INVERTER SIZING RATIO FOR PV PLANT IN THE TROPICS

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A project report submitted in partial fulfilment of the
requirements for the award of Bachelor of Engineering (Honours)
Electrical and Electronic Engineering

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APRIL 2021

DECLARATION

I hereby declare that this project report is based on my original work except for citations and quotations which have been duly acknowledged. I also declare that it has not been previously and concurrently submitted for any other degree or award at UTAR or other institutions.

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APPROVAL FOR SUBMISSION

I certify that this project report entitled **"INVERTER SIZING RATIO FOR PV PLANT IN THE TROPICS"** was prepared by **WINSTON LIM JUN LIANG** has met the required standard for submission in partial fulfilment of the requirements for the award of Bachelor of Engineering (Honours) Electrical and Electronic Engineering at Universiti Tunku Abdul Rahman.

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ACKNOWLEDGMENT

I would like to thank everyone who had contributed to the successful completion of this project. I would like to express my gratitude to my research supervisor, Dr. Lim Boon Han for his invaluable advice, guidance and his enormous patience throughout the development of the research.

In addition, I would also like to express my gratitude to my family and friends who had given me encouragement throughout this whole project.

ABSTRACT

An inverter is used to convert the electricity generated by a photovoltaic (PV) system from direct current (DC) to alternating current (AC). The larger the power rating of an inverter, the higher the cost of the PV system. An inverter can cost more than 10 million ringgit for a 50 MW large-scale solar PV plant. Therefore, it can be downsized to save the capital cost because a PV system does not perform 100% of its rated capacity due to several losses. A specific term known as “inverter sizing ratio” (ISR) is used to show the ratio of DC power rating generate by the PV array to the ratio of AC power rating of the inverter. The drawback of downsizing (high ISR) is the possibility of power clipping during occasional high solar irradiance which leads to loss of income. There exists an optimal ISR to balance the amount of cost-saving and the amount of lost income. There is a lack of research study on optimal ISR in Malaysia despite some in other non-tropic countries. This study aims to provide a reference of optimal ISR for the PV industry in the tropics. The main objective of this study is to analyse the influence of the key parameters of a PV plant on the optimal ISR and levelised cost of electricity (LCOE) through sensitivity analysis. A special technique to divide the performance ratio into a fixed component and a variable component was used in this study based on the characteristic of the projects in the tropics. This technique helps to ease the sensitivity analysis. In addition, a method of processing the solar irradiance data which will affect the value of optimal ISR is adopted, compared and discussed. The solar irradiance data were sampled in a 5-minutes interval rather than averaged out within the time interval which was done by previous work. The sampled method means the solar irradiance data is taken for every X-minute interval for one year data where X can be five, ten, twenty, thirty or sixty minutes. The averaged method means the solar irradiance data in every X-minute interval is sum up then the data is averaged out with the value of X where X can be five, ten, twenty, thirty or sixty minutes. All the parameters in this study are the latest information on the PV industry. The graphs for sensitivity analysis were plotted and interpreted. The summary of all the sensitivity analysis was discussed. The sensitivity analysis of changing the specific cost of the PV system with the specific cost of the inverter has a great influence on optimal ISR. When the specific cost of the inverter is more expensive, it allows higher optimal ISR for saving cost. The recommended range for the optimal ISR is from 1.50-1.80 for a 10 MW plant in the tropics. In a nutshell, the results from this study can provide guidelines on choosing the right ISR for the PV industry player. Besides that, the PV industry player can estimate the percentage change for the optimal ISR when the sensitivity analysis is different from the nominal value via the trend of the lines plotted from the sensitivity analysis.

TABLE OF CONTENTS

CHAPTER

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS / ABBREVIATIONS

AC	Alternating current
AM	Air mass
DC	Direct current
GHI	Global Horizontal Irradiance
GTI	Global Tilted Irradiance
ISR	Inverter sizing ratio
LCOE	Levelised cost of electricity
LSS	Large-scale solar
MPPT	Maximum power point tracking
O & M	Operation and maintenance
PV	Photovoltaic
PR	Performance ratio
PR_{fixed}	Fixed component of performance ratio
STC	Standard test conditions

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 General Introduction

The demand for using renewable energy such as solar energy is increasing in the world to prevent global warming. Solar energy is a type of free energy provided by the sun and does not cause any pollution to the environment. Solar energy is abundant in tropical areas. Photovoltaic (PV) system is an application that uses solar energy to produce electricity (Khatib et al., 2017).

The current generated from the PV system before passing through the inverter is direct current (DC). The function of an inverter is to convert the DC become alternating current (AC) (Lai and Lim, 2019a). Therefore, the inverter is essential in a grid-connected PV system. The inverter power capacity is normally sized to the rated capacity of the PV system in certain sites. The rated capacity of a PV system is determined based on the power of the PV panels measured under standard test conditions (STC) in which the solar irradiance is 1000 W/m^2, the sunlight spectrum is air mass (AM) 1.5 and the PV module operating temperature is 25 °C (Khatib et al., 2017). Besides that, the inverter is normally equipped with the function of maximum power point tracking (MPPT) to achieve the highest power injection to the grid. However, solar irradiance does not always stay stable or constant. A PV system can generate power that is higher than the rated capacity of the inverter. The reason for causing this situation is the presence of higher solar irradiance than the STC. During this condition, the inverter will clip the extra power from the PV system. Power clipping causes power loss to the system (Lai and Lim, 2019a). This can be observed in Figure 1.1. Power clipping indicating the loss of a profit for the owner of a PV power plant since the generated electricity is sold at a certain tariff, RM/kWh.

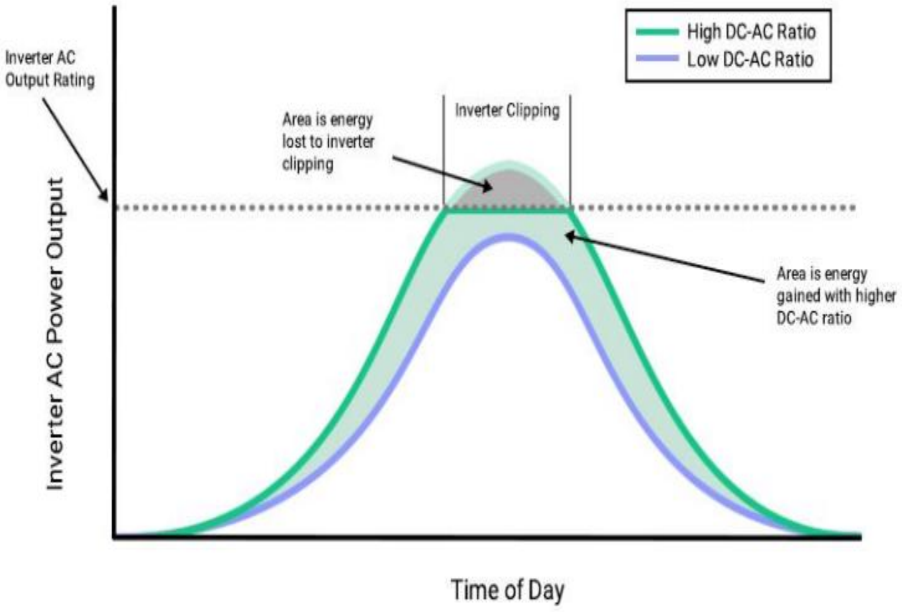


Figure 1.1: The graph of clipping energy by an inverter. (Kathie, 2018)

The higher the rating power of an inverter, the higher the cost for the inverter because an inverter price is sold based on RM/W. Hence, most of the time, the rated capacity (or called size) of an inverter is selected to have a lower power rating than the DC rated value of the PV plant to save the cost. This method can be applied because the PV system will not perform exactly 100% of the rated capacity most of the time. First, there are losses during the generation of electricity such as ohmic loss, inverter conversion loss, optical loss by soiling of the solar panels and reflection of the glass etc. Second, the solar irradiance in a particular area or site for most of the time is below 1 kW/m^2. On the other hand, if some part of the solar irradiance in that particular area or site is greater than 1 kW/m^2, downsize the inverter (referring to use the lower power rating and not referring to the physical size of the inverter) is still possible to reduce the levelised cost of electricity (LCOE), depends on the amount of high solar irradiance. In some cases, the loss of profit due to the total clipped energy by the inverter for 25 years could be less than the cost saved by changing an inverter to a lower power rating inverter. In other words, the total loss of income in 25 years due to using a higher DC-AC ratio as shown in Figure 1.1 may less than the cost saved from the undersized inverter (Lai and Lim, 2019a).

A specific term known as “inverter sizing ratio” (ISR) is used to show the ratio of DC power rating generate by the PV array to the ratio of AC power rating of the inverter. The major factors that have an impact on determining the optimal ISR for a PV power plant in the tropics are the efficiency of the inverter and solar resources because other factors can be controlled or designed to achieve the desired performance ratio of the PV plant (Lai and Lim, 2019a).

1.2 Problem Statement

Previous work has been carried out to investigate the ISR for eight sites in Malaysia. It is found that the optimal ISR for the eight sites ranges from 1.475 to 1.525, which is solely based on the changes of annual solar irradiation of the sites (Lai and Lim, 2019a). However, there is some shortage of previous research work. In the previous work, the solar irradiance database is obtained from the satellite-derived data where the data have been averaged out within the time interval of an hour, to form hourly solar irradiance database. The disadvantage is that it cannot reveal the cases of short and rapid change of high solar irradiance. Because of this reason, the optimal ISRs appear to be higher. In addition, the price of a PV system has dropped significantly since the past two years. Therefore, it is worth to review the optimal ISR with new prices.

Moreover, the sensitivity analysis has not been conducted yet in the previous work. The parameters for sensitivity analysis are such as changing the degradation rates of the PV module, changing the specific cost of the inverter and the operation and maintenance (O & M) cost for the PV plant etc. In this project, the parameters for sensitivity analysis were studied.

1.3 Aims and Objectives

The aims and objectives in this project is defined as below:

1) To investigate the effect of optimal inverter sizing ratio for large-scale photovoltaic plants operating in the tropics using various interval sampled solar irradiance data.
2) To analyses the influence of the key parameters of a photovoltaic plant on the optimal inverter sizing ratio and levelised cost of electricity through sensitivity analysis.

1.4 Importance and Contribution of the Study

The cost of an inverter is normally expressed in dollars per watt. Hence, the higher the total rated power of all inverters, the higher the cost to build the PV power plant and the higher the cost of the levelised cost of electricity (LCOE) for the generated electricity (Lai and Lim, 2019a). It is crucial important to study whether an inverter size used for a certain site is suitable to prevent the case of too much electricity clipped resulted from using an inverter with a low power rating at a site that has a large portion of high solar irradiance. It will be great to reduce the capital cost of the PV plant by using the optimal ISR. Figure 1.2 shows the large-scale solar (LSS) farm. Figure 1.3 shows the central inverter for LSS that costs millions of ringgit.

Figure 1.2: The large-scale solar (LSS) farm. (Samaiden, n.d.)

Figure 1.3: Central inverter for LSS that costs millions of ringgit.

Besides that, there is a lack of research report on the optimal ISR for a PV system in Malaysia, particularly a country in the tropical region. There are some research papers for the optimal ISR for a PV system in other countries such as Finland, Brazil and United State. It is very important to give the solar industry a reference range of optimal ISR of a PV plant in the tropics. In this project, the solar irradiance database was obtained from a ground-mounted weather station which the data has not been averaged out yet. The solar irradiance database in this project is in a one-minute interval. This study has used a higher resolution solar irradiance database that can provide a more accurate value of optimal ISR which can help the industry to achieve a cost-effective plant design and further bringing down the cost of generation. In return, it promotes more adoption of solar energy to combat climate change.

