International Journal of Renewable Energy Resources 5 (2015) 28-37

OPTIMAL SOLAR CABLE SELECTION FOR PHOTOVOLTAIC SYSTEMS

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ABSTRACT
This paper presents a novel method for selecting optimal solar cable capacity for grid-connected solar Photovoltaic (PV) systems. The optimization method proposed in this paper is formulated that takes into consideration the cost of losses and solar cable investment cost throughout the technical lifespan of the cable. In addition, the effect of using actual field data of different time resolution irradiation data on the calculation of energy losses are also presented and discussed in this paper. The key findings of the paper suggest that oversizing the solar cable for PV system plays an important role in losses reduction and at the same time provide monetary savings in the long run.

Keywords: Solar PV System, Losses, Optimal Solar Cable Sizing.

1. INTRODUCTION

As one of the solutions for the depletion of fossil fuel and serious environmental problems, Photovoltaic (PV) system has been a growing interest around the world in the last decades. In this regard, the number of grid connected PV system installations worldwide has been increasing, from few kilowatts (kW) to many of megawatts (MW). Grid connected PV system design methodology has grown mature enough (Malamaki and Demoulias, 2014). This methodology focuses mainly on the suitable selection of PV panels (Kornelakis, 2010; Villa et al., 2012; Shams El-Dein, Kazerani and Salama, 2013), PV inverter sizing (Demoulias, 2010; Chen et al., 2013; Muñoz, Martínez-Moreno and Lorenzo, 2010), optimum tilt angle of the PV solar modules (Mehleri et al., 2010; Kaldellis, Kavadias and Zafirakis, 2012; Soulayman and Sabbagh, 2015), and suitable matching of the PV panels and PV inverters (Bakas, Papastergiou and Norrga, 2011; Camps et al., 2015; Khatib, Mohamed and Sopian, 2013; Hussin et al., 2011). However, not much attention has been given to the effect of losses on the main solar cable. In present, the common practice to select the main solar cable in the PV system design is mainly based on the maximum voltage drop constraint and corresponds to the thermal requirements (MS: 1837, 2010). Neglecting the joule losses inside the cable may affect the overall long term technical and economic performance of the PV system. Thus, it will be interesting to investigate on how the effect of losses will influence the optimal selection of solar cable for PV applications. In (Recio, 2013), the author suggests that oversizing the cable cross sectional area has the positive influence on the life cycle cost of the PV systems installation.

In light of this, this study aims to achieve optimal solar cable selection by taking into account both the investment cost of the solar cable and cost of losses due to joule effect throughout the life cycle of the PV system. Intuitively, the selection of larger conductor size will reduce the losses of energy because of lower resistance. However, the investment cost in larger cable will be higher. The balance of these two contradicting cost elements can be sought within a Life Cycle Assessment (LCA) framework (Gan et al., 2014).

This paper is structured as follows; Section 2 presents the methodology used for the selection of optimal solar cable followed by the comprehensive case study applications in Section 3. Finally, the finding of this work is concluded in Section 4.

2. METHODOLOGY

The methodology used in this paper for optimal solar cable sizing in PV systems is based on (Maillo, 2013).

A. Cable Sizing According to the Standards

Normally, a photovoltaic system array consists of a number of strings, these strings are connected in parallel to a junction box. Each string includes a number of PV modules connected in series. Therefore, for any given string in a PV array, the overall voltage of this string is the sum of the voltages of each module in the string. This voltage is the applied voltage at the level of junction box. It can be expressed as in the following Equation:

$$V = V_{MPP} \times N_{module} \quad \text{..................................(1)}$$

Where:

N_{module}	is the number of modules connected in series in a string.
V_{MPP}	is the voltage of one module at maximum power point.

The current value of a string is same as the current value of one module, because in a string the modules are connected in series. For a number of strings connected in parallel per junction box, the current at the level of junction box is the sum of the current of each string connected to that junction box. It can be expressed by the following Equation:

$$I = I_{MPP} \times N_{string} \quad \text{.................................. (2)}$$

Where, I_{MPP} is the current of a string at maximum power point.
N_{string} is the number of strings per junction box.
To maximize the allowed current calculated from Equation (2), this current must be increased by a margin, according to the installation standards, which vary from one country to another. In Malaysia, according to Malaysian standards MS 1837, (2010), that current should be increased by a margin of 1.3. Temperature correction also must be added to the current value if the ambient temperature reaches 40 °C or more (MS 1837, 2010). Then, conductor section is chosen according to the resulting current by using Table B.52-1 of IEC 60364-5-52.

The maximum allowed voltage drop must be according to the installation standards. In Malaysia, the maximum allowed voltage drop between the PV array and inverter shall be less than 5% (MS 1837, 2010). The resulting voltage from Equation (1) is multiplied by the maximum allowed percentage voltage drop to get the voltage drop value (e). The voltage drop value will be used in the following Equation (Maillo, 2013):

$A = L * I/\gamma * e$ ………………………………... (3)

Where:
A = Cross section area of the cable *(mm²)*.
L = Length of the cable *(m)*.
I = Nominal current *(Amp.)*.
γ = Conductivity of copper *(m/Ω. mm²)*.
e = Maximum voltage drop *(V)*.

The result of Equation (3) represents the cable cross section area *(A)*, which is calculated according to maximum allowed voltage drop in (*mm²*).

