
2	Enough strength of the existing structure (roof, rooftop, etc.)
3	Space to install the peripheral equipment (inverter, junction box, etc.)
4	Enough capacity of existing power system (transformer, distribution lines, etc.)
5	Safety with respect to human error, harmony with surrounding landscape
6	Approval from site owner

2.2 Examination method to check obstructions against solar irradiation

1) Obstacles against sunlight on PV Array

As Male' is already crowded with existing buildings, it will be necessary to install PV systems on building rooftops. Therefore, potential sites for PV systems have to be selected as sunlight on PV array is not shielded by surrounding buildings, etc. while taking into account changes in the direction and angle of sunlight by season and time. Generally, if direct sunlight is shielded and PV array is fell into shadow, generated power output could fall by 10~20% compared with the case of no obstacles.

2) Measures to avoid shielding sunlight

In case candidate sites are located on building rooftops or roofs, surrounding obstacles will be surveyed using shade examination maps to check for angle of elevation and direction of such obstacles. The surveyed results will be used to evaluate the potential site. It is ideal to conduct site survey between AM 9:00~PM3:00 in the winter solstice when the possible shadow by obstacles is the largest. The following tools will be used to project the area of shade during the field survey:

① Shade examination map: Chart projecting the trajectory of the sun onto a circular graph at the target area and time (Please refer to ANNEX 1)

② Transit: An instrument to measure the angle of elevation of obstructions

③ Compass: An instrument to measure the direction of obstructions

In the field survey, equipment that can simultaneously measure ② and ③ above must be utilized (Please see Photograph 1). In Figure 2-1Table 2-1 Requirements for potential sites, the red shaded area between the red line and the trajectory of the sun will be affected by shadow. According to this graph, the site will be affected by shadow between 09:30~11:00 in the winter solstice when shadows are the largest.

The drawing on the Figure 2-1 shows the case where the angle of direction of the building edge is directed to the east angle between 15°and 50°, and the angle of elevation is 70° at point A and 40° at point B based on the conditions given in Figure 2-2

Photo 1 Transit

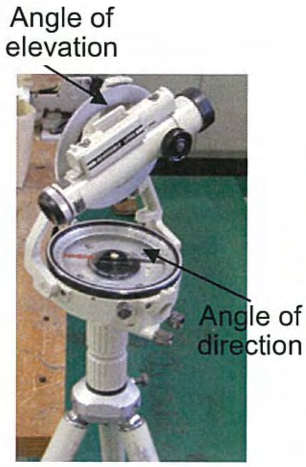


Photo 2 Transit

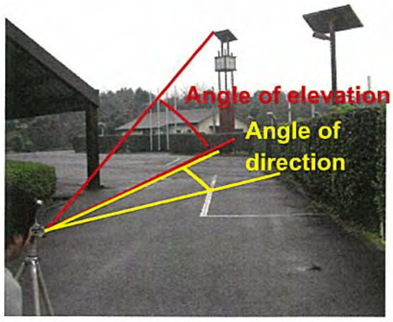
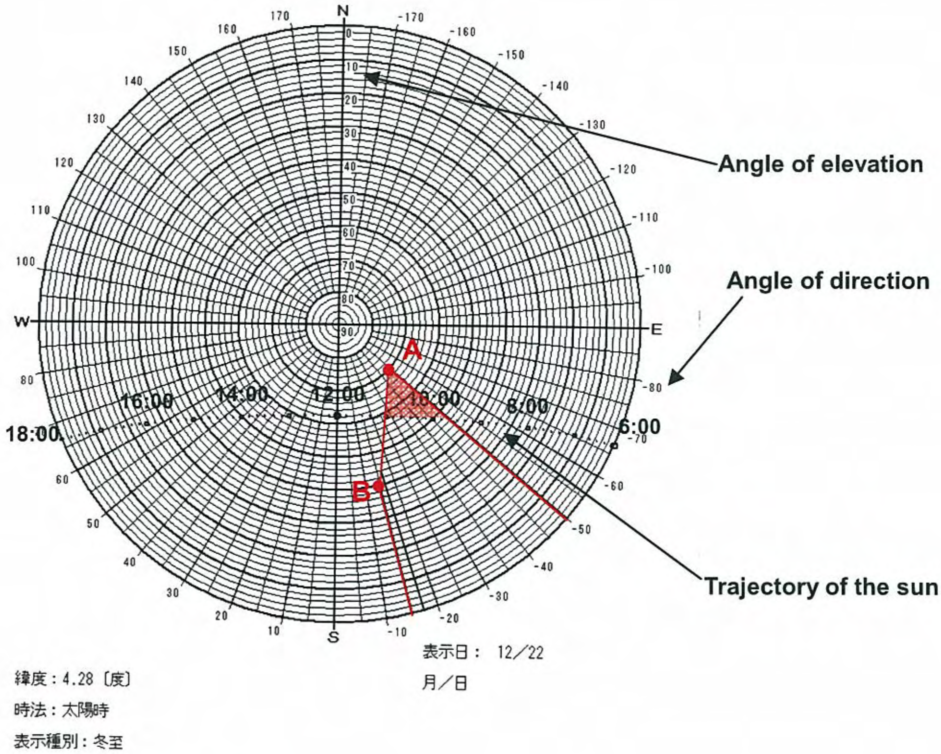