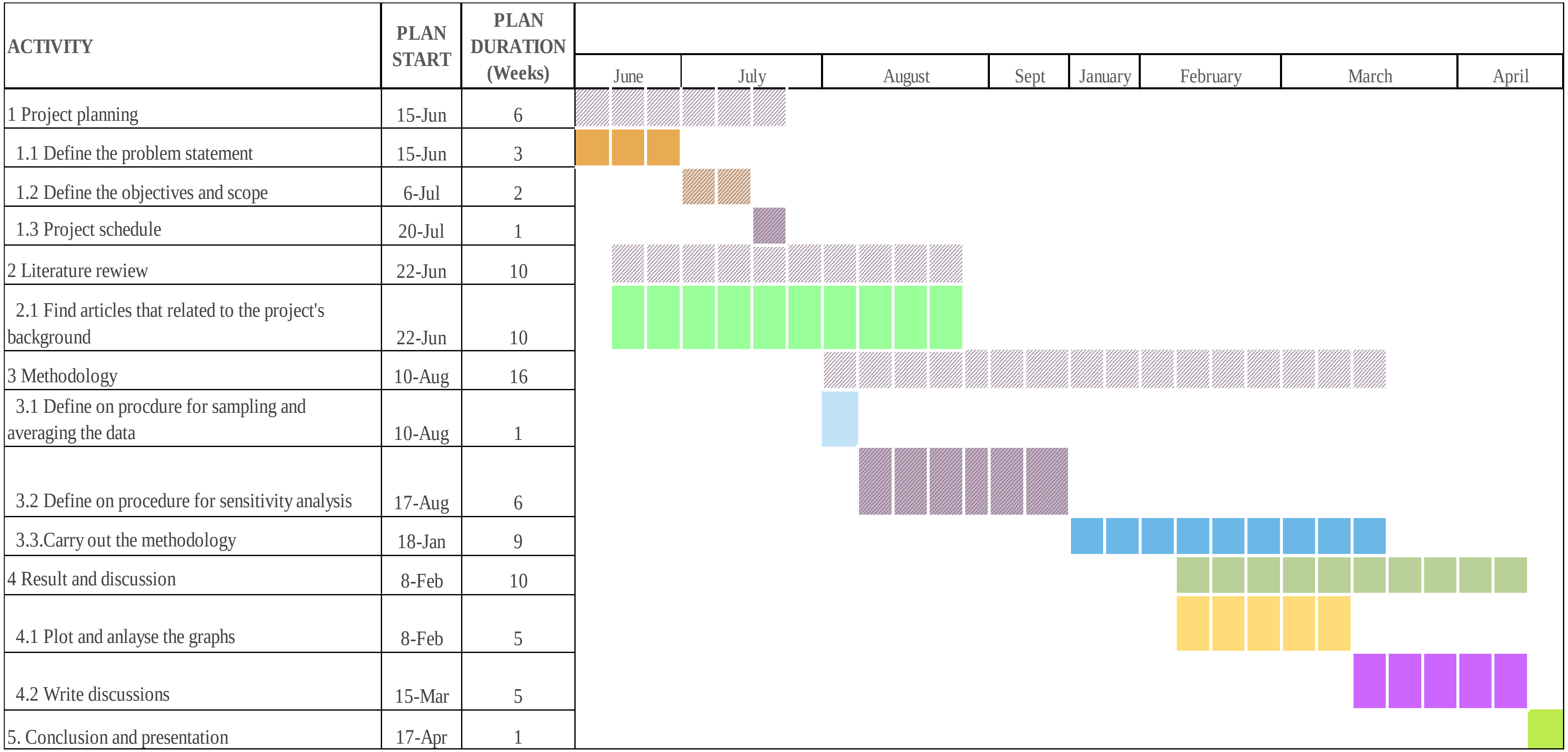
This study is also essential for the future PV industry in tropical climate countries like Malaysia. The parameters in this study are up-to-date industrial information. There is also a lack of research report on sensitivity analysis such as changing the degradation rate or specific cost of the inverter. This study not only can give the reference on the trend of the sensitivity analysis to the industry player, but also the value of the optimal ISR. Industry players can refer to the optimal ISR from sensitivity analysis during the process of designing their PV system to save cost and have a shorter payback period.

1.5 Scope and Limitation of the Study

This project only studied in a tropical area, which is Malaysia only. Malaysia has a lot of potential sites that can be conducted the study of the ISR of the PV power plant. However, this project is limited to one site to investigate the ISR of the PV power plant in Malaysia. The crystalline silicon solar panels were used in this study to design the PV power plant. Besides that, the scope of this project only focused on ground-mounted large-scale solar farms. Moreover, this project does not include any annual payment and interest on the loan or incentives. The net present value of the future cost did not take into consideration in this project.

1.6 Gantt Chart

There are a lot of tasks that need to carry out in this study. Thus, scheduling of the tasks is important to prevent the case of delaying the project. Figure 1.4 shows the Gantt chart for the project.



ACTIVITY	**PLAN START**	**PLAN DURATION (Weeks)**
1 Project planning	15-Jun	6
1.1 Define the problem statement	15-Jun	3
1.2 Define the objectives and scope	6-Jul	2
1.3 Project schedule	20-Jul	1
2 Literature rewiew	22-Jun	10
2.1 Find articles that related to the project's background	22-Jun	10
3 Methodology	10-Aug	16
3.1 Define on procdure for sampling and averaging the data	10-Aug	1
3.2 Define on procedure for sensitivity analysis	17-Aug	6
3.3.Carry out the methodology	18-Jan	9
4 Result and discussion	8-Feb	10
4.1 Plot and anlayse the graphs	8-Feb	5
4.2 Write discussions	15-Mar	5
5. Conclusion and presentation	17-Apr	1

Figure 1.4: Gantt chart of the project.

1.7 Outline of the Report

There are few chapters in this report. Each chapter elaborates the respective topics and contents to let readers can understand easily. The short briefing for each chapter is written below.

Chapter 1 Introduction

An introduction is briefly explained about the background, aim and objectives of the overall project. Moreover, the importance of this project is also discussed.

Chapter 2 Literature Review

This chapter is discussed about researches that have been done by other researchers related to the project's background.

Chapter 3 Methodology and Work Plan

The flow of the project is presented in the flowchart. The equations that needed to be used are listed and explained. The nominal value for each sensitivity analysis was listed in table form.

Chapter 4 Results and Discussions

The comparison of the optimal ISR determined by using GHI and GTI is discussed. Besides that, the trend of each result is presented in the graphs and interpreted. Last, three of the sensitivity analysis are presented in the graph and the results are explained.

Chapter 5 Conclusion and Recommendations for Future Work

A summary of the overall project was discussed. Moreover, some opinions will be suggested in this chapter to improve the present project.

CHAPTER 2

LITERATURE REVIEW

2.1 The Large-scale solar Projects in Malaysia

The energy commission of Malaysia had conducted the bidding competition of large-scale solar (LSS) farms. This competition had conducted three times. Besides that, the government of Malaysia is planning to launch the LSS4 in 2023. During the first cycle of the large-scale solar (LSS1), the maximum capacity of the photovoltaic (PV) system that can bid by the investor is 50 MW. During the second cycle of the large-scale solar (LSS2), the maximum capacity of the PV system that can bid by the investor is 30 MW. The government wants more companies to participate in the competition since the capital cost for PV plants of 30 MW is lower than PV plants of 50 MW (Liew, 2018). For the project of LSS3, four bidders had successfully bided the development of PV plants with a capacity of 100 MW. Two of the PV system are located in Marang, and the other two are located in Pekan and Keriah (Bellini, 2020). The government offered two ranges of the capacity of the PV system during the fourth round of the large-scale solar (LSS4). The first range of the PV capacity is from 10 MW to 30 MW the other one is from 30 MW to 50 MW. From LSS1 to LSS4, the common capacity of PV plants in Malaysia is 10MW, 30 MW, 50 MW and 100 MW (Martin, 2020a).

2.2 Grid-connected PV System Configuration

Grid-connected PV systems is connected to the local electricity grid through an inverter as shown in Figure 2.1. The PV panels only generated DC power and inverter is needed. The function of an inverter is mentioned in Section 1.1.

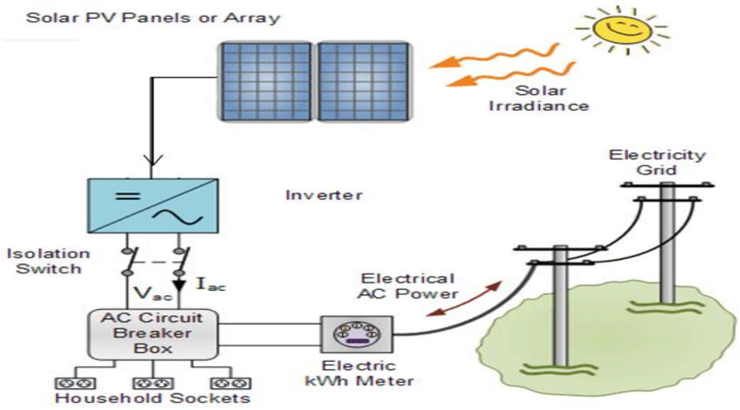


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Figure 2.1: The grid-connected PV System circuit diagram . (Grid Connected PV System, n.d.)

There are four types of configuration for the grid-connected PV system as presented in Figure 2.2 and Figure 2.3. The implementation of the types of configuration depends on the power rating. The first type is known as module inverter. This inverter usually will be implemented for a small-scale PV system as presented in Figure 2.2 (green rectangular). The module PV converter has the ability of MPPT tracking at each PV panel, which can be getting more energy. The function of the converter is to step up or step down the DC voltage. This configuration comes with a drawback that needs a high value of conversion ratio of a direct current (DC) to DC converter. The generated DC voltage of the PV system is small due to the number of panels is limited, the DC voltage needed to be step up and converted to AC voltage via inverter so that it can be connected to the high alternating current (AC) voltage of the grid (Blaabjerg, Sangwongwanich and Yang, 2018).

The second type of configuration is known as single string inverter which is presented in Figure 2.2 (blue rectangular). The third types of configuration are the central inverter which is presented in Figure 2.2 (red rectangular). Multiple string inverter is also a type of configuration for grid-connected PV system which is shown in Figure 2.3. Single string inverter, multiple string inverter or central inverter will be implemented for medium or large-scale PV systems due to the high efficiency of conversion. The generated

DC voltage from the PV system will be passed to the AC grid without using DC to DC converter or using a smaller conversion ratio of a DC to DC converter. This is due to the DC generated voltage is high due to the number of PV panels is lot. The string and multistring inverters are getting famous and more people using them in the market. The reasons are the string inverter has high reliability and the process of installation is simple (Blaabjerg, Sangwongwanich and Yang, 2018).

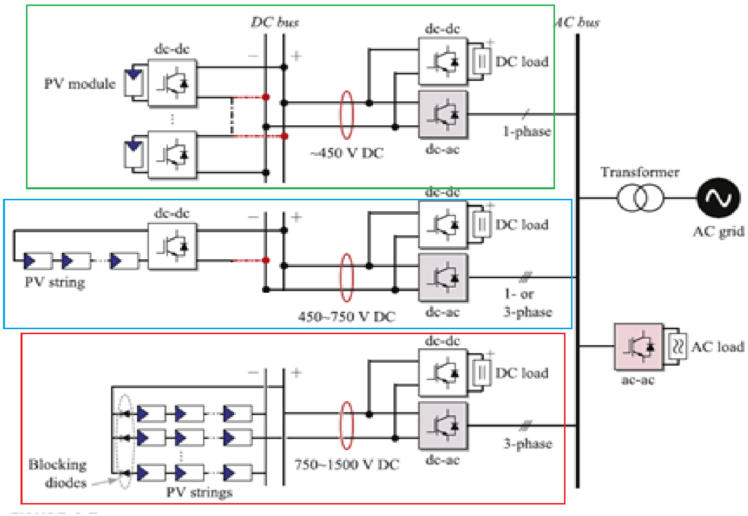


Figure 2.2: Different configuration of grid-connected PV inverter structures . (Blaabjerg, Sangwongwanich and Yang, 2018)

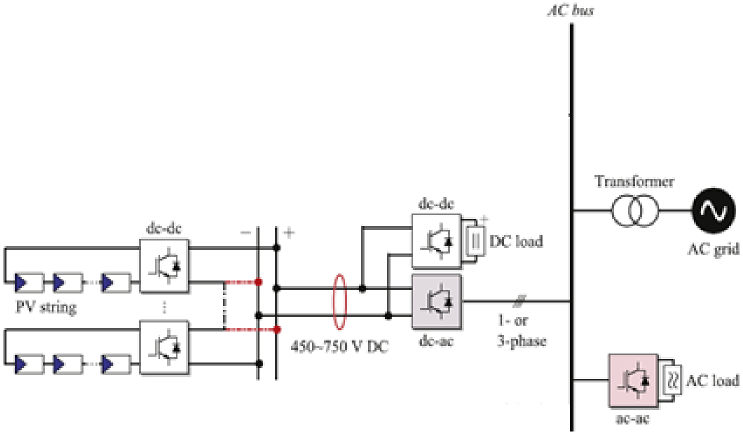


Figure 2.3: Multiple string configuration of grid-connected PV inverter structures. (Blaabjerg, Sangwongwanich and Yang, 2018)

2.3 PV System Installation Cost Break Down

The initial capital money to build a PV power plant will be expected to decrease from time to time. The percentage of the cost of each part such as inverter or PV module to total cost for installation fees for a PV system is presented in Figure 2.4. The PV module is standing 41% to the total cost for installation cost for the PV system in 2019 and the percentage of this cost is keep reducing as shown in this figure. The percentage cost for inverter, project cost and wiring the circuit had the same trend as the PV module which the percentage occupied to the total cost for construct the PV system is reduced from time to time. This means the capital for constructing the PV system for the same power rating in the future will be expected to be cheaper than now. This can attract the investors to invest their money in the PV system project as the investors also wish to reduce the costing for the component such as inverter specific cost to earn more money. The trend of reduction of price for the components such as PV module and inverter is faster than the trend of reduced cost for installation fees. The overhead cost will be assumed to remain constant (Fischer, 2020).