It is important to note that, if the cable section, which has been resulted from the maximum allowed current calculations, is bigger than the cable section, which has been resulted from the maximum allowed voltage drop calculations, and vice versa, the bigger cable section must be selected, because the resulting cable section must fulfills both criteria maximum allowed current and maximum voltage drop standards.

B. Economic Cable Section Calculations

Increasing the cable section will not lead to higher investment cost only, but also to lower losses. Therefore, the payback time of the conductor sections larger than the cable section defined by standards needs to be analyzed.

For any cable, the power losses are determined by:

$P = R \times I^2$ ……………………….………………(4)

Where:
R is the resistance of the cable.
I is the current of the cable.

In time *(t)*, the energy lost is calculated using:

$E_{lost} = R \times I^2 \times t$ ………………………………(5)

Current time distribution follows the solar radiation (zero during night and maximum during day) (Maillo, 2013). Then, Equation (5) will be:

$E_{lost} = \int R(t) \times I^2(t) \times dt$ ……………………(6)

R(t) can be considered to be constant, without worthy error, thus Equation (6) will be:

$E_{lost} \approx R \times \int I^2(t) \times dt$ …………………………(7)

To simplify the calculations, the sum of discrete values is used (see Figure 1), starting from the hourly incident radiation for each hour of the year, thus Equation (7) will be:

$E_{lost} \approx R \times \sum_{i=1}^{d} I_i^2 \times t_i$ ………………………(8)

Where:
d is the number of daylight hours through a year.
i is a specific hour for calculation.
I_i is the current at an hour i.

For one hour interval, the final expression will be:

$E_{lost} \approx R \times I_i^2$ ……………………………………(9)

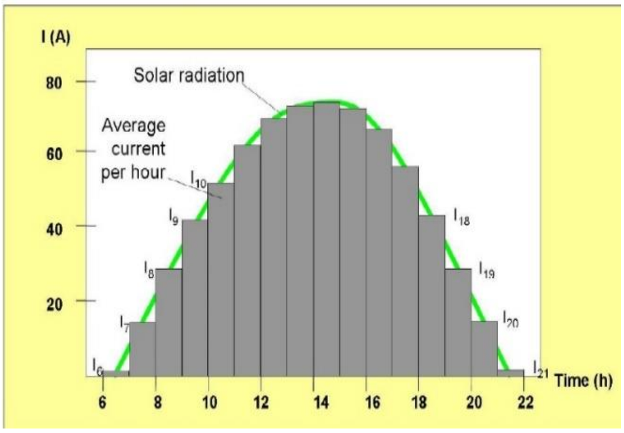

Figure 1 Discretization of solar radiation and current (Maillo, 2013).

To calculate the current based on the solar radiation, the following assumptions will be made:

- The current is proportional to the solar radiation (Ettah, Obiefuna and Njar, 2011).
- The nominal current of a PV module is 90% of the short-circuit current *(Is.c)* (Solanki, 2013).
- The standard test conditions (STC) of a PV module are given for a solar radiation of 1000 *W/m2*.

Thus, the current for one string will be as follows:

$I_{string} = 0.9 \times I_{S.C} \times G_i/1000$ ……………….. (10)

Where:

G_i is the solar radiation at an hour i.

$G_i/1000$ is to convert from standard test conditions to real conditions.

$I_{S.C}$ is the short circuit current of a PV module at standard test conditions.

If there are a number of strings (N_{string}) connected in parallel to one junction box, the current in the main solar cable at an hour i will be as follow:

$$I(t_i) = 0.9 \times N_{string} \times I_{s.c} \times G_i/1000 \text{ ………..(11)}$$

Thus, the energy lost on the main solar cables, which run from the junction box to the inverter, will be as in the following equation:

$$E_{lost} = R \times \sum I(t_i)^2 \ \ (kWh) \text{ …………………... (12)}$$

Equation (12) can be used to easily calculate the annual energy losses in the solar cables by using any time resolution of solar radiation data.

After calculating the energy lost E_{lost} from Equation (12), the cost of energy losses (C_{losses}) can be calculated (not sold at the applicable Feed in Tariff (FiT)) as follows:

$$C_{losses} = FiT(RM/kWh) \times E_{lost}(kWh)(RM) \text{ ... (13)}$$

After calculating the energy losses cost from Equation (13), this must be compared to the investment cost of solar cable. Thus, the overall cost ($C_{standards}$) of the cable cross section area that has been selected according to the standards ($A_{standards}$) will be (Maillo, 2013):

$$C_{standards} = (L \times P) + (C_{losses} \times t)\ (RM) \text{ ……… (14)}$$

Where:

L is the length of the cable (m).

P is the cable price (RM/m).

t is the time (years).

For a cable section of a cross section A, Equation (14) is generalized as follow:

$$C_A = (L \times P) + (C_{losses} \times [A_{standards}/A] \times t)(RM) \text{ ……………………………………………………(15)}$$

The payback period for each section of conductor beyond the conductor section chosen according to the standards can be calculated by using the following equation (Global Sustainable Energy Solutions, 2012):

$$T = C_{investment}/S \text{ ………………………………(16)}$$

Where, $C_{investment}$ is the investment cost (i.e. the difference between bigger cable section price and standards cable section price). S is the saving of a year that can be achieved when a bigger cable section is used (i.e. the difference between the annual energy losses cost when the standards cable is used and the annual energy losses cost when a bigger cable is used).

To calculate the life cycle savings, following equation is used (Maillo, 2013):

$$S_{life\ cycle} = (S \times n) - C_{investment} \text{ ……………(17)}$$

Where, n is the lifespan of PV system in years.