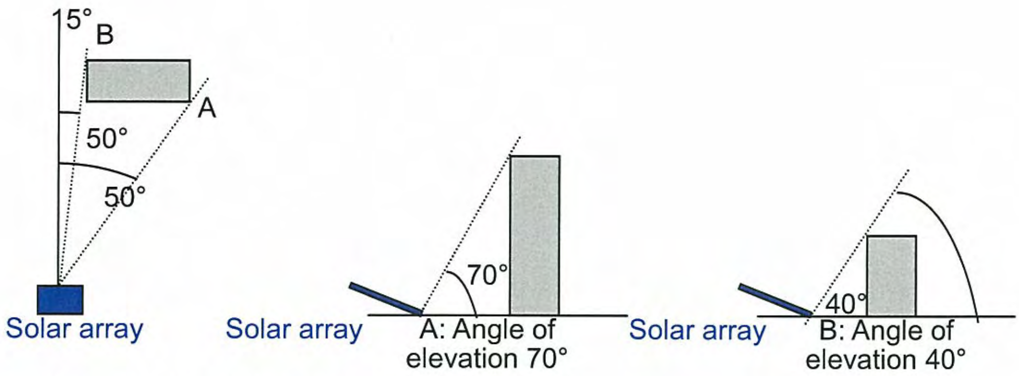
Photo 3 Site Survey

Shade Map



Source: Prepared by the Study Team

Figure 2-1 Shade Examination Map for Maldives (North Lat. 4.8˚, winter solstice)



Source: Prepared by the Study Team

Figure 2-2 Conditions to draw Shade Examination Map (Figure 2-1)

2.3 Evaluation criteria for candidate sites

In order to evaluate candidate sites, as much as possible information must be collected during the field survey.

The following items are necessary information which can be criteria for the evaluation.

Table 2-2 Evaluation criteria

Necessary Information	Points of view
PV installation area	- Angle, direction - Mounting method - Structural strength
PV capacity (kW), Estimated power generation (kWh)	- Daily insolation (kWh/m2/day) - Impact of shade from surrounding obstructions
Grid-connection	- Connection point - Capacity of existing transformer and distribution lines - Load demand - Power quality
Installation work	- Allowable duration for black out work - Space for carrying in and installing peripheral equipments - Space for temporary storage - Cable routes
Operation and maintenance	- Skill and knowledge of operators - Issues for protection relays - Maintenance space
Ownership of sites	- Approval from site owners
Safety & environmental impact	- Risk of human failure (break, theft) - Harmonization with surrounding environment
Cost	- Equipment costs, installation costs - Generating cost, cost effectiveness

3 DESIGN OF GRID-CONNECTED PV SYSTEM

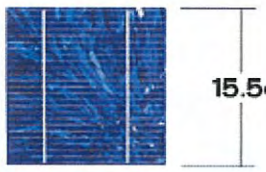
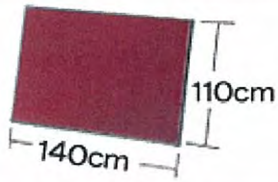
3.1 Selection of PV module type

There are many types of PV module in the world market. Among of them, silicon type of PV module is popular. In general, there are tree (3) types of silicon PV module. The following table shows comparison of each type of PV module.