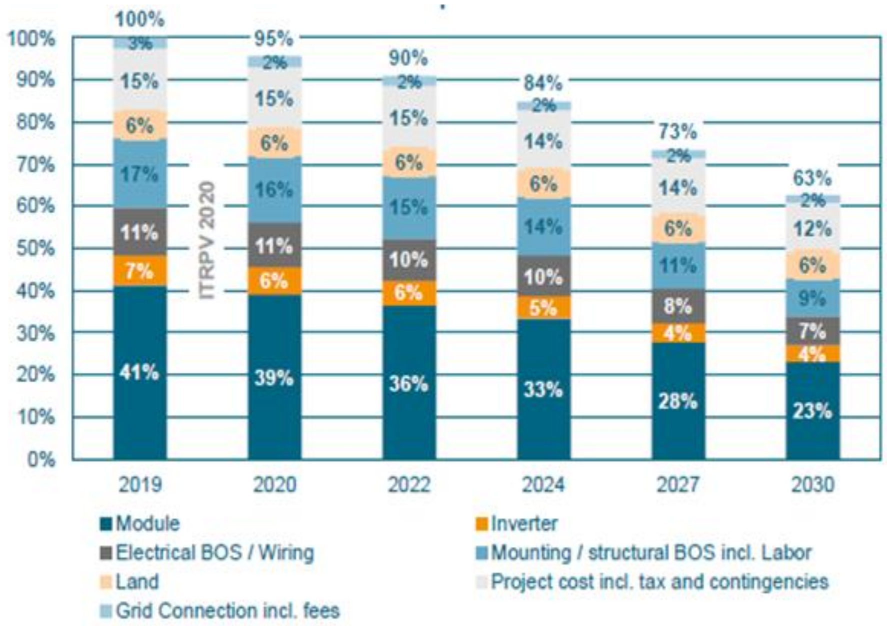


Figure 2.4: The expected trend for PV system installation cost from 2019 to 2030. (Fischer, 2020)

2.3.1 Price for Generation Electricity Per Watts

Nowadays, the range for the cost for generation of electricity for the PV module is from USD 0.16/W to USD 0.40/W depends on the type of PV module that used as presented in Figure 2.5. The trend for generated one-watt electricity for the all types PV module will be decreased from time to time which is shown in Figure 2.5. It is expected the price generation of one-watt electricity for the PV module will be reduced in future to make the prediction of the percentage ratio of cost for the PV module to the total cost of installation for PV system become true (refer to Section 2.3 Figure 2.4) (Martin, 2020b).

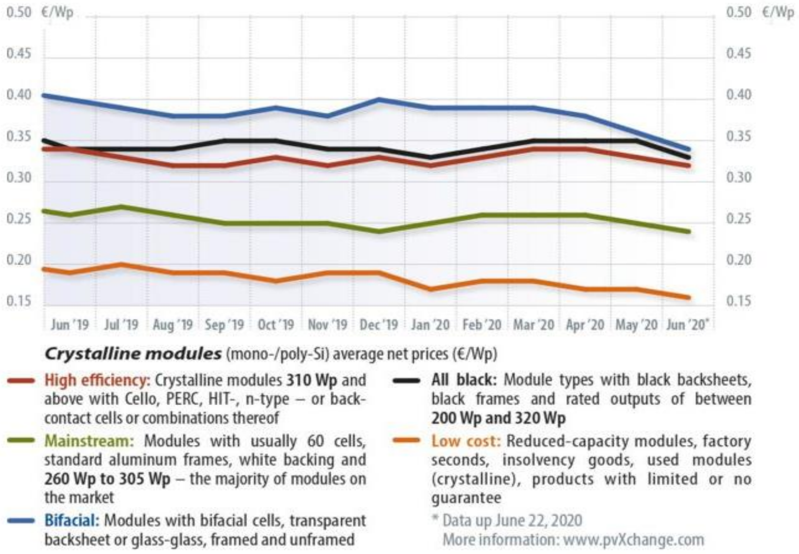


Figure 2.5: The graph of price generation of electricity versus time for different types of PV modules. (Martin, 2020b)

The range for the price for the generation of electricity in the inverter is from USD 0.06/W to USD 0.18/W as presented in Figure 2.6. For various kinds of inverter used, different ranges of the price will be implemented. It can be observed in Figure 2.6 that the central inverter use for the utility sector has the lowest price for all the time compare to string inverter in residential and commercial. It is also predicted that the price for the generation of electricity for inverter will be dropped so that in future the more investor will invest in the PV system project (David and Robert, 2019).

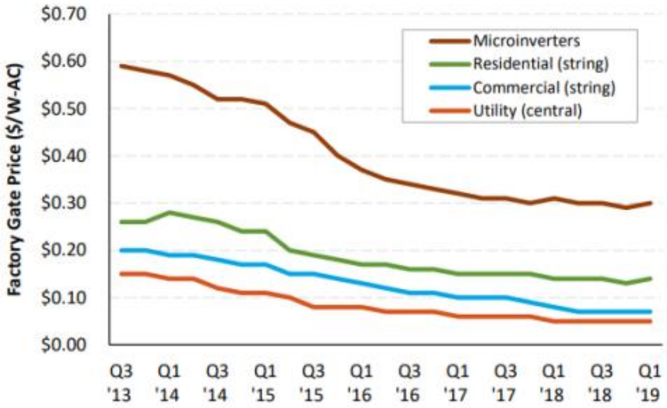


Figure 2.6: The trend of price of generation per watts(in USD) versus time for different types of inverter. (David and Robert, 2019)

2.4 Performance Ratio (PR)

The PR will be expressed as percent and indicated the relationship between the actual and theoretical generated electricity outputs of the PV plant. PR will be showed the impact of losses on the generated output of a PV system due to shading factor and degradation of the module etc (Reich, et al., 2012).

2.4.1 Types of Losses that Affects the PR of PV System

There are many factors that can reduce the PR of PV system. All the possible losses in the PV system are shown in Figure 2.7.

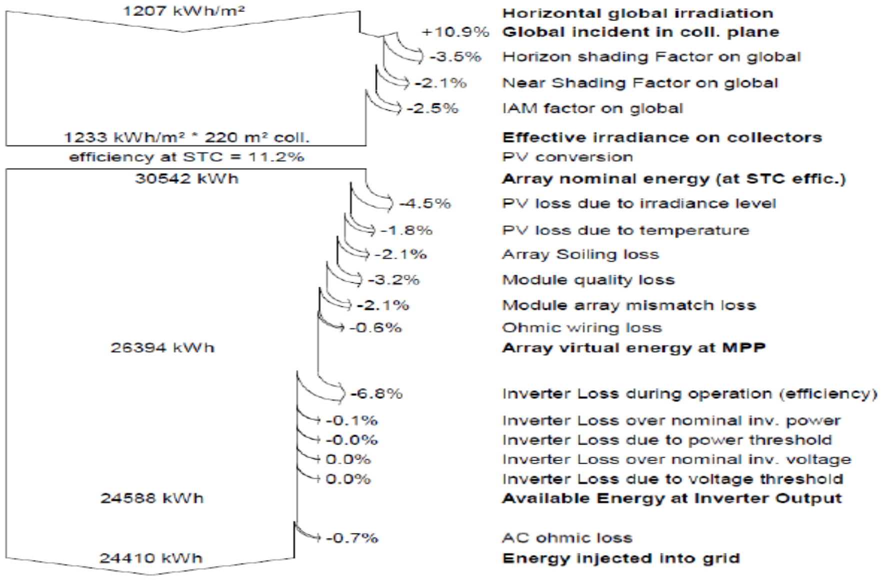


Figure 2.7: The types of loss in PV system. (Mermoud, 2010)

The shading factor will be contributed to the loss of energy in the PV system. When the small section of the PV panel is blocked by tree branches, then the output power will be decreased (Salih and Taha, 2013). The next types of loss in the PV system are the incident angle modifier (IAM). The solar irradiation incident on the PV panel has more chance to reflect on the panel surface as the incident angle increases. This means that as the orientation of the sunlight is changed, the IAM loss may also be higher (Tawa, et al., 2020).

The efficiency of a PV system can be affected by the temperature and the amount of solar irradiation. When the temperature of the PV panels increases, the efficiency will drop linearly. This is because the peak power generated by the PV panels is at STC which is at 25℃ (Tsoutsos, et al., 2011).

When the PV array does not clean for some time, soiling is the effect of particles or dust deposition on the PV panel. Soiling can decrease the generated electricity of the PV system. This is because the particles of soiling can act as dielectrics which can absorb incident light into the PV module (Urrejola, et al., 2016).

Mismatch loss can reduce the output power of the system. The change in irradiance level which also known as partial shading can lead to mismatch loss (Lorente, et al., 2014).

2.5 Ross Coefficient

Ross coefficient is a famous method used to approximate the module temperature of the PV. Ross coefficient has a relationship with surrounding temperature. Besides that, it also has a relationship with solar irradiance data and temperature for the PV module. Various models of the temperature module were created to approximate the temperature of the module. Thus, the PV engineer able to approximate the efficiency drop due to the impact of the temperature. One of the most commonly used models is shown in Eqn. (2.1) (Lai and Lim, 2019b).

$$T_{mod} - T_{amb} = kG_{mod} \tag{2.1}$$

Where

T_{mod} = module temperature, °C

T_{amb} = ambient temperature, °C

k= Ross Coefficient, °C/(W/m^2)

G_{mod} = in-plane solar irradiation , W/m^2

2.6 Existing ISR Methodologies

From the Finland research paper, the data of optimal array-to-inverter sizing ratio (AISR) had been determined through analysing the one-second solar irradiance data instead of one-hour solar irradiance data. This is to prevent some of the information on the irradiance data to be lost and to get a better result on the undersized inverter. This research paper was studied one of the cities in Finland which is Jyväskylä. Figure 2.8 shows the annual irradiance in Jyväskylä (Väisänen, et al., 2019).

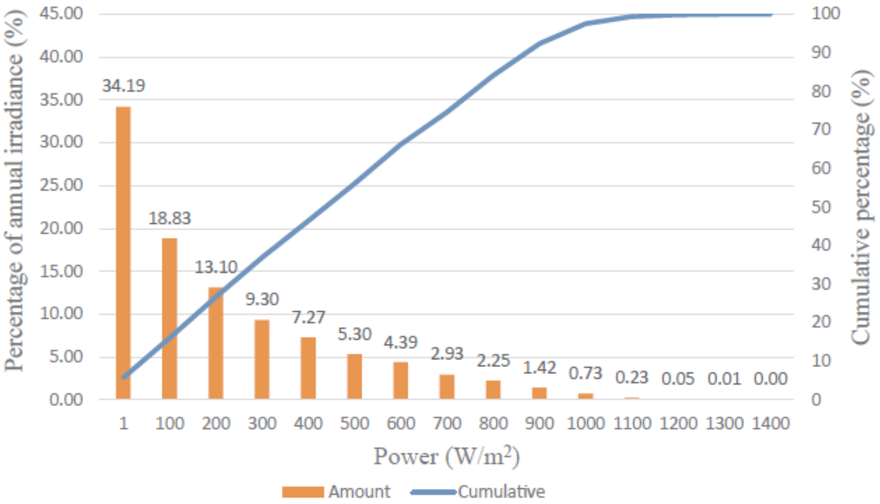


Figure 2.8: Annual irradiance in Jyväskylä. (Väisänen, et al., 2019)

Chen (2011) determined the ISR by analysing the one-minute solar irradiance data from 2009 instead of one-second solar irradiance data for the two sites which are Eugene and Las Vegas. Chen (2011) considered the effect of protection delay into account when calculating the ISR. Figure 2.9 shows the distribution profiles for Eugene and Las Vegas in 2009.

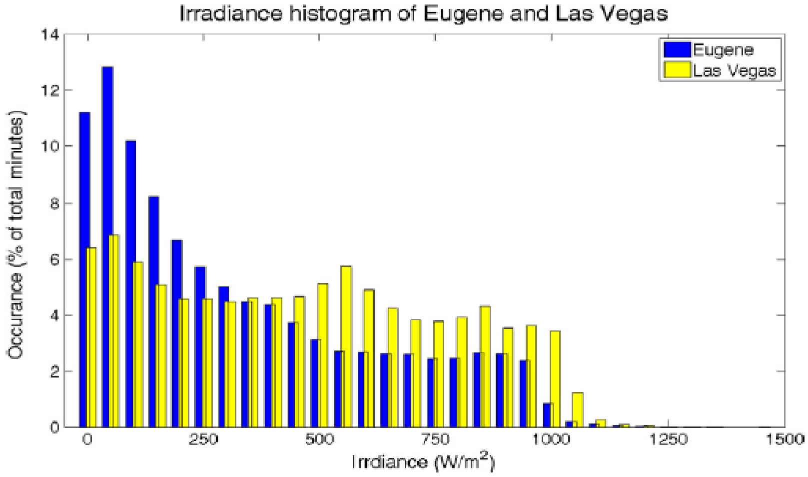


Figure 2.9: Distribution profiles for Eugene and Las Vegas in 2009. (Chen, et al., 2013)

Paiva et al. (2017) analysed on ISR in PV distributed generation (DG) in the central region of Brazil. 12 years of solar irradiance data is given by manufacturers to analysed the ISR in this research paper. The ISR is determined by using the hourly solar irradiance data provided by the Brazilian National Institute of Meteorology (INMET) as presented in Figure 2.10. The inverter is considered to have a lifetime of 25 years. This research paper got took the factor of the module degradation (Paiva, et al., 2017).