Net present value *(NPV)* of the life cycle savings is calculated as follows (Ong and Thum, 2013):

$$NPV = \sum_{j=1}^{n} \left(\frac{S_j}{(1+r)^j}\right) - C_{investment} \text{ …………(18)}$$

Where:

r is the discount rate.

j is a specific year for calculation.

3. CASE STUDY

The proposed PV system features are:

- Module installation mode: Fixed, tilted at 15 degree facing south.
- Number of modules in each string: 16.
- Number of strings: 33.
- Maximum ambient temperature: 35 $°C$.
- Cable type: PV1-F.
- System peak power 100 kW.

Type of module used is crystalline silicon (Atersa A-222P), electrical characteristics of the module are illustrated in Table 1.

Table 1 Electrical Characteristics of PV module at STC

Description	Nominal Rating
Peak power (W at test ±2 %)	222 W
Number of cells in series	60
Efficiency (module)	13.63 $\%$
Max. Power current (I_{MPP})	7,44 A
Max. Power voltage (V_{MPP})	29.84 V
Short circuit current ($I_{S.C}$)	7.96 A
Open circuit voltage ($V_{O.C}$)	37,20 V
Thermal coefficient of $I_{S.C}$ (α)	0.05 $\%/^{\circ}C$
Thermal coefficient of $V_{O.C}$ (β)	-129 $mV/^{\circ}C$
Coefficient of temperature P (γ)	-0.46 $\%/^{\circ}C$
Max. Voltage system	1000 V

Modules peak power = 16 × 33 × 222 W = 117.216 kW

Inverter power = system nominal power = 100 kW

The system consists of three sub arrays. Each sub array with eleven strings is connected into one junction box, and in each string, there are sixteen modules connected in series. Overall, there are three junction boxes, and each one has eleven strings. We will focus on the cable between one junction box and the inverter as illustrated in Figure 2.

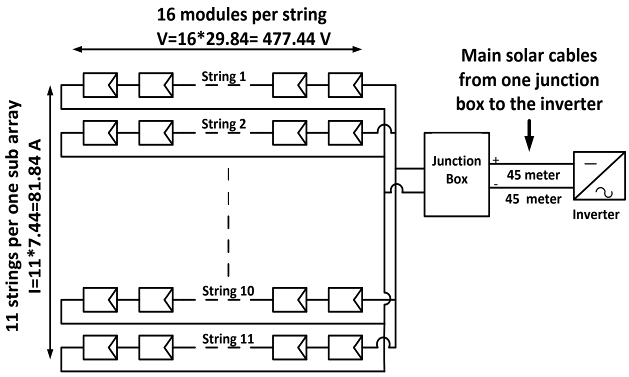

Figure 2 Proposed System Configuration (Maillo, 2013).

A. Cable Sizing According to the Standards

First, the voltage and current for one junction box at maximum power point is calculated. Then, the cable section is derived according to the voltage and current calculated.

For one string in the proposed system, there are sixteen modules connected in series (see Figure 2), so by using Equation (1), the voltage at the junction box will be:

$$V = V_{MPP} \times 16 = 29.84 \times 16 = 477.44\, V$$

There are eleven strings per junction box connected in parallel (see Figure 2), so by using Equation (2), the current at the junction box will be:

$$I = I_{MPP} \times 11 = 7.44 \times 11 = 81.84\, Amp.$$

According to Malaysian standards (MS: 1837, 2010), minimum current by which cable cross-sectional area should be chosen, must be increased by a margin of 1.3, therefore, the current will be:

$$I_{standards} = 81.84 \times 1.3 = 106.392\, Amp.$$

As mentioned in (MS: 1837, 2010), temperature correction must be applied to the current if the maximum ambient temperature reaches 40 $℃$. According to (Accuweather, 2015), maximum ambient temperature does not reach 40 $℃$ in Melaka, therefore, temperature correction will not be applied. Since 106.392 Amp is the corrected value of the current, this value is used in Table B.52-1 of IEC 60364-5-52 (Maillo, 2013). As referred from the table, the cable cross section area is 16 mm^2 for copper conductor.

After selecting the cable section according to the maximum allowed current, now, the cable section has to be selected according to maximum allowed voltage drop. According to (MS: 1837, 2010), the voltage drop between the PV array and the inverter shall be less than 5%. The main solar cable is assumed responsible for 2.5% of voltage drop and the remaining voltage drop is because of the rest of the cable between the modules. Thus, the allowed maximum voltage drop will be:

$$e = 0.025 \times 477.44 = 11.936\, V$$

Equation (3) is used to calculate the cable section according to maximum allowed voltage drop:

$$A = (81.84 \times 90)/(11.936 \times 46.82) = 13.18\, mm^2$$

Where, 90 is the length of the cable (positive and negative) in (m), 81.84 is the nominal current in ($Amp.$) and 46.82 is the conductivity of the copper ($m/\Omega.mm^2$). Since there is no 13.18 mm^2 cable section, therefore, 16 mm^2 cable section is chosen.

In this case, the resulting cross section which is equal to 16 mm^2, has achieved the two conditions according to the standards (maximum allowed current and maximum allowed voltage drop).