In Maldives, the crystalline silicon type is recommendable to install on the rooftop because the necessary space is smaller than amorphous type due to the high efficiency.

The efficiency and price depends on the manufacturer and also marketability must be considered. Therefore, it is better to ask quotation to suppliers. At the same time, latest catalogue and specification sheet is required for system design.

Table 3-1 Comparison of Silicon Solar Cell

	Monocrystallne Silicon	Polycrystalline Silicon	Amorphous Silicon
Type			
Efficiency	15~20%	12~17%	8~12%
Price	5~6 US$/W	4 US$/W	4~5 US$/W
Characteristics	Higher efficiency but more expensive than polycrystalline silicon.	Manufacturing process is easier than monocrystalline silicon. Lower price but lower efficiency than monocrystalline silicon.	Thinner than crystal silicon. Light and flexible.

Source : Prepared by the Study Team based on data from NEDO and NEF

3.2 Examination of PV panel layout

In accordance with acquired available space for PV array and module size, PV panel layout can be examined.

For easy computation, the approximate PV capacity can be calculated based on available area utilizing the following formula.

$$\text{PV capacity [kWp]} = \text{Available area [m}^2\text{]} / \text{Module efficiency [\%]} / 100$$

In order to determine the exact PV capacity, the dimension and connection must be considered.

For the investigation of PV module connection, the specification of inverter is necessary.

The number of series connection can be calculated as follows:

$$\text{Series number of PV module } (S_n) = \frac{\text{DC input voltage of inverter } (V_{DCIN})}{\text{Maximum Power Voltage } (V_{pmax})}$$

Layout of PV panels can be arranged taking into consideration this series number, module size, cable connection and shade condition.

Each group of PV modules must be composed of multiples of series number. In case that there is enough space, it is advisable to consider the maintenance space to clean the panels. The sample layout is shown in Figure 3-1.

After the determination of PV layout, the rated PV array output can be calculated as follows:

$$P_{array} = P_{module} * N$$

Where

P_{array} : Rated PV array output (kWp)

P_{module} : Rated PV module output (kWp)

N : Total number of PV modules

On the other hand, the parallel number of PV array can be determined as follows.

Parallel number of panels (P_n) = Number of panels (N) / Series number of panels (S_n)