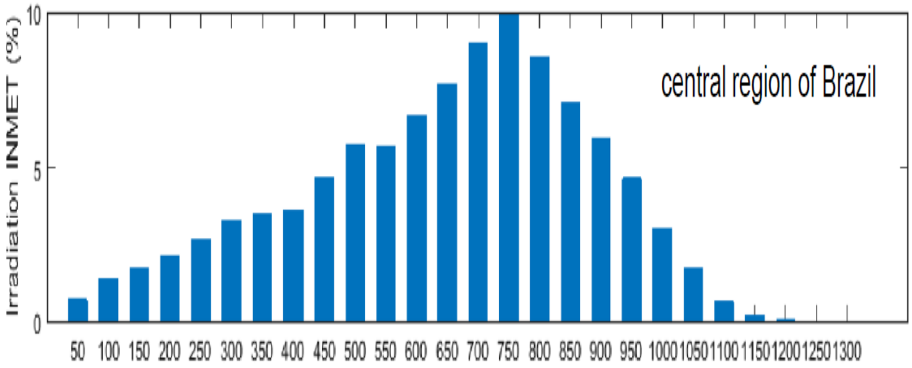


Figure 2.10: The hourly solar irradiance data provided from INMET in central region of Brazil. (Paiva, et al., 2017)

Figure 2.11 shows the solar irradiance distribution profile for various irradiance levels for eight sites in Malaysia. In Finland, it has different solar irradiance distribution profiles as compared to the tropics like Malaysia. Similar case for Eugene and Las Vegas. This can be observed in Figure 2.8 and Figure 2.9 as compared to Figure 2.11. On the other hand, the solar irradiance distribution profiles for Brazil are very similar to Malaysia. From Figure 2.10, Brazil has a relatively high component of solar irradiance between 600 W/m^2 to 800 W/m^2. A similar trend for Malaysia can be observed in Figure 2.11. This could due to these two countries are located in tropical areas.

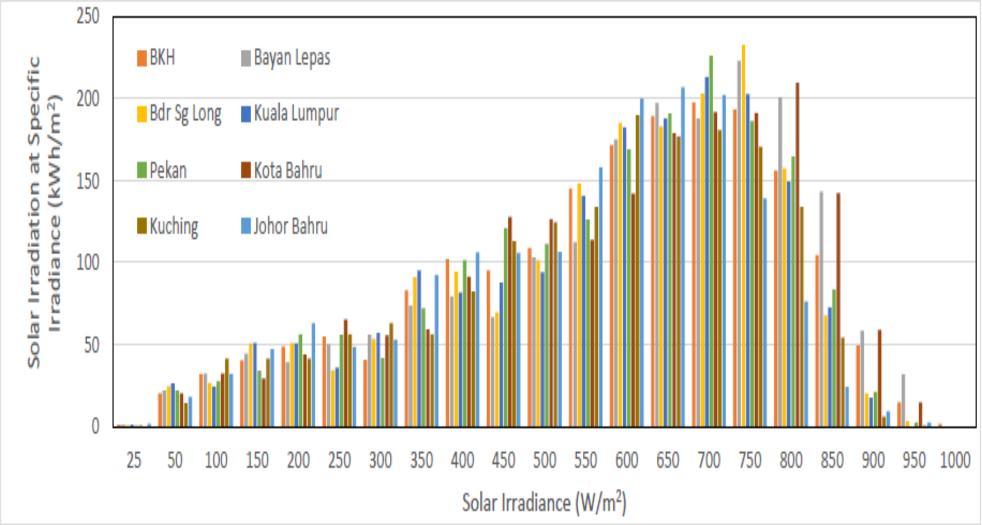


Figure 2.11: Solar irradiance distribution profile for various irradiance levels for eight sites in Malaysia. (Lai and Lim, 2019a)

Lai and Lim (2019a) used one-hour interval solar irradiance data to find out the find the optimal ISR of the eight sites in Malaysia. Lai and Lim (2019a) also expected that the inverter could be overload for 10% of the rated power. This is a normal characteristic that the inverter must have in real-life applications. The consideration of using 110% of the inverter rated capacity can lead to a higher range of optimal ISR. This characteristic is not taken into account when during the process of determining the sizing inverter ratio in other research papers such as the Finland or Brazil research paper.

Moreover, Lai and Lim (2019a) have been taken into account that the PV module will degrade each year in their research paper. This means that the PV system used for the first year will have higher efficiency than the PV system used for ten years. This consideration is important in industry application because in the industry the components such as inverter or PV module in the PV system do not have the same efficiency in the first year compared to the components that used for a decade. The consideration of the degradation rate of the PV module also had not been considered in other research papers except for the Brazil research paper (Lai and Lim, 2019a).

2.7 Factors Affect the Inverter Sizing Ratio

The first factor that has an impact on ISR is the amount of solar irradiance. For two PV system that has the same power rating, they also can have a different value of optimal ISR depend on the amount of high solar irradiance. Two different locations that have different solar irradiance are compared in this case. The weather for one location is mostly cloudy with low solar irradiance every day; the other location has the equally distributed solar irradiance for most of the time. The results in the research paper had been demonstrated that the technique of undersized inverter is more suitable in the low-irradiance place to reduce the over-irradiance events and wastage of energy (Chen, 2011).

Moreover, different time intervals for the solar irradiance to analysis can cause different trends for the solar irradiance graph. The irradiance data that measured for every 10 seconds is sampled into the interval of 1-min,10-min and hourly to analyse and the graph is shown in Figure 2.12. The trend of 1-hour and 10-min at the low irradiance levels is not much different but at high irradiance levels which is after the 750/Wm^2 it can be seen that the trend starts to different. It is observed that increasing the irradiance time interval from 10 s to 1 min is not much different but increases the time interval for the irradiance to 10 min or 1-hour has a great impact. Hourly data will ignore most of the high frequency of the highest irradiances and does not take into account that the energy generated at this intensity will have a significant impact during determining the optimal inverter sizing ratio. In other words, the impact of increasing the electricity loss will happen if neglect the high resolution of irradiances (Zhu, et al., 2011).

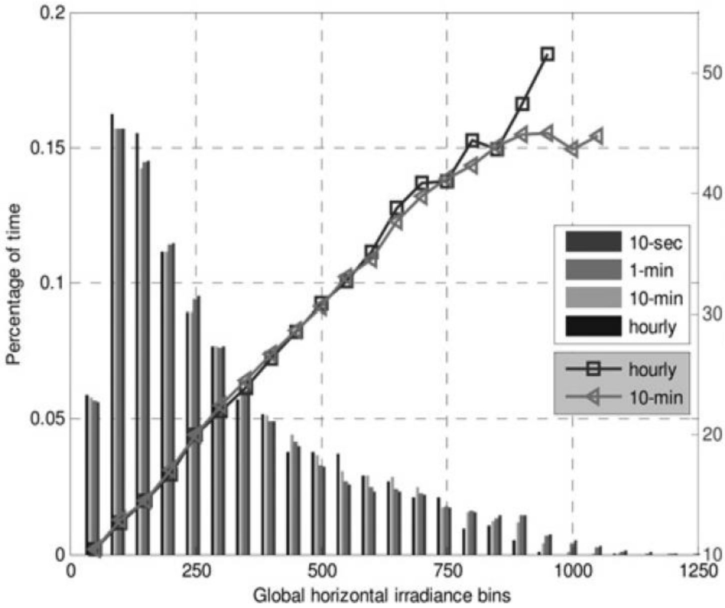


Figure 2.12: The graph of global horizontal irradiance with solar irradiance width of 50 W/m^2 and corresponding temperature.(Zhu, et al., 2011)

Two solar irradiation distribution profile at specific solar irradiance of two time-intervals databases is shown in Figure 2.13, where one is the 5-minute interval (orange) and the other one is the hourly interval (black). The 5-minute interval data is the high resolution data while the hourly interval data is the low resolution data. From Figure 2.13, it can be observed that the 5-minute data interval had higher resolution data when solar irradiance is greater than 1000 W/m^2. It also can be seen that the hourly data interval lost the data of higher resolution at the point of solar irradiance is greater than 1000 W/m^2. The optimal ISR determined by using the high resolution data will cause the optimal ISR to be smaller due to high resolution data can detect the high and quick change of solar irradiance data.

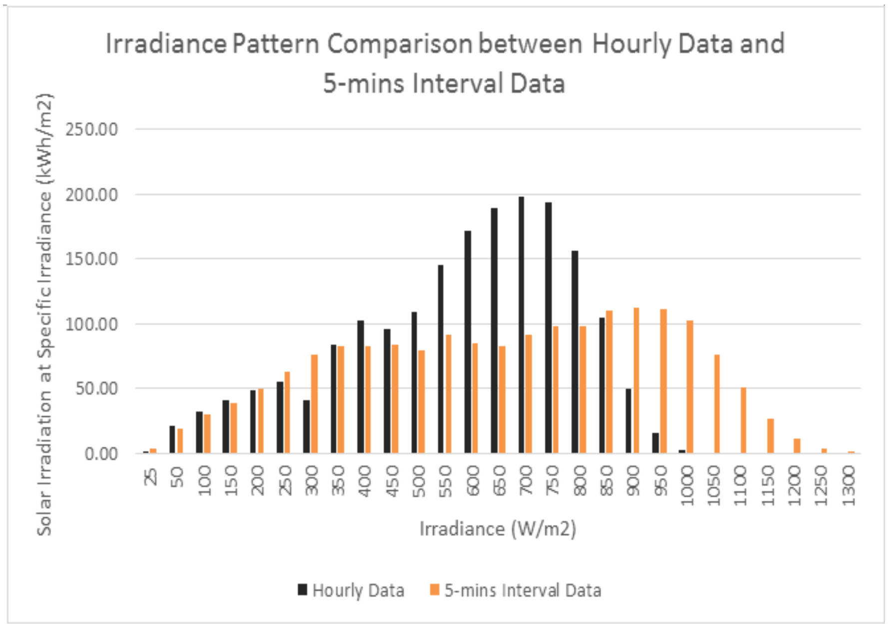


Figure 2.13: Solar irradiance pattern comparison between hourly data and 5-mins interval data.

2.8 Summary

In a nutshell, the common capacities of the PV plant were mentioned. Moreover, there are four types of configuration for the grid-connected PV system. In addition, the price for constructing the PV power plant in the future will be decreased due to the price of the PV module is expects to be reduced. The price of generating electricity is also expected to be reduced in the future.

PR is the ratio of actual output power to the theoretical output power. The types of losses in the PV system are shading factor, IAM, mismatch and PV losses due to temperature etc. The Ross coefficient is explained.

The existing ISR methodology is using the interval of one second, one minute and one hour solar irradiance data to find the ISR. Different countries have different solar irradiance distribution profiles. Lai and Lim (2019a) considered the factor of degradation rate for the PV panel and the inverter can overload for 10% of the rated power. There are several factors that will have impacted on determining the optimal ISR.

CHAPTER 3

METHODOLOGY AND WORK PLAN

3.1 Introduction

A flowchart was done to provide a better understanding about the project. The flowchart of the project is shown in Figure 3.1. The procedure of the project to achieve the objectives was discussed in this chapter. As mentioned in Section 1.1, the inverter can be downsized due to the PV system does not have 100 % efficiency. The drawback of downsizing is the possibility of power clipping during occasional high irradiance which leads to loss of income. The calculation on the loss of income due to clipped electricity is essential. This is because in some cases the saving from the undersized inverter is more than the loss of profit. The unclipped electricity is also essential in this project as it is required for the calculation of the levelised cost of electricity (LCOE). Therefore, a series of formulas were built in a Microsoft Excel spreadsheet to determine the amount of clipped power and unclipped power.

The solar irradiance data in Sungai Long was obtained from a ground-mounted weather station. Firstly, the process of sampling the data into various interval data was discussed. The reason for sampling the solar irradiance data into different intervals is due to different interval data have different annual irradiation. Different annual solar irradiation can affect the optimal inverter sizing ratio (ISR). Besides that, the procedure of the averaged method was discussed. The objective of studying the averaged method is to investigate its influence on the optimal ISR. The explanation of the procedure on sampled and averaged methods will be discussed in the next two sections.