B. Economic Cable Section Calculation:

Using Equation (10), the current of one string is calculated as follow:

$$I_{string} = 0.9 \times I_{S.C} \times G_i/1000$$

$$= 0.9 \times 7.96 \times G_i/1000$$

$$= 7.164 \times 10^{-3} \times G_i \;\; (Amp)$$

There are eleven strings per junction box (see Figure 2), so the current at an hour i in the main solar cable is calculated using Equation (11) as follow:

$$I(t_i) = 11 \times I_{string} = 11 \times 7.164 \times 10^{-3} \times G_i$$

$$= 0.078804 \times G_i \quad (Amp)$$

Now, according to Equation (12), the annual energy lost in the main solar cable is calculated as follow:

$$E_{lost} = R \times \sum I(I_i)^2 = (0.078804)^2 \times R \times \sum G_i^2$$
(kWh)

Thus, solar radiation data can be used to calculate the annual energy lost E_{lost}. In this work, three sets of radiation along one year (One-minute, Five-minute, and Hourly) starting from 1 May 2014 to 31 March 2015 have been used, collected from the lab at Universiti Teknikal Malaysia Melaka (UTeM).

For the purpose of accuracy, resistance of the Copper for a cable section of 16 mm^2 has been considered at 55 $℃$, instead of using a manufacturer resistance value which is at 20 $℃$, (35 $℃$ from an environment temperature and 20 $℃$ comes from conductor heating due to joule effect).Thus, the resistance value of a cable section of 16 mm^2 at 55 $℃$ is 0.0013 Ω/m.
By using the collected solar radiation and the resistance value, the annual energy lost (E_{lost}) when

the standard cable section (16 mm^2) is applied, has been calculated according to each type of radiation which is summarized in Table 2.

The cost of annual energy losses C_{losses}, has been calculated using Equation (13) which is summarized in Table 2 also. Two scenarios have been used. The first one is FiT of 0.6977 RM/kWh taken from (Seda.gov.my, 2015) and the second (for sensitivity analysis) is if the FiT rate decreased by a margin of 25% to be equal to 0.5232 RM/kWh.

Table 2 Annual Energy Lost and Energy Losses Cost at Different Data Resolution

Types of radiation	One-minute	Five-minute	Hourly
(E_{lost}) kWh	1007.35	897.84	846.59
(C_{losses}) at FiT (0.6977 RM/kWh) (RM)	702.83	626.43	590.67
(C_{losses}) at FiT (0.5232 RM/kWh) (RM)	527.05	469.75	442.94

As seen from Table 2, the energy lost calculated using One-minute radiation is higher than the energy lost when Five-minutes and Hourly radiation are used, because the One-minute radiation is higher than the Five-minute and Hourly radiations, also the energy lost when Five-minute radiation used is higher than the energy lost when Hourly radiation is used, because the Five-minute radiation is higher than the Hourly radiation, as illustrated in Figures 3, 4 and 5. That is because, in the Hourly radiation, many peaks values of radiation are lost, but in the Five-minute radiation, less peaks values are lost compared to Hourly radiation. Of course in the One-minute radiation, more less peaks values are lost compared to Five-minute and Hourly radiation. Figure 3, 4 and 5 present One-minute, Five-minute and Hourly radiations versus time for samples of three days, namely cloudy day, normal day and sunny day.

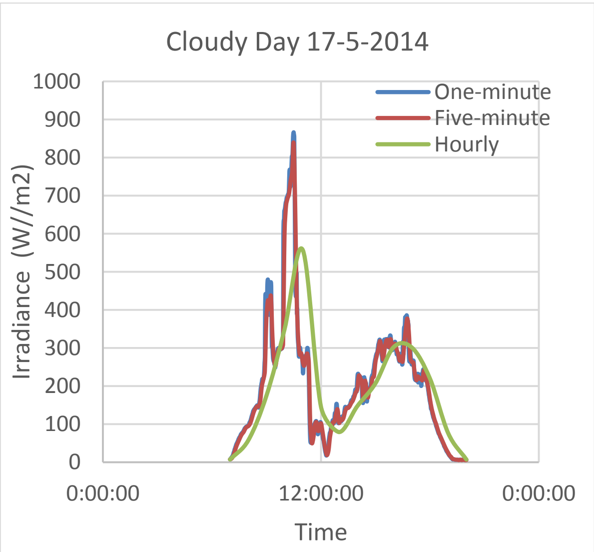

Figure 3 Irradiance versus time along one cloudy day (17 May 2014).

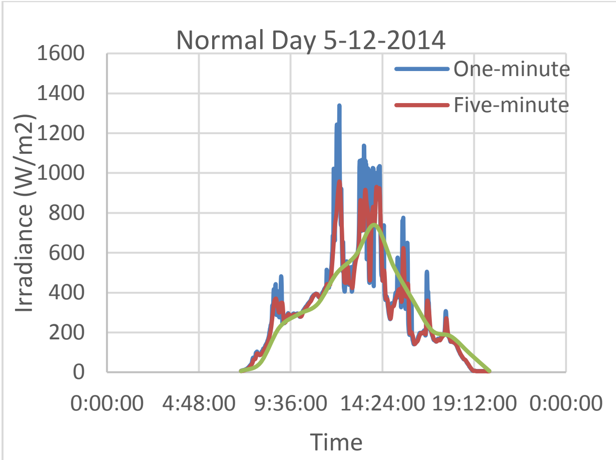

Figure 4 Irradiance versus time along one normal day (5 December 2014).