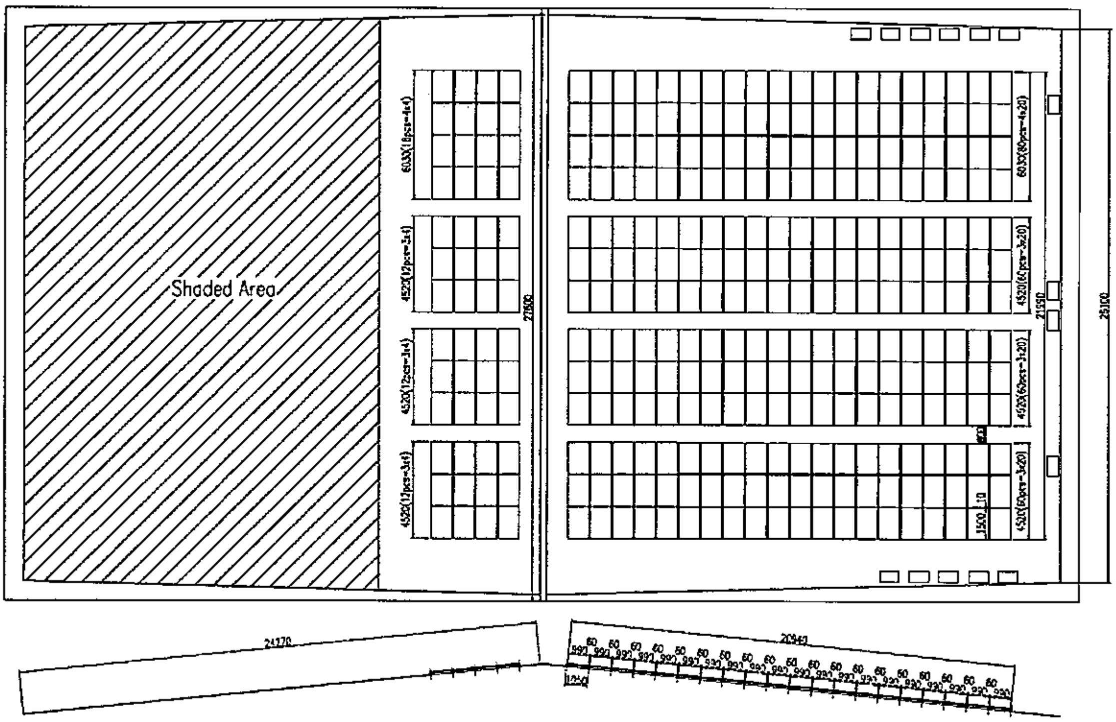


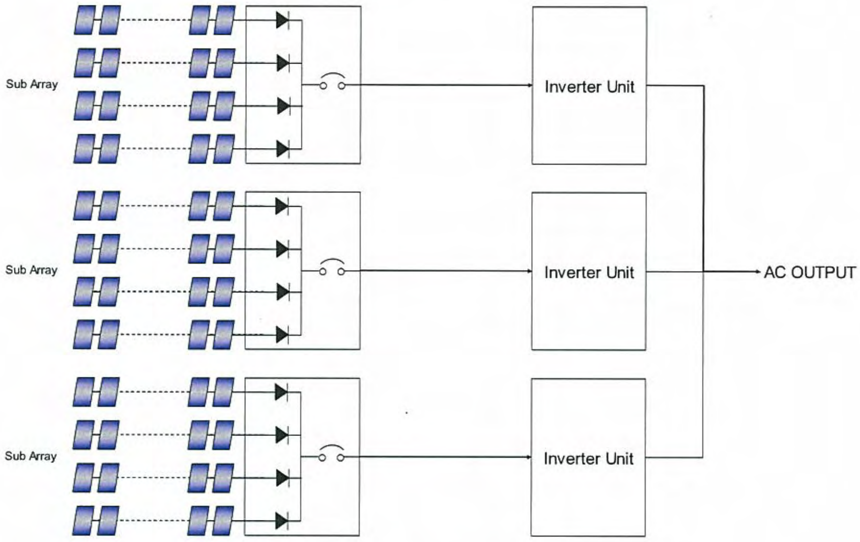
Figure 3-1 Sample PV panel layout (Series Number = 12 pcs)

3.3 Sizing of grid-connected PV inverter

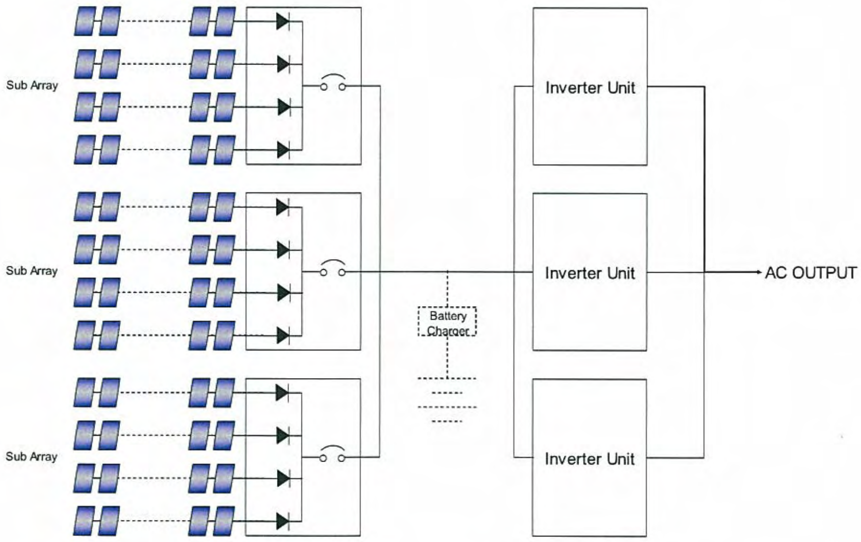
Based on the rated PV array output, capacity of the grid-connected PV inverter can be determined.

Usually the inverter capacity is same or more than the rated PV array output. However the plural inverters also can be applied depending on the availability in the market.