Moreover, the process of studying the sensitivity analysis was discussed. The sensitivity analysis only used the 5-Minutes sampled solar irradiance database. As mentioned in Section 1.4, the goal of the sensitivity analysis is to give guidelines on choosing the right ISR for the PV industry player. The nominal value for each parameter was listed down. Dr.Lim Boon Han provided the nominal value where the value is up-to-date industrial information. Moreover, he also provided the range of the value for each sensitivity analysis which is related to the latest information in the photovoltaic (PV) industry. Sensitivity analysis such as increased operation and maintenance, or increased specific cost of the inverter can affect the LCOE. The optimal ISR is also affected since it is chosen based on the lowest LCOE. All the LCOE was calculated for PV plants that going to be used for 21 years. The parameter for best and worst-case scenarios was also listed down. Lastly, the process of combining optimal ISR and LCOE from all the sensitivity analysis was mentioned. The range of the value for each parameter was converted into percentage different (step size) from the nominal value. The aim is to give the trend of the lines plotted through the sensitivity analysis that can be used as a reference for the PV industry in the tropics. The briefing about the flowchart was done. The details of the flowchart will be discussed in several sub chapters.

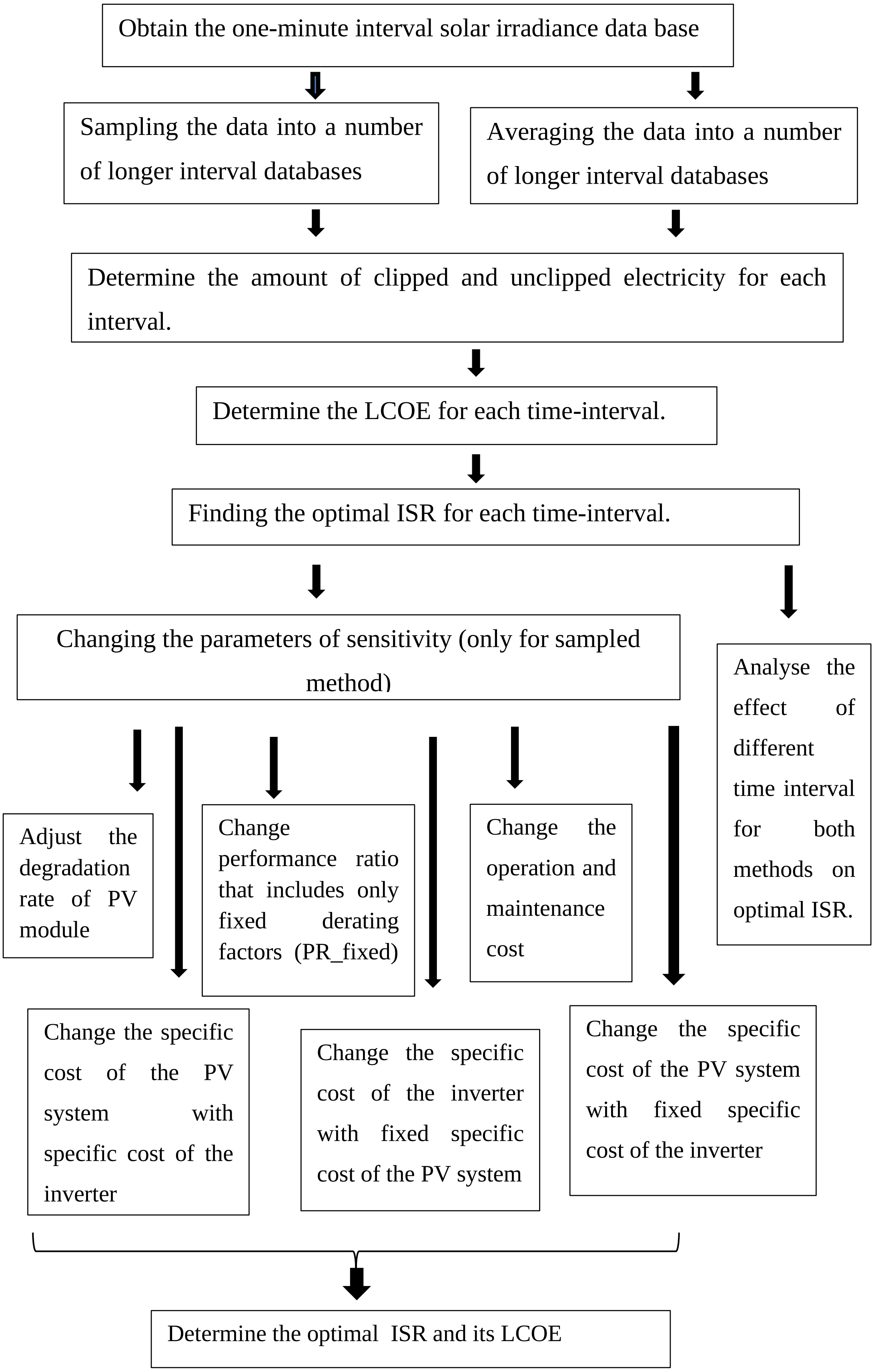


Figure 3.1: The flowchart of the project.

3.1.1 Way to Obtain Solar Irradiance Data

The site known as ‘Sungai Long’ was studied in this project. The solar irradiance data provided from the ground-mounted weather station database for the Sungai Long is in the one-minute interval database. The data provided in Sungai Long was in 2020.

3.1.1.1 Types of Solar Irradiance Data

The solar irradiance used by this study in Sungai Long is global horizontal irradiance (GHI) and global tilted irradiance (GTI). The purpose is to observe the effect of various irradiance on the optimal ISR. The graph for solar irradiance distribution profiles was plotted. The formula for percentage difference for annual GHI and GTI is shown in Eqn. (3.1). Section 4.2 is discussed about the comparison of GHI and GTI. Eqn. (3.1) was applied in Section 4.2 to check the percentage difference between GHI and GTI.

$$\%\,difference = \frac{GTI-GHI}{GTI} * 100\% \tag{3.1}$$

3.1.2 Sampling the Data into Different Time Interval

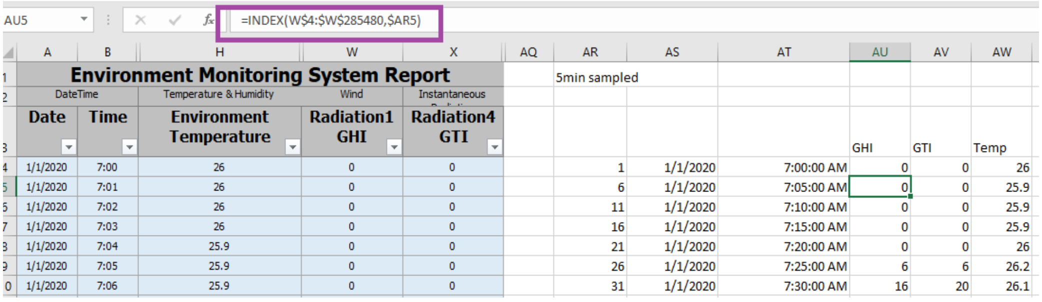
Previous work that used the solar irradiance data from photovoltaic geographical information system (PVGIS) are averaging out the data within the interval. Hence, the sampled method was proposed in this project to study its influence on the optimal ISR. The objective of sampling the data into different time intervals is to investigate its effect on optimal ISR. This section is important as the sampled 5-Minutes interval data is needed to be used in Section 3.3. The process of sampling the data takes every X-minute interval data from the one-minute interval data for one year data where X can be five, ten ,twenty, thirty or sixty. The higher resolution data (one-minute data interval in Sungai Long) was sampled into five different time intervals which are five-minute data interval, ten-minute data interval, twenty-minute data interval, thirty-minute data interval and hourly data interval. The sampled data is the lower resolution data. The one minute-interval was acted as a high-resolution database to create multiple longer-interval databases. This is a technique to maintain the consistency of the databases rather than relying on the measurement of solar irradiances at individual time-interval, which will create fluctuations. The Eqn. (3.2) was programmed in Microsoft Excel to obtain one sampled data. After that, Eqn. (3.2) was repeated to use until sampled solar irradiance data for one year was obtained. Figure 3.2 shows a portion of 5-minutes sampled data in Sungai Long. From this figure, the formula was developed in the command (purple rectangular area) to obtain 5-minute sampled data. Figure 3.3 shows a portion of 10-minutes sampled data in Sungai Long.

$$Data\ = Index\ (Range\ of\ specific\ data, row\ of\ the\ specific\ data) \tag{3.2}$$

Where

Range of specific data = Range for the one-minute solar irradiance for one year

Row of specific data = The row where the solar irradiance at specific time

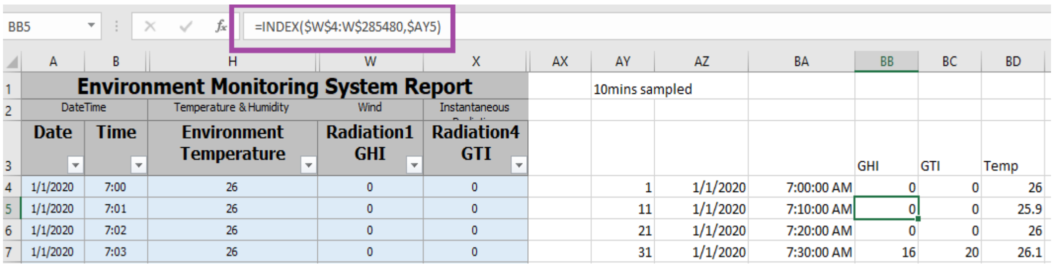


AU5

=INDEX(W$4:$W$285480,$AR5)

A	B	H	W	X	AQ	AR	AS	AT	AU	AV	AW
Environment Monitoring System Report						5min sampled					
DateTime		Temperature & Humidity	Wind	Instantaneous							
Date	Time	Environment Temperature	Radiation1 GHI	Radiation4 GTI					GHI	GTI	Temp
1/1/2020	7:00	26	0	0		1	1/1/2020	7:00:00 AM	0	0	26
1/1/2020	7:01	26	0	0		6	1/1/2020	7:05:00 AM	0	0	25.9
1/1/2020	7:02	26	0	0		11	1/1/2020	7:10:00 AM	0	0	25.9
1/1/2020	7:03	26	0	0		16	1/1/2020	7:15:00 AM	0	0	25.9
1/1/2020	7:04	25.9	0	0		21	1/1/2020	7:20:00 AM	0	0	26
1/1/2020	7:05	25.9	0	0		26	1/1/2020	7:25:00 AM	6	6	26.2
1/1/2020	7:06	25.9	0	0		31	1/1/2020	7:30:00 AM	16	20	26.1

Figure 3.2: Portion of 5-minutes sampled data in Sungai Long.



BB5

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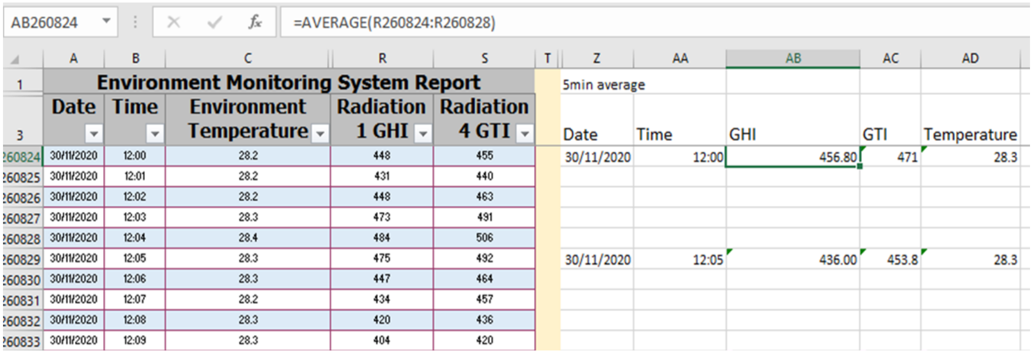
A	B	H	W	X	AX	AY	AZ	BA	BB	BC	BD
Environment Monitoring System Report						10mins sampled					
DateTime		Temperature & Humidity	Wind	Instantaneous							
Date	Time	Environment Temperature	Radiation1 GHI	Radiation4 GTI					GHI	GTI	Temp
1/1/2020	7:00	26	0	0		1	1/1/2020	7:00:00 AM	0	0	26
1/1/2020	7:01	26	0	0		11	1/1/2020	7:10:00 AM	0	0	25.9
1/1/2020	7:02	26	0	0		21	1/1/2020	7:20:00 AM	0	0	26
1/1/2020	7:03	26	0	0		31	1/1/2020	7:30:00 AM	16	20	26.1

Figure 3.3: Portion of 10-minutes sampled data in Sungai Long.