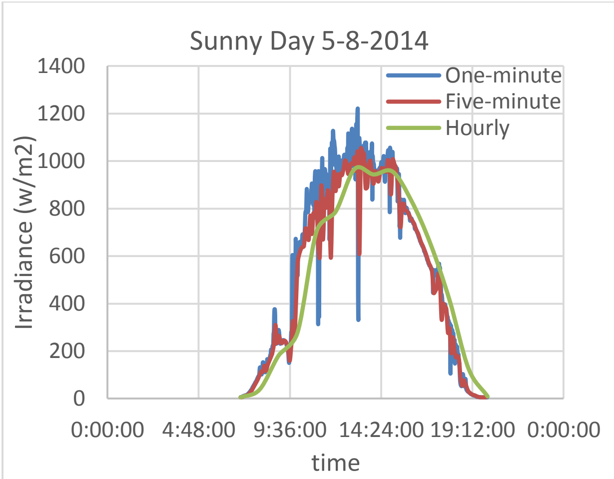

Figure 5. Irradiance versus time along one sunny day 5 August 2014).

After determining the annual cost of energy losses, in the 16 mm^2 cable section, according to each type of radiation, it is compared to the investment cost of the cable (cable price). Solar cable prices are obtained from the solar cable vender (Yr-group.cn, 2015). By using Equation (14), the overall cost (investment cost plus energy losses cost) according to each type of radiation is as follows:

- According to One-minute radiation:

$C_{16} = 90 \times P + 702.83 \times t$ at FiT 0.6977 RM/kWh

$C_{16} = 90 \times P + 527.05 \times t$ at FiT 0.5232 RM/kWh

- According to Five-minute radiation:

$C_{16} = 90 \times P + 626.43 \times t$ at FiT 0.6977 RM/kWh

$C_{16} = 90 \times P + 469.75 \times t$ at FiT 0.5232 RM/kWh

- According to Hourly radiation:

$C_{16} = 90 \times P + 590.67 \times t$ at FiT 0.6977 RM/kWh

$C_{16} = 90 \times P + 442.94 \times t$ at FiT 0.5232 RM/kWh

To minimize the annual energy losses cost in the standards cable section (16 mm^2), we have to increase the cable section. For example, if a cable of section 25 mm^2 is used instead of the standards cable section (16 mm^2), then, the annual energy losses cost, according to One-minute radiation and FiT rate of 0.6977 RM/kWh, will be minimized by a margin of (702.83 $\times$ 16/25), to be equal to 449.81 RM (see Table 3).

An annual saving of 702.84 – 449.81 = 253 RM can be achieved, when using a cable section of 25 mm^2. But, of course, increasing the standards cable section will lead to higher investment cost, therefore, a tradeoff between the investment cost and the losses cost is applied using Equation (15) for each section beyond the standards cable section. The payback period and the life cycle savings (21 year) according of each cable section beyond the standards cable section is calculated using Equation (16) and Equation (17) respectively. The calculations for each cable section according to each type of radiation and FiT rate, are as summarized in Tables 3 to 8:

Table 3 Payback Periods and Savings over 21 Years According to One-minute Radiation at FiT 0.6977 RM/kWh

Price *(P)* *(RM/m)*	$\boldsymbol{C_A = 90 \times P + 702.83 \times 16/A \times t}$	Payback (years)	Saving *(RM)*
6.17	$C_{16} = 555.3 + 702.83 \times t$	-	0
9.27	$C_{25} = 834.3 + 449.81 \times t$	1.10	5034
13.58	$C_{35} = 1222.2 + 321.3 \times t$	1.75	7345
18.96	$C_{50} = 1706.4 + 224.9 \times t$	2.41	8885
26.52	$C_{70} = 2386.8 + 160.65 \times t$	3.38	9554
35.13	$C_{95} = 3161.7 + 118.37 \times t$	4.46	9667
42.28	$C_{120} = 3805.2 + 93.71 \times t$	5.34	9542
53.28	$C_{150} = 4795.2 + 74.97 \times t$	6.75	8945
65.03	$C_{185} = 5852.7 + 60.79 \times t$	8.25	8186
85.69	$C_{240} = 7712.1 + 46.86 \times t$	10.91	6619

Table 4 Payback Periods and Savings over 21 Years According to One-minute Radiation at FiT 0.5232 RM/kWh

Price *(P)* *(RM/m)*	$\boldsymbol{C_A = 90 \times P + 527.05 \times 16/A \times t}$	Payback (years)	Saving *(RM)*
6.17	$C_{16} = 555.3 + 527.05 \times t$	-	0
9.27	$C_{25} = 834.3 + 337.31 \times t$	1.47	3706
13.58	$C_{35} = 1222.2 + 240.94 \times t$	2.33	5342
18.96	$C_{50} = 1706.4 + 168.66 \times t$	3.21	6375
26.52	$C_{70} = 2386.8 + 120.47 \times t$	4.50	6707
35.13	$C_{95} = 3161.7 + 88.77 \times t$	5.95	6598
42.28	$C_{120} = 3805.2 + 70.27 \times t$	7.11	6342
53.28	$C_{150} = 4795.2 + 56.22 \times t$	9.01	5648
65.03	$C_{185} = 5852.7 + 45.58 \times t$	11.00	4813
85.69	$C_{240} = 7712.1 + 35.14 \times t$	14.55	3173

Table 5 Payback Periods and Savings over 21 Years According to Five -minute Radiation at FiT 0.6977 RM/kWh