In case of that, two types of system can be considered as shown in Figure 3-2. Type (b) can reduce the cable length. However the signal interchange among inverters is required. Battery base system uses type (b).



(a) DC division type



(b) DC common type

Figure 3-2 Type of inverter composition

The inverter capacity can be calculated as follows:

$$P_{INV} = P_{array} / PF$$

Where

P_{INV} : Inverter output (kVA)

P_{array} : Rated PV array output (kW)

PF : Rated power factor

4 ESTIMATION OF POWER PRODUCTION

4.1 Daily Insolation

In order to estimate the power production from grid-connected PV system, daily insolation data is necessary.

The shows the monthly average insolation data in Male. Also hourly data are attached in ANNEX 2.

If the PV location has shade influence, insolation during shading time must be eliminated from total daily insolation.

For example, in case that the location has an impact of shade from 6 a.m. to 8 a.m. in January, The daily insolation at the site will be 4.808 kWh/m²/day.

Month	Monthly Average Insolation [kWh/m²/day]
1	5.23
2	5.61
3	5.99
4	5.24
5	4.86
6	5.06
7	4.51
8	5.60
9	4.56
10	6.06
11	4.00
12	5.10
AVE	5.15

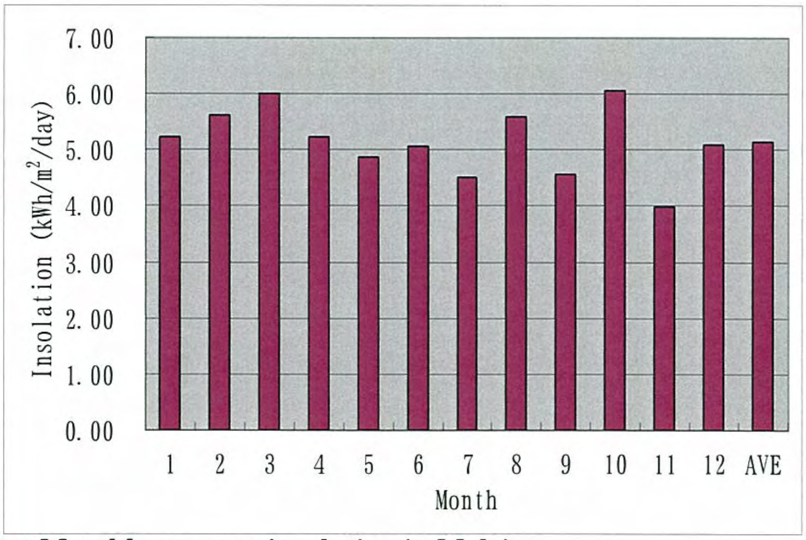


Figure 4-1 Monthly average insolation in Male'

Table 4-1 Example of calculation of insolation reduction by shade

Time	Month
	Jan
1	0.000
2	0.000
3	0.000
4	0.000
5	0.000
6	0.000
7	0.127
8	0.295
9	0.469
10	0.620
11	0.724
12	0.760
13	0.724
14	0.620
15	0.469
16	0.295
17	0.127
18	0.000
19	0.000
20	0.000
21	0.000
22	0.000
23	0.000
24	0.000
Total	5.230

[Shade impact]

Insolation from 6 a.m. to 8 a.m. = 0.127+0.295 = 0.422 kWh/m^2

[Daily insolation]

Daily insolation = Monthly average insolation – Shade impact

= 5.230 – 0.422

= 4.808 kWh/m^2/day

4.2 Estimation of annual PV power generation

The annual PV power generation can be estimated utilizing the following formula:

$$Ep = \Sigma \; H_A / G_S * K * P$$

Where

- Ep : Estimated annual power generation (kWh/year)
- H_A : Monthly average insolation at location ($kWh/m^2/day$)
- Gs : Irradiance @ STC (Standard Testing Condition) = 1 (kW/m^2)
- K : Loss coefficient = Kd * Kt * η_{INV} * η_{TR}

Kd : PV loss coefficient. Dirt on the PV surface, loss caused by irradiance fluctuation, difference of PV characteristics. Usually 0.8.