3.1.3 Average the Data into Different Time Interval

The solar irradiance data obtained from the satellite is in averaged form. The study on the distribution profile by using an averaged method in detail is to investigate its effect on the optimal ISR in this case. The process of averaging the data takes every X-minute interval data to average out with X from the one-minute interval data where X can be five, ten, twenty , thirty or sixty. The averaged solar irradiance data can affect the optimal ISR. The averaged method cannot detect the cases of rapid and short changes as mention in Section 1.2. Thus, it has a great influence on the optimal ISR. Figure 3.4 shows the portion result of 5-minutes averaged data in Sungai Long.


AB260824 =AVERAGE(R260824:R260828)

	A	B	C	R	S	T	Z	AA	AB	AC	AD
1	Environment Monitoring System Report						5min average				
3	Date	Time	Environment Temperature	Radiation 1 GHI	Radiation 4 GTI		Date	Time	GHI	GTI	Temperature
260824	30/11/2020	12:00	28.2	448	455		30/11/2020	12:00	456.80	471	28.3
260825	30/11/2020	12:01	28.2	431	440						
260826	30/11/2020	12:02	28.2	448	463						
260827	30/11/2020	12:03	28.3	473	491						
260828	30/11/2020	12:04	28.4	484	506						
260829	30/11/2020	12:05	28.3	475	492		30/11/2020	12:05	436.00	453.8	28.3
260830	30/11/2020	12:06	28.3	447	464						
260831	30/11/2020	12:07	28.2	434	457						
260832	30/11/2020	12:08	28.3	420	436						
260833	30/11/2020	12:09	28.3	404	420						

Figure 3.4: Portion of 5-minutes averaged data in Sungai Long.

3.1.4 Estimate the Electricity Yield

The electricity yield for daily AC of a PV system, E_{AC_N} was calculated as the following: (Lai and Lim, 2019a)

$$E_{AC_N} = \sum_{t=0}^{t=1440}\left[D \times \left(\mathrm{P}_{PV} \times PR(t) \times \mathrm{G}_{tilt}(t)\right)\right] \tag{3.3}$$

Where

P_{pv} = capacity of the PV system , MW

PR(t) = performance ratio at the corresponding time, t

Gtilt(t) = global tilted solar irradiance received by the solar panels at the corresponding time, t , W/m^2

D = duration for the discrete value of the output power, minute

The data from the database is in one-minute format, t is in the one-minute interval, starting from 0 to 1440, and D is equal to one minute (Lai and Lim, 2019a).

The performance ratio (PR) of a PV system is affected by many derating factors. They are shadings irradiance loss, inverter conversion loss, power loss due to impedance of the wire, soiling loss and mismatch loss. The loss can be classified into two groups which are fixed loss and unfixed loss, especially for the scenario in the tropics. Some of the losses have less effect on the PR during power clipped such as ohmic wiring loss and soiling loss. Inverter conversion loss will vary with the loading factor of an inverter while the amount of PV loss will be affected by the solar irradiance and the ambient temperature. These two factors have a more significant effect on PR (Lai and Lim, 2019a).

The fixed component of performance ratio (PR_{fixed}) was specially used in this study to ease the sensitivity analysis. PR_{fixed} was assumed particularly for tropics because PR in the tropics does not change significantly. The losses such as near shading loss, mismatch loss, soiling loss, low irradiance loss and ohmic wiring loss are classified into the group of PR_{fixed}. Figure 3.5 shows the inverter efficiency against loading factor. Different loading factors to the inverter, the efficiency of the inverter will be varied (Lai and Lim, 2019a).

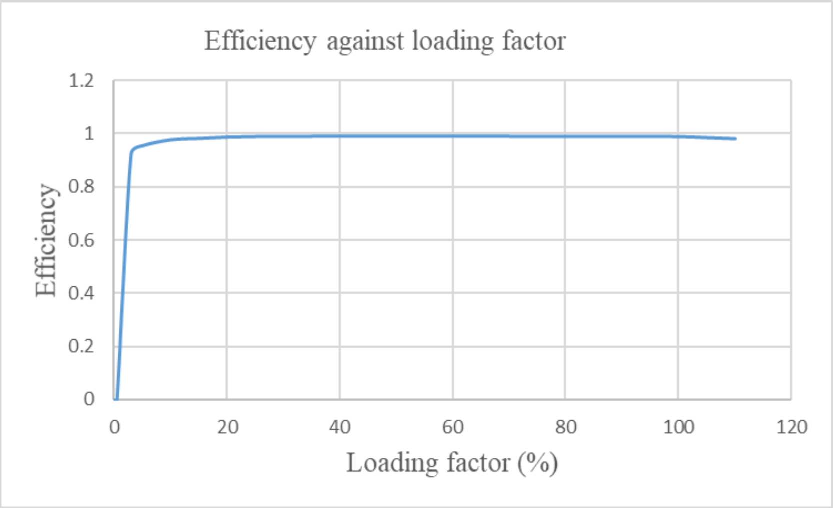


Figure 3.5: Inverter efficiency against loading factor. (Lai and Lim, 2019a)

$$PR(t) = PR_{fixed} \times \eta_{inv}(l) \times f_{temp}(t) \tag{3.4}$$

Where

PR_{fixed} = fixed component of performance ratio

η inv(l) = inverter conversion efficiency based on the loading factor of the inverter

f_{temp} (t) = derating factor for a PV module due to temperature

$$f_{temp}(t) = 1 + \gamma(T(t) - T_{STC} \tag{3.5}$$

Where

γ = temperature coefficient for power for the PV module, ℃

T(t) = the instantaneous module temperature, ℃

T_{STC} = the reference temperature given in the Standard Test Conditions (STC) which is 25 ºC

The Ross coefficient use in this project is 0.0234 ºC per W/m^2. Lai and Lim (2019a) mentioned that this value can be implemented in the tropical area since it can be taken as a generalised value.

$$T(t) = T_{amb}(t) + G_{tilt}(t) \times C_{Ross} \tag{3.6}$$

Where

T(t) = module temperature, ℃

T_{amb} = ambient temperature, ℃

C_{Ross} = Ross coefficient , ºC / (W/m^2)

By combine the from Eqn. (3.3) to Eqn. (3.6), the instantaneous output power , $P_{AC\_exp}(t)$, without consider any clipping power at the time, it can be written as the following: (Lai and Lim, 2019a)

$$P_{AC\_exp}(t) = P_{PV} \times G_{tilt}(t) \times PR_{fixed} \times \eta_{inv}(l) \times \{1 + \gamma[(T_{amb}(t) + G_{tilt}(t) \times C_{Ross}) - 25℃]\} \tag{3.7}$$

Nevertheless, at high solar irradiance, process of clipped power will happen if the maximum AC output power of an inverter, P_{AC_MAX} is less than P_{AC_exp} (t). The P_{AC_MAX} of an inverter is design to be 1.10 times greater than the rated power, P_{AC_rated} . Therefore, the actual output of the PV system, P_{actual} (t): (Lai and Lim, 2019a)

$$P_{actual}(t) = \begin{cases} P_{AC\_exp}(t)\ for\ P_{ACexp}(t) < P_{AC_{MAX}} \\ P_{AC_{MAX}}\ \ for\ P_{ACexp}(t) > P_{AC_{MAX}} \end{cases} \tag{3.8}$$

$$P_{AC,max} = \frac{P_{PV}}{ISR} * 1.10 \tag{3.9}$$

Where ISR =$\frac{P_{PV}}{P_{AC_{actual}}}$

The daily electricity yield with cases of sometimes have the cases of clip power, $E_{AC\_N\_actual}$, can be obtain by modified Eqn. (3.3) to become Eqn. (3.10): (Lai and Lim, 2019a)

$$E_{AC_{N_{actual}}} = \sum_{t=0}^{t=1440}[\,D \times \mathrm{P}_{actual}\,(t)] \tag{3.10}$$

The total electricity for one year can be obtain by summation number of daily electricity in one year. Nevertheless, the degradation of PV module is different each year. Thus, the electricity yield, $E_{AC\_y\_actual}$ for a specific year only, can be determine by using Eqn. (3.11): (Lai and Lim, 2019a)

$$E_{AC_{y_{actual}}} = (1 - yd)\sum_{N=1}^{N=365} E_{AC_{N_{actual}}} \tag{3.11}$$

Where

N = number of days

d = degradation rate of the PV module

y = number of years used

The total electricity yield,$E_{AC\_S\_actual}$, within a specific time frame, L is Eqn. (3.12): (Lai and Lim, 2019a)

$$E_{AC_{S_{actual}}} = \sum_{y=1}^{y=L} E_{AC_{y_{actual}}} \tag{3.12}$$

LCOE for this generalised method can be determined by Eqn. (3.13): (Lai and Lim, 2019a)

$$LCOE = \frac{Capital+Maintenance\ Cost}{E_{AC_{S_{actual}}}} \tag{3.13}$$

The cost saving of undersized inverter can be determine by Eqn. (3.14):

$$\$_{inv,exp} = P_{PV}\left(1 - \frac{1}{optimal_{ISR}}\right) * Price_{inv} \tag{3.14}$$

Where

$\$_{inv,exp}$ = cost saving of undersized inverter which included the clipped electricity.

$Price_{inv}$ = specific price for inverter, RM/W

The net saving of undersized the inverter can be determine by Eqn. (3.15) :

$$\$_{inv,net} = \$_{inv,exp} - \left(P_{AC\_exp} - P_{actual}\right) * \$_{tarrifs} \tag{3.15}$$

Where

$\$_{inv,net}$ = Net saving cost from undersized inverter

$\$_{tarrifs}$ = Specific price of the electricity sell for the specific plant size.

Incentives does not include as the net present value of the future cost. The capital is the cost after calculating the cost save from the undersized inverter. It can be calculated as below: (Lai and Lim, 2019a)

$$Capital = P_{PV}\left[Price_{PV\_sys}\right] - \$_{inv,exp} \tag{3.16}$$

Where

$Price_{PV\_sys}$ = specific price for PV system, RM/W

3.1.5 Software

All the formulas in Section 3.1.4 were programmed in Microsoft Excel. Microsoft Excel was used by this study to process the data and determine the amount of clipped electricity and unclipped electricity. The purpose of determining the amount of clipped electricity and unclipped electricity is to calculate the loss of profit and levelised cost of electricity (LCOE) respectively.

3.2 Investigation of different interval data on optimal ISR

The goal of studying different interval data on optimal ISR because different sampled interval data could have different optimal ISR as the total amount of irradiation is different in each interval data. Similarly for the averaged method. Table 3.1 shows the nominal value for each parameter for 10 MW. The nominal value is provided by Dr.Lim Boon Han who is an Honorary Member of Malaysia Photovoltaic Industry Association (MPiA). He had 21 years of experience in the field with both industrial and academic experience, especially in the field of solar energy and electrical engineering. The value of each parameter for every interval data was set to a nominal value as presented in Table 3.1. The summation of the specific cost of the inverter and other costs such as installation cost is the specific cost of the PV system. In Section 3.1.4, the $\mathrm{PR}_{\mathrm{fixed}}$ was mention that it is specially used in this study to ease sensitivity analysis.

Table 3.1: The nominal value of each parameters for 10 MW.

DC capacity (MW)				Nominal $\mathrm{PR}_{\mathrm{fixed}}$	Nominal operation and maintenance (O & M) cost (RM/year)	Nominal tariffs (RM/kWh)	Nominal degradation rate (%/year)
	Other costs (RM/W)	Inverter specific cost (RM/W)	Nominal specify cost of system (RM/W)	Remark: Nominal PR is 0.82			
10	1.68	0.52	2.20	0.92	200,000.00	0.28	0.40

The 5-Minutes interval data was used to determine the optimal ISR. After that, the project is repeated by using sampled ten-minute data interval, twenty-minute data interval, thirty-minute data interval and hourly data interval to find out the optimal ISR at each interval. The optimal ISR was chosen based on the lowest LCOE for 21 years for sampled method and averaged method. The study on the effect of using different sampled interval data on optimal ISR was done and the result was discussed. Similar case for the averaged method, the solar irradiance data were averaged out for different intervals to find out the optimal ISR at different intervals. After that, the result of optimal ISR for both methods was compared and discussed.

3.3 Changing the parameter for different types of sensitivity analysis

Several types of parameters were modified to study the sensitivity on optimal ISR and LCOE. The purpose of studying sensitivity analysis in detail is to investigate whether the parameters have great or less influence on the optimal ISR. The PV module that was chosen to study is the crystalline silicon PV module. The 5-Minutes sampled interval data was used for all the sensitivity analysis in this section. All the sensitivity analysis except for degradation rates of the PV module is studied by using the GHI data only. The results of degradation rate were done by using GHI and GTI data to study. When the sensitivity analysis is performed, only one parameter varies and the other parameters are kept constant. All the LCOE was calculated for PV plants that going to be used for 21 years.

The PV capacity of 10 MW, 50 MW and 100 MW were chosen to study for all the sensitivity analysis. These are the common capacity of the PV power plants in Malaysia as mentioned in Section 2.1. Based on Eqn. (3.3), the different PV capacity has a different value of the electricity yield. Dr. Lim Boon Han had provided all the nominal values in this section. These numbers are usually not available on the public media or journal articles because they are commercially confidential.