Price *(P)* *(RM/m)*	$\boldsymbol{C_A = 90 \times P + 626.43 \times 16/A \times t}$	Payback (years)	Saving *(RM)*
6.17	$C_{16} = 555.3 + 626.43 \times t$	-	0
9.27	$C_{25} = 834.3 + 400.91 \times t$	1.24	4457
13.58	$C_{35} = 1222.2 + 286.37 \times t$	1.96	6474
18.96	$C_{50} = 1706.4 + 200.46 \times t$	2.70	7794
26.52	$C_{70} = 2386.8 + 143.18 \times t$	3.79	8317
35.13	$C_{95} = 3161.7 + 105.50 \times t$	5.00	8333
42.28	$C_{120} = 3805.2 + 83.52 \times t$	5.99	8151
53.28	$C_{150} = 4795.2 + 66.82 \times t$	7.58	7512
65.03	$C_{185} = 5852.7 + 54.18 \times t$	9.26	6720
85.69	$C_{240} = 7712.1 + 41.76 \times t$	12.24	5121

Table 6 Payback Periods and Savings over 21 Years According to Five -minute Radiation at FiT 0.5232 RM/kWh

Price *(P)* *(RM/m)*	$\boldsymbol{C_A = 90 \times P + 469.75 \times 16/A \times t}$	Payback (years)	Saving *(RM)*
6.17	$C_{16} = 555.3 + 469.75 \times t$	-	0
9.27	$C_{25} = 834.3 + 300.64 \times t$	1.65	3272
13.58	$C_{35} = 1222.2 + 214.74 \times t$	2.62	4688
18.96	$C_{50} = 1706.4 + 150.32 \times t$	3.60	5557
26.52	$C_{70} = 2386.8 + 107.37 \times t$	5.05	5779
35.13	$C_{95} = 3161.7 + 79.12 \times t$	6.67	5597
42.28	$C_{120} = 3805.2 + 62.63 \times t$	7.98	5300
53.28	$C_{150} = 4795.2 + 50.11 \times t$	10.10	4573
65.03	$C_{185} = 5852.7 + 40.63 \times t$	12.34	3714
85.69	$C_{240} = 7712.1 + 31.32 \times t$	16.32	2050

Table 7 Payback Periods and Savings over 21 Years According to hourly Radiation at FiT 0.6977 RM/kWh

Price *(P)* *(RM/m)*	$\boldsymbol{C_A = 90 \times P + 590.67 \times 16/A \times t}$	Payback (years)	Saving *(RM)*
6.17	$C_{16} = 555.3 + 590.67 \times t$	-	0
9.27	$C_{25} = 834.3 + 378.03 \times t$	1.31	4186
13.58	$C_{35} = 1222.2 + 270.02 \times t$	2.08	6067
18.96	$C_{50} = 1706.4 + 189.01 \times t$	2.87	7284
26.52	$C_{70} = 2386.8 + 135.01 \times t$	4.02	7737
35.13	$C_{95} = 3161.7 + 99.48 \times t$	5.31	7709
42.28	$C_{120} = 3805.2 + 78.76 \times t$	6.35	7500
53.28	$C_{150} = 4795.2 + 63.00 \times t$	8.04	6841
65.03	$C_{185} = 5852.7 + 51.08 \times t$	9.82	6034
85.69	$C_{240} = 7712.1 + 39.38 \times t$	12.98	4420

The savings over 21 years should be multiplied by three, since the system consists of three junction boxes, and since the focus is on the main solar cables between one junction box and the inverter, it is assumed that the length of the three main solar cables is equal.

Table 8 Payback Periods and Savings over 21 Years According to hourly Radiation at FiT 0.5232 *RM/kWh*

Price *(P)* *(RM/m)*	$\boldsymbol{C_A = 90 \times P + 442.94 \times 16/A \times t}$	Payback (years)	Saving *(RM)*
6.17	$C_{16} = 555.3 + 442.94 \times t$	-	0
9.27	$C_{25} = 834.3 + 283.48 \times t$	1.75	3067
13.58	$C_{35} = 1222.2 + 202.49 \times t$	2.77	4383
18.96	$C_{50} = 1706.4 + 141.74 \times t$	3.82	5174
26.52	$C_{70} = 2386.8 + 101.24 \times t$	5.36	5344
35.13	$C_{95} = 3161.7 + 74.60 \times t$	7.08	5129
42.28	$C_{120} = 3805.2 + 59.06 \times t$	8.47	4812
53.28	$C_{150} = 4795.2 + 47.25 \times t$	10.72	4070
65.03	$C_{185} = 5852.7 + 38.31 \times t$	13.09	3200
85.69	$C_{240} = 7712.1 + 29.53 \times t$	17.31	1525

Based on Tables 3 to 8, the optimal solar cable size is selected, according to the life cycle savings and the payback period. The cable which achieves a highest life cycle savings and an acceptably low payback period can be selected as the optimal one. As seen from Table 3, at FiT rate 0.6977 *RM/kWh* and at One-minute radiation, the 95 *mm²* cable section achieves the highest life cycle saving (over 21 years), which is equal to 9667 *RM* and the payback period takes 4.46 years, therefore it can be chosen as the optimal cable. When the FiT rate decreased to 0.5232 *RM/kWh* the optimal cable size at one-minute radiation is 70 *mm²* (see Table 4), this section achieves saving over 21 years which equal to 6706.7 *RM* and the payback period takes 4.50 years.