Kt : Temperature correction coefficient. Correction coefficient to consider the change of PV efficiency by heat

$$Kt = 1 + \alpha \; (Tm - 25) / 100$$

α: Temperature coefficient @ maximum output (% · ℃$^{-1}$)

= - 0.5 (% · ℃$^{-1}$) [In case of Crystalline Silicon]

Tm: Module temperature (℃) = Tav + ΔT

Tav: Monthly average temperature (℃)

ΔT: Module temperature increase (℃)

Open back type	18.4
Roof installation type	21.5

η_{INV}: Inverter efficiency. Usually 0.9 – 0.95

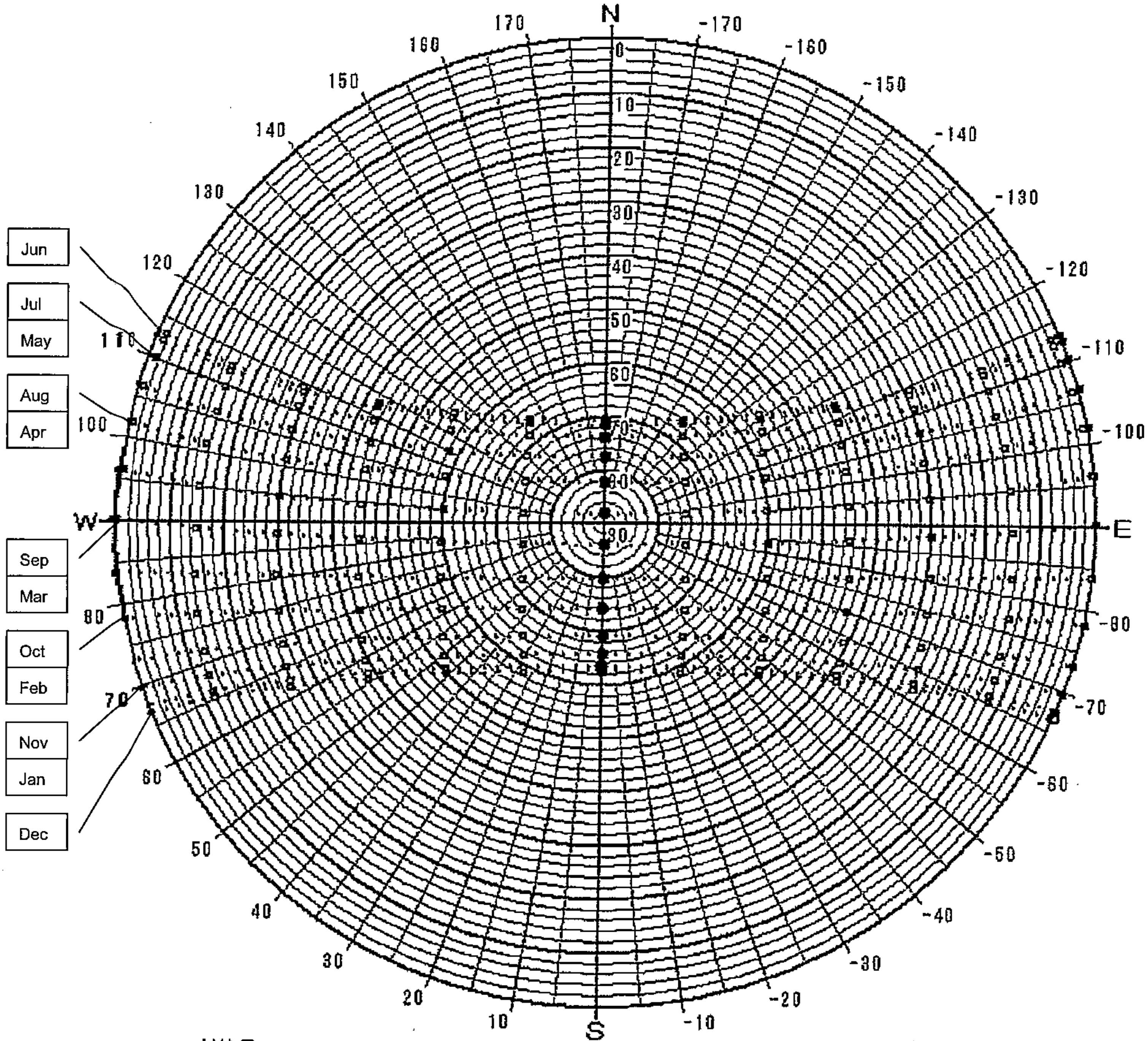
η_{TR}: Transformer efficiency. Usually 0.98 – 0.99

Σ means the integration of each month.