3.3.1 Different degradation rates of PV module

The study on the effect of different degradation rates of PV modules on optimal ISR and LCOE was performed. The reason for choosing different degradation rates of PV modules for the study is because different degradation rates have a different amount of clipped electricity along the project lifetime. For this project, the degradation rates of the PV module were adjusted from 0.30% to 0.60% with a step size of 0.10% per year. The reason of choose this range is due to the lowest degradation rate of the PV module is 0.25% per year (John, 2018). Hence, the degradation rate in this project was assumed to be slightly higher than 0.25% per year which is 0.30% per year. The degradation rate for double glass modules is about 0.45% per year (PV-Manufacturing, n.d.). The formula for degradation rate of PV module can be referred at Eqn. (3.11). Table 3.2 shows the list of parameters for degradation rate. Different PV capacity has a different nominal value. The graph of optimal ISR and LCOE versus degradation rate was plotted and the result was discussed.

Table 3.2: The list of parameters for degradation rate.

DC capacity (MW)				Nominal PR$_{fixed}$	Nominal O & M cost (RM/year)	Nominal tariffs (RM/kWh)	Degradation rate (%/year)
	Other costs (RM/W)	Specific cost of inverter (RM/W)	Nominal specific cost of the PV system (RM/W)	Remark: Nominal PR is 0.82			
10	1.68	0.52	2.20	0.92	200,000.00	0.28	0.30
							0.40
							0.50
							0.60
50	1.50	0.40	1.90	0.92	500,000.00	0.22	0.30
							0.40
							0.50
							0.60
100	1.38	0.32	1.70	0.92	600,000.00	0.20	0.30
							0.40
							0.50
							0.60

3.3.2 Different of fixed component of performance ratio (PR_{fixed})

The investigation on the effect of different PR_{fixed} on optimal ISR and LCOE was carried out. The reason for choosing this parameter for the study is because different PR_{fixed} can cause the PV system to have a different amount of unclipped electricity along the project lifetime. Based on Eqn. (3.13), the amount of unclipped electricity can affect the LCOE if the operation and maintenance (O & M) cost and capital cost are fixed. The optimal ISR is affected as it is selected based on the lowest LCOE. For this project, the PR_{fixed} was set to a step size of 0.025 from 0.85 to 0.975. The reason of choose this range is due to the PR_{fixed} is not common to set below 0.85 in Malaysia. In practical cases, it is impossible for the PR_{fixed} to achieve 1. Table 3.3 shows the list of parameters for PR_{fixed}. Similar to Section 3.3.1, different capacity has a different nominal value. The graph of optimal ISR and LCOE versus PR was plotted. The details of the discussion were done.

Table 3.3: The list of parameters for PR_{fixed}.

DC capacity (MW)				Nominal degradation rate (%/year)	Nominal O & M cost (RM/year)	Nominal tariffs (RM/kWh)	PR_{fixed}
	Other costs (RM/W)	Specific cost of the inverter (RM/W)	Nominal specific cost of the PV system (RM/W)				
10	1.68	0.52	2.20	0.50	200,000.00	0.28	Remark: Nominal PR is 0.82
							0.875
							0.900
							0.925
							0.950
							0.975
50	1.50	0.40	1.90	0.50	500,000.00	0.22	0.850
							0.875
							0.900
							0.925
							0.950

							0.975
100	1.38	0.32	1.70	0.50	600,000.00	0.20	0.850
							0.875
							0.900
							0.925
							0.950
							0.975

3.3.3 Change of operation and maintenance (O & M) cost

The study on the operation and maintenance (O & M) cost is important as the PV system is required to clean every month. The purpose of clean the PV system is to improve the efficiency of the PV module. Figure 3.6 shows the efficiency of the PV system for a clean and dusty condition for the PV module. The output power with a clean PV module is higher than the dusty PV module. Based on Eqn. (3.13), different O & M cost can cause the PV system to have different LCOE. The optimal ISR is affected as it is selected based on the lowest LCOE. Table 3.4 shows the list of parameters for PR_{fixed}. The study on the effect of different O & M cost on optimal ISR and LCOE was performed. The graph of optimal ISR and LCOE versus O & M cost was plotted.

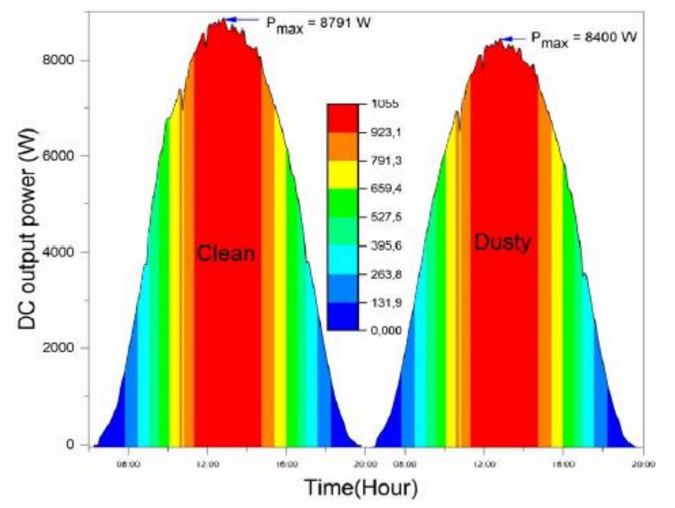


Figure 3.6: The DC output power under clean and dusty condition.
(Mostefaoui, 2018)

Table 3.4: The list of parameters for O & M cost.

DC capacity (MW)				Nominal degradation rate (%/year)	Nominal PR_{fixed}	Nominal tariffs (RM/kWh)	O & M cost (RM/year)
	Other costs (RM/W)	Specific cost of the inverter (RM/W)	Nominal specific cost of the PV system (RM/W)		Remark: Nominal PR is 0.82		
10	1.68	0.52	2.20	0.50	0.92	0.28	100,000.00
							120,000.00
							140,000.00
							160,000.00
							180,000.00
							200,000.00
50	1.50	0.40	1.90	0.50	0.92	0.22	200,000,00
							250,000,00
							300,000,00
							350,000,00
							400,000,00
							450,000,00
							500,000,00
100	1.38	0.32	1.70	0.50	0.92	0.20	250,000,00
							300,000,00
							350,000,00
							400,000,00
							450,000,00
							500,000,00
							550,000,00
							600,000.00

3.3.4 Sensitivity analysis on specific costs of the PV system and inverter

There are 3 cases of sensitivity analysis in this part. The first case is changing of the cost of the PV system with fixed specific cost of the inverter. The purpose of this case is to investigate the specific cost of the PV system without changing the specific cost of the inverter on the optimal ISR and LCOE. The second case is changing of the specific cost of the PV system together with the change of specific cost of the inverter. The reason for this case is to find out the effect of changing the specific cost of the inverter on the optimal ISR and LCOE. After that, the results from these two cases were compared and discussed.

The third case is changing of the specific cost of the inverter with fixed specific cost of the PV system. The purpose in this case is to observe the influence of changing the specific cost of the inverter where the specific cost of the PV system remains constant on the optimal ISR and LCOE.

3.3.4.1 Specific cost of the PV system with the fixed specific cost of the inverter

In this section, the specific cost of an inverter remained constant and the specific cost of the PV system was adjusted by this study to investigate its effect on LCOE and optimal ISR. Based on Eqn. (3.16), the capital cost increases as the specific cost of the PV system increases. Based on Eqn. (3.13), the LCOE increases as the capital cost increases. The optimal ISR is affected as it is chosen at the lowest LCOE. Table 3.5 shows the list of parameters for the specific cost of the PV system with the fixed specific cost of the inverter. The specific cost of the PV system has a step size of RM 0.10 for every PV capacity. The graph of optimal ISR and LCOE versus specific cost of the PV system was plotted.

Table 3.5: The list of parameters for the specific cost of the PV system with the fixed specific cost of the inverter.

DC capacity (MW)	Nominal PR_{fixed}	Nominal degradation rate (%/year)	Nominal O & M cost (RM/year)	Nominal tariffs (RM/kWh)			
	Remark: Nominal PR is 0.82				Inverter specify cost (RM/W)	Other costs (RM/W)	Specific cost of the PV system (RM/W)
10	0.92	0.5	200,000.00	0.28	0.52	1.28	1.8
						1.38	1.9
						1.48	2.0
						1.58	2.1
						1.68	2.2
						1.78	2.3
						1.88	2.4
						1.98	2.5
50	0.92	0.5	500,000.00	0.22	0.40	1.20	1.6
						1.30	1.7
						1.40	1.8
						1.50	1.9
						1.60	2.0
						1.70	2.1
						1.80	2.2
100	0.92	0.5	600,000.00	0.20	0.32	1.08	1.4
						1.18	1.5
						1.28	1.6
						1.38	1.7
						1.48	1.8
						1.58	1.9
						1.68	2.0

3.3.4.2 Specific cost of the PV system changes with the specific cost of the inverter

In this section, the specific cost of the PV system change with the specific cost of the inverter was adjusted in this study to investigate its effect on LCOE and optimal ISR. From Eqn. (3.14), the saving of undersized inverter which included the clipped electricity increases as the specific cost of the inverter increases. Based on Eqn. (3.16), the capital cost increases as the specific cost of the PV system increases. Based on Eqn. (3.13), the LCOE increases as the capital cost increases. The optimal ISR is affected as it is chosen at the lowest LCOE. Table 3.6 shows the list of parameters for the specific cost of the PV system change with the specific cost of the inverter. The specific cost of the PV system is included the specific cost of the inverter and other costs. Similar to Section 3.3.1, different capacity has a different nominal value. The graph of optimal ISR and LCOE against the specific cost of the inverter was plotted. The graph of optimal ISR and LCOE against the specific cost of the PV system was plotted.

Table 3.6: The list of parameters for specific cost of the PV system with specific cost of the inverter.

DC capacity (MW)	Nominal PR_{fixed}	Nominal degradation rate (%/year)	Nominal O & M cost (RM/year)	Nominal tariffs (RM/kWh)			
	Remark: Nominal PR is 0.82				Other costs (RM/W)	Specific cost of the inverter (RM/W)	Specific cost of the PV system (RM/W)
10	0.92	0.50	200,000.00	0.26	1.50	0.30	1.80
						0.40	1.90
						0.50	2.00
						0.60	2.10
						0.70	2.20
						0.80	2.30
50	0.92	0.50	500,000.00	0.14	1.30	0.30	1.60
						0.40	1.70

						0.50	1.80
						0.60	1.60
						0.70	1.90
						0.80	2.00
						0.90	2.10
						1.00	2.20
100	0.92	0.50	600,000.00	0.12	1.10	0.20	1.30
						0.30	1.40
						0.40	1.50
						0.50	1.60
						0.60	1.70
						0.70	1.80
						0.80	1.90
						0.90	2.00

3.3.4.3 Change specific cost of the inverter with the fixed specific cost of the PV system

In this section, the specific cost of the PV system remained constant and the specific cost of the inverter was adjusted in this study to investigate its influence on LCOE and optimal ISR. From Eqn. (3.14), the saving of the undersized inverter which included the clipped electricity increases as the specific cost of the inverter increases. From Eqn. (3.16), the value of the capital cost is only affected by the saving of undersized inverter which included the clipped electricity if the specific cost of the PV system was remained constant in this part. In this section, the capital cost decreases as the specific cost of the PV system increases unlike in Section 3.3.4.2. Based on Eqn. (3.13), the LCOE decreases as the capital cost decreases. The optimal ISR is affected as it is chosen at the lowest LCOE. Table 3.7 shows the list of parameters for the specific cost of the inverter with the fixed specific cost of the PV system. The specific cost of the PV system is fixed to RM 2.0/W, RM 1.8/W and RM1.6/W for 10 MW, 50 MW and 100 MW respectively. The graph of optimal ISR and LCOE versus the specific cost of the inverter was plotted.

Table 3.7: The list of parameters for specific cost of the inverter with the fixed specific cost of the PV system.

DC capacity (MW)	Nominal PR_{fixed}	Nominal degradation rate (%/year)	Nominal O & M cost (RM/year)	Nominal tariffs (RM/kWh)		
	Remark: Nominal PR is 0.82				Specific cost of the PV system (RM/W)	Specific cost of the inverter (RM/W)
10	0.92	0.50	200,000.00	0.26	2.00	0.30
						0.40
						0.50
						0.60
						0.70
						0.80
50	0.92	0.50	500,000.00	0.14	1.80	0.30
						0.40
						0.50
						0.60
						0.70
						0.80
100	0.92	0.50	600,000.00	0.12	1.60	0.20
						0.30
						0.40
						0.50
						0.60
						0.70

3.4 Comparison of 6 sensitivity analysis.

The results from sensitivity analysis (Section 3.3 only) were compared. The purpose of doing this study is to investigate the influence of different sensitivity analysis on the optimal ISR and LCOE. Table 3.8, Table 3.9 and Table 3.10 show percentages different from nominal for degradation rates, PR_{fixed} and O & M cost respectively. Table 3.11, Table 3.12 and Table 3.13 show percentage different from nominal for change the specific cost of the PV system with the fixed specific cost of the inverter, change the specific cost of the PV system with the specific cost of the inverter and change the specific cost of the inverter with the fixed specific cost of the PV system respectively. The graphs of optimal ISR and LCOE against percentages different from the nominal were plotted.