Figures 6 to 11 below show the annuitized total cost (investment cost and losses cost) versus the cable size, for each cable size starting from 16 *mm²* to 240 *mm²* and for each type of radiation and FiT rate. As illustrated from Figures 6 to 11, when the cable section increased the losses cost decreased, but the investment cost increased, until we reach a specific cable section where the investment cost and the losses cost are lower than the investment cost and losses cost of other cables, this specific cable section can be considered as the optimal cable section, because it achieves optimal tradeoff between the investment cost and the losses cost. As illustrated from Figure 6, for the 16 *mm²* cable section the losses cost is high, but the investment cost is low. After increasing the cable section, the losses cost begins to decrease, while the investment cost begins to increase, until we reach to the 95 *mm²* cable section, where the investment cost and the losses cost are lower than the investment cost and losses cost of other cable sections, therefore, the 95 *mm²* cable section is the optimal cable section at One-minute radiation and FiT rate of 0.6977 *RM/kWh*, which is matched with the optimal cable section that has been chosen based on life cycle saving and payback period at One-minute radiation and FiT rate of 0.6977 *RM/kWh*.

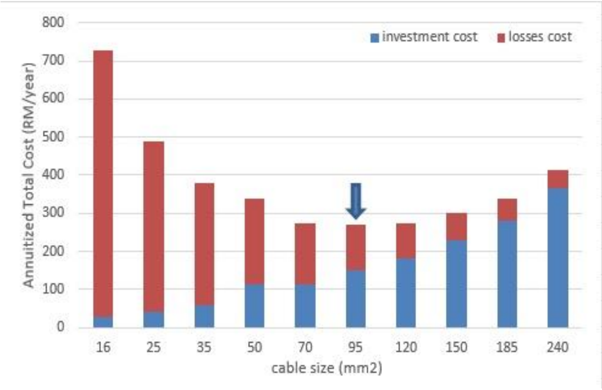

Figure 6 Annuitized Total Cost versus Cable Size at One- Minute Radiation and FiT (0.6977 *RM/kWh*)

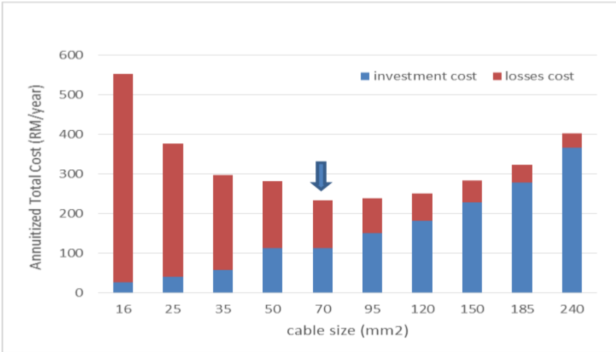

Figure 7 Annuitized Total Cost versus Cable Size at One- Minute Radiation and FiT (0.5232 *RM/kWh*)

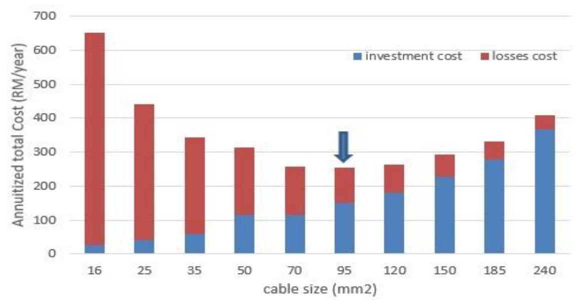

Figure 8 Annuitized Total Cost versus Cable Size at Five- Minute Radiation and FiT (0.6977 *RM/kWh*)

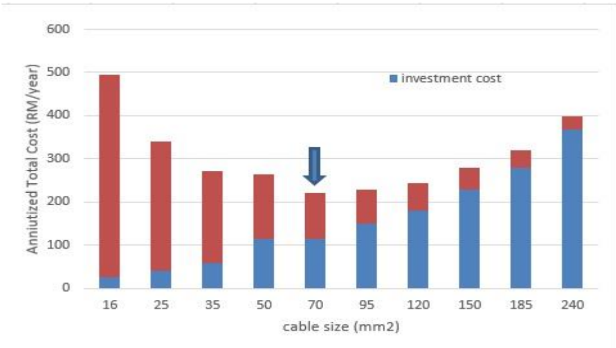

Figure 9 Annuitized Total Cost versus Cable Size at Five- Minute Radiation and FiT (0.5232 *RM/kWh*)

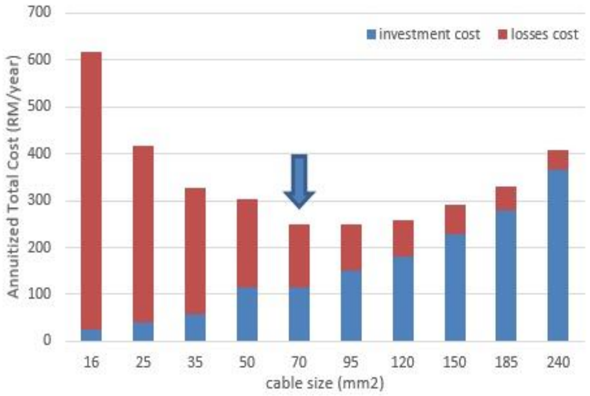

Figure 10 Annuitized Total Cost versus Cable Size at Hourly Radiation and FiT (0.6977 *RM/kWh*)