In order to reduce the time for investigation, the calculation template (Excel file) has been developed as shown in ANNEX 3.

Input methods also are described in the same sample.

Shade Examination Map



Site Name : MALE

Latitude : 4.18 [°]

Indicated Date :

6/21	
6/6	7/7
5/21	7/23
5/6	8/8
4/20	8/23
4/5	9/8
3/21	9/23
3/6	10/9
2/20	10/24
2/4	11/9
1/20	11/23
1/6	12/7
	12/22

Hourly Average Insolation in Male'

[kWh/m²/day]

Time	Month											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
3	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
4	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
6	0.000	0.000	0.000	0.006	0.010	0.013	0.011	0.009	0.002	0.000	0.000	0.000
7	0.127	0.141	0.157	0.143	0.136	0.144	0.128	0.155	0.122	0.155	0.098	0.123
8	0.295	0.320	0.345	0.304	0.284	0.297	0.265	0.326	0.264	0.347	0.226	0.287
9	0.469	0.503	0.538	0.470	0.435	0.453	0.404	0.502	0.410	0.544	0.358	0.457
10	0.620	0.663	0.706	0.613	0.566	0.588	0.525	0.653	0.536	0.716	0.473	0.606
11	0.724	0.773	0.820	0.711	0.654	0.679	0.607	0.756	0.622	0.833	0.552	0.707
12	0.760	0.811	0.860	0.745	0.686	0.711	0.636	0.793	0.653	0.874	0.580	0.743
13	0.724	0.773	0.820	0.711	0.654	0.679	0.607	0.756	0.622	0.833	0.552	0.707
14	0.620	0.663	0.706	0.613	0.566	0.588	0.525	0.653	0.536	0.716	0.473	0.606
15	0.469	0.503	0.538	0.470	0.435	0.453	0.404	0.502	0.410	0.544	0.358	0.457
16	0.295	0.320	0.345	0.304	0.284	0.297	0.265	0.326	0.264	0.347	0.226	0.287
17	0.127	0.141	0.157	0.143	0.136	0.144	0.128	0.155	0.122	0.155	0.098	0.123
18	0.000	0.000	0.000	0.006	0.010	0.013	0.011	0.009	0.002	0.000	0.000	0.000
19	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
20	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
21	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
22	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
23	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
24	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Total	5.230	5.611	5.990	5.237	4.858	5.058	4.514	5.595	4.563	6.063	3.996	5.103

ANNEX 3

Excel template for estimation of annual PV power generation

Location	
Island:	Male'
Place:	

PV Spec		
PV Capacity (kWp):	100	kWp

Please input rated PV array output

Coefficient	
η_{INV}: Inverter efficiency	0.95
Kd: PV loss coefficient	0.8
α : Temp. coefficient @ Pmax	-0.5
η_{TR}: Transformer efficiency	0.98

Data from spec. sheet

Data from spec. sheet

Default is no shade condition. In case of shade, please input calculated insolation data.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
H_A: Daily Insolation [kWh/m²/day]	5.23	5.61	5.99	5.24	4.86	5.06	4.51	5.60	4.56	6.06	4.00	5.10	-
Monthly Days	31	28	31	30	31	30	31	31	30	31	30	31	365
Hm: Mnthly Integrated Insolation [kWh/m²]	162.1	157.1	185.7	157.2	150.7	151.8	139.8	173.6	136.8	187.9	120.0	158.1	1880.7
Average of daily maximum temperature [°C]	30.5	30.9	31.5	31.8	31.5	31	30.7	30.6	30.4	30.4	30.2	30.1	-
Kt: Temperature correction coefficient	0.865	0.863	0.86	0.8585	0.86	0.8625	0.864	0.8645	0.8655	0.8655	0.8665	0.867	-
Ep: Estimated PV Power Generation(kWh)	10,445	10,097	11,894	10,052	9,650	9,751	8,997	11,178	8,818	12,110	7,744	10,209	**120,946**

Data form Department of Meteorology