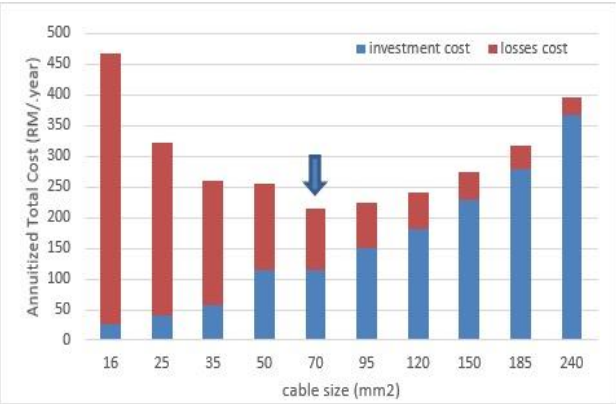

Figure 11 Annuitized Total Cost versus Cable Size at Hourly Radiation and FiT (0.5232 *RM/kWh*)

Table 9 below summarizes the optimal cable section for each type of radiation and for the two scenarios of FiT rate.

Table 9 Optimal Cable Size According to Radiation Type and FiT Rate

Radiation Type	Optimal cable size (mm^2)	
	At FiT (0.6977 *RM/kWh*)	At FiT (0.5232 *RM/kWh*)
One-minute radiation	95	70
Five-minute radiation	95	70
Hourly radiation	70	70

As seen from Table 9, when One-minute radiation is used at FiT rate (0.6977 *RM/kWh*) to optimum cable size of 95 mm^2, the Five-minute radiation used at FiT rate (0.6977 *RM/kwh*) also showed optimum cable size of 95 mm^2, but for the Hourly radiation at same FiT rate, the optimum cable size is 70 mm^2. Therefore, it can be concluded that, for time resolution impact of the solar radiation on the optimum cable selection, it is enough to apply Five-minute radiation instead of One-minute radiation (i.e. no need to adopt more time resolution solar radiation data than the Five-minute time resolution data), because both of them achieves the same optimal cable size, but it is inadequate to adopt the Hourly radiation instead of the Five-minute or One-minute radiation, because as seen from Table 9, the cable size decreases to 70 mm^2 when the Hourly radiation is used at the same FiT rate.

When the optimal cable section (95 mm^2) is applied instead of the standard section, the life cycle savings at FiT rate of 0.6977 *RM/kWh* and One-minute radiation, is equal to 9667 *RM* (see Table 3), since the system consists of three main solar cable as mentioned previously, therefore the cumulated savings of the 100 *kW* PV system at FiT rate of 0.6977 *RM/kWh* and One-minute radiation, is around (9667×3 = 29001 *RM*).

Net present value for the commuted savings is calculated using Equation (18). Tables 10, 11 and 12 show the impact of different interest rates, when an initial overinvestment is considered (difference between the standards cable price and the optimal cable price), on the cumulated savings over the life cycle of the system (21 years).

Table 10 Net Present Value at FiT (0.6977 *RM/kWh*) and (0.5232 *RM/kWh*) According to One-minute Radiation

Interest rate (%)	Net present value at FiT (0.6977 *RM/kWh*) *RM*	Net present value at FiT (0.5232 *RM/kWh*) *RM*
0	29001	20120
0.5	27052	18764
1	25244	17506
2	22008	15255
3	19209	13308
4	16779	11617
5	14661	10144
6	12808	8855
7	11180	7722

Table 11 Net Present Value at FiT (0.6977 *RM/kWh*) and (0.5232 *RM/kWh*) According to Five-minute Radiation

Interest rate (%)	Net present value at FiT (0.6977 *RM/kWh*) *RM*	Net present value at FiT (0.5232 *RM/kWh*) *RM*
0	24999	17335
0.5	23262	16127
1	21650	15006
2	18766	12999
3	16271	11264
4	14105	9757
5	12218	8444
6	10566	7295
7	9114	6285

Table 12 Net Present Value at FiT (0.6977 RM/kWh) and (0.5232 RM/kWh) according to Hourly Radiation

Interest rate (%)	Net present value at FiT (0.6977 *RM/kWh*) *RM*	Net present value at FiT (0.5232 *RM/kWh*) *RM*
0	23212	16033
0.5	21692	14893
1	20283	13836
2	17759	11944
3	15578	10307
4	13683	8887
5	12032	7648
6	10587	6565
7	9317	5613

4. CONCLUSION

The optimal solar cable sizing for PV systems has been studied in this study by taking into consideration the solar cable investment cost and the cost of losses due to joule effect throughout the technical operational lifespan of the system. The main aim is to select the optimal solar cable for the PV systems that offer economic saving in the long run. The presented study considers the main solar cable from the PV sub-array junction box to the inverter. More importantly, annual irradiance data of One-minute, Five-minute and Hourly interval data in Malacca, Malaysia have been considered in this study. The annual energy losses in the standard cable according to each type of radiation and the annual energy losses cost according to each type of radiation are calculated using different feed–in tariff. The annual energy losses cost according to each type of radiation has been compared and analyzed accordingly. In addition, the calculated losses cost has also been compared to the investment cost. Subsequently, the payback period, the savings over 21 years for each section of the cable and the net present value for the life cycle savings have been determined. The findings suggest that the optimal rating of the solar cable for PV applications should be considerably oversized in order to achieve long term economical saving.

ACKNOWLEDGEMENT

The authors would like to gratefully acknowledge the solar radiation data provided by the Research Laboratory of Solar PV System & Smart Grid located at Faculty of Electrical Engineering, UTeM.

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