Table 3.8: The percentage different from nominal for degradation rates.

Capacity (MW)	Nominal degradation rate (%)	Degradation rates (%)	Percentage different from nominal (%)
10	0.50	0.30	-40
		0.40	-20
		0.50	0
		0.60	20

Table 3.9: The percentage different from nominal for PR_{fixed}.

Capacity (MW)	Nominal PR_{fixed}	PR_{fixed}	Percentage different from nominal (%)
10	0.920	0.850	-8
		0.875	-5
		0.900	-2
		0.925	1
		0.950	3
		0.975	6

Table 3.10: The percentage different from nominal for operation and maintenance (O & M) cost.

Capacity (MW)	Nominal O & M cost (RM/year)	Nominal O & M cost (RM/year)	Percentage different from nominal (%)
10	200,000	100,000.00	-50
		120,000.00	-40
		140,000.00	-30
		160,000.00	-20
		180,000.00	-10

		200,000.00	0

Table 3.11: The percentage different from nominal for change the specific cost of the PV system with the fixed specific cost of the inverter.

Capacity (MW)	Nominal specific cost of the PV system (RM/W)	Specific cost of the PV system (RM/W)	Percentage different from nominal (%)
10	2.20	1.80	-18
		1.90	-14
		2.00	-9
		2.10	-5
		2.20	0
		2.30	5
		2.40	9
		2.50	14

Table 3.12: The percentage different from nominal for change the specific cost of the PV system with the specific cost of the inverter.

Capacity (MW)	Nominal specific cost of the PV system (RM/W)	Specific cost of the PV system (RM/W)	Percentage different from nominal (%)
10	2.20	1.8	-18
		1.9	-14
		2.0	-9
		2.1	-5
		2.2	0
		2.3	5

Table 3.13: The percentage different from nominal for change the specific cost of the inverter with fixed specific cost of the PV system

Capacity (MW)	Nominal specific cost of the inverter (RM/W)	Specific cost of the inverter (RM/W)	Percentage different from nominal (%)
10	0.52	0.3	-42
		0.4	-23
		0.5	-4
		0.6	15
		0.7	35
		0.8	54

3.5 Parameters in the best and the worst case scenarios for 10 MW plant.

In this section, the parameters of best and worst case scenarios were carried out. The goal of this study is to compare the optimal ISR of these two cases. The parameters were mentioned in Table 3.14.

Table 3.14: The list of parameters for best and worst case scenario.

	DC capacity (MW)	Nominal tariffs (RM/kWh)	Nominal O & M cost (RM/year)	Nominal degradation rate (%/year)	Nominal PR_{fixed}		
					Remark: Nominal PR is 0.82	Specific cost of the PV system (RM/W)	Specific inverter cost (RM/W)
Best case	10	0.28	200,000.00	0.60	0.850	2.30	0.80
Worst case				0.30	0.975	1.80	0.30

3.6 Problem encounter and solution

The problem encountered in this study is two of the sensitivity analysis does not give a clear trend on the optimal ISR which may lead the results not accurate. The sensitivity analysis is O & M cost and the specific cost of the PV system with the fixed specific cost of the inverter. To improve the accuracy of the result, the simulation is run with a smaller step size to find out the optimal ISR. Table 3.15 shows the simulation result before and after adjustment for O & M cost. Table 3.16 shows the simulation result before and after adjustment. It can be observed that the simulation which runs with a smaller step size gives a clearer change on the optimal ISR.

Table 3.15: The optimal ISR before and after adjustment for O & M cost.

Capacity (MW)	Operation and maintenance (RM/year)	Optimal ISR determined by step size of 0.010	Optimal ISR determined by step size of 0.005
10	100,000.00	1.630	1.635
	120,000.00	1.630	1.630
	140,000.00	1.620	1.620
	160,000.00	1.610	1.610
	180,000.00	1.610	1.610
	200,000.00	1.610	1.605

Table 3.16: The optimal ISR before and after adjustment for specific cost of the PV system with the fixed specific cost of the inverter.

Capacity (MW)	Specific cost of the PV system (RM/W)	Optimal ISR determined by step size of 0.010	Optimal ISR determined by step size of 0.005
10	1.8	1.640	1.645
	1.9	1.640	1.640
	2.0	1.630	1.630
	2.1	1.610	1.610
	2.2	1.610	1.605
	2.3	1.600	1.600
	2.4	1.590	1.595
	2.5	1.590	1.590
50	1.6	1.640	1.640
	1.7	1.620	1.620
	1.8	1.610	1.610
	1.9	1.600	1.600
	2.0	1.590	1.595
	2.1	1.590	1.585
	2.2	1.580	1.580
100	1.4	1.630	1.630
	1.5	1.600	1.605
	1.6	1.600	1.595
	1.7	1.590	1.590
	1.8	1.580	1.580
	1.9	1.570	1.575
	2.0	1.570	1.570

CHAPTER 4

RESULT AND DISCUSSION

4.1 Introduction

Firstly, the result of two distribution profiles for different irradiation was interpreted. In addition, the optimal ISR of sampled method and averaged method were compared and discussed. Moreover, the simulation on sensitivity analysis was done and discussed. Besides that, the comparison of all sensitivity analysis was discussed. The discussion on the result of best and worst-case scenarios was done. Lastly, the summary of all sensitivity analysis was discussed in the last part of this chapter.

4.2 Comparison of two types of solar irradiance

Figure 4.1 shows the two solar irradiance distribution profiles at various irradiance levels in Sungai Long for 2020. When the solar irradiance more than 900 W/m^2, the percentage over annual irradiation for global horizontal irradiation (GHI) is lower than the percentage over annual irradiation for global tilted irradiation (GTI). The total irradiation in one year for GHI was calculated as 1526.50 kWh/m^2 while for GTI was calculated as 1555.31 kWh/m^2. Although annual GTI and GHI only differ by 1.85%, the distribution profile is quite different. The reason is that the 10 degree of GTI at Sungai Long is closer to the optimal tilting angle than the GHI. The study on the distribution profile in detail is to investigate its effect on the optimal ISR in this case. Figure 4.2 shows the relationship of optimal ISR of sites to the solar irradiation of the sites. From Figure 4.2, it can be seen that different irradiance profiles will have different optimal ISR (Lai and Lim, 2019a).

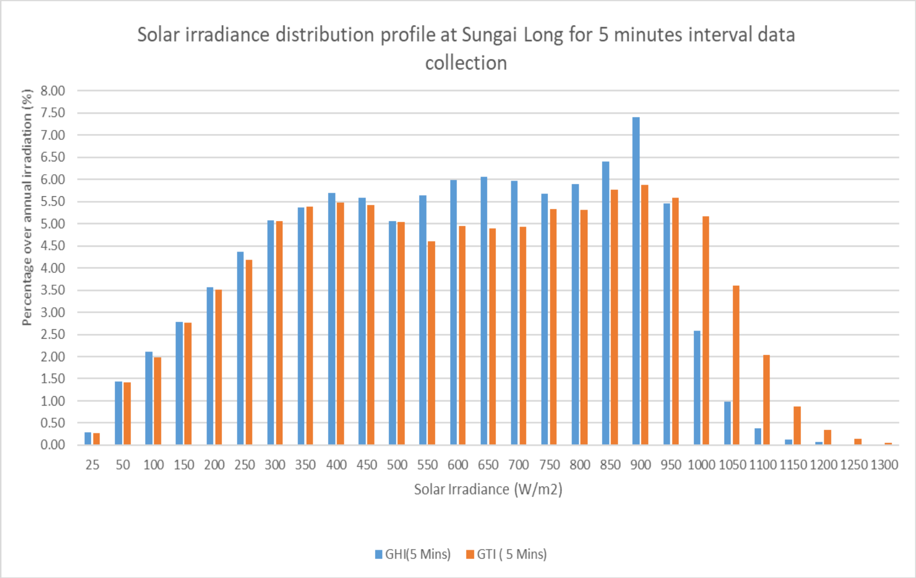


Figure 4.1: Different solar irradiance distribution profiles at various irradiance levels in Sungai Long 2020.

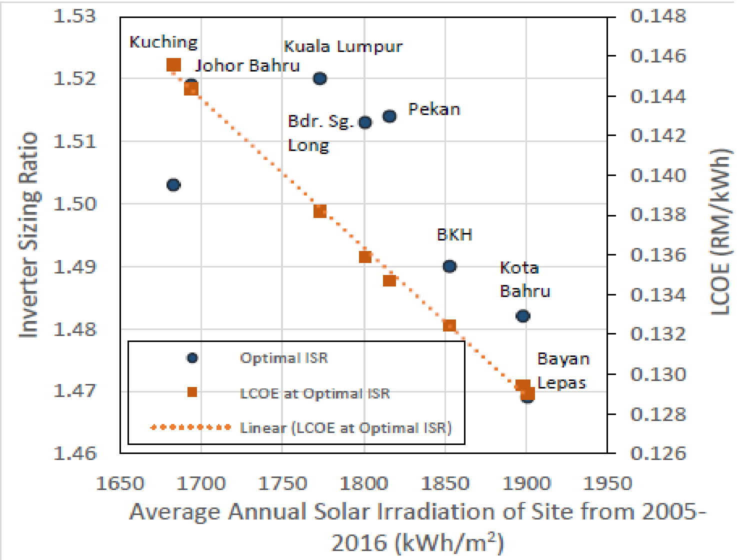


Figure 4.2: The relationship of optimal inverter sizing ratio of sites to the solar irradiation of the sites. (Lai and Lim, 2019a)

The Eqn. (3.1) was used to show the percentage different of annual GHI and GTI:

$$\% \, different = \frac{GTI - GHI}{GTI} * 100\%$$

$$\% \, different = \frac{1555.31 - 1526.5}{1555.31} * 100\%$$

$$\% \, different = \ 1.85\%$$

Figure 4.3 shows the distribution profile of GHI and GTI at Sungai Long 2020. From Figure 4.3, it can be seen that the number of days for both GHI and GTI are mostly different for various range of irradiation ranges. The GHI and GTI have the same number of days in irradiation range from 0.25 to 1.50, 2.25, 3.00 and 5.50 kWh/m^2. From Figure 4.3, it can be observed that there were two days the GTI achieved 7.25 kWh/m^2 in 2020. The weather for these days is sunny for the whole day. Hence, these days had achieved a high amount of solar irradiation. There were some days the irradiation is below 0.75 kWh/m^2. The weather for these days was cloudy or rainy.

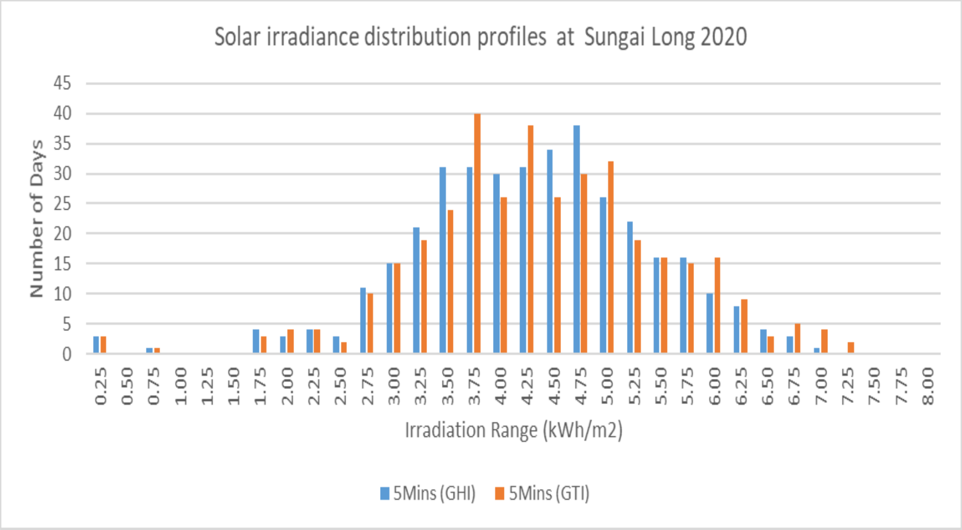


Figure 4.3: Distribution profiles of GHI and GTI at Sungai Long 2020.

Figure 4.4 shows the sampled method of solar irradiance distribution profile at Sungai Long for different interval data for the GHI case. It can be observed that the distribution profile for all interval data is quite similar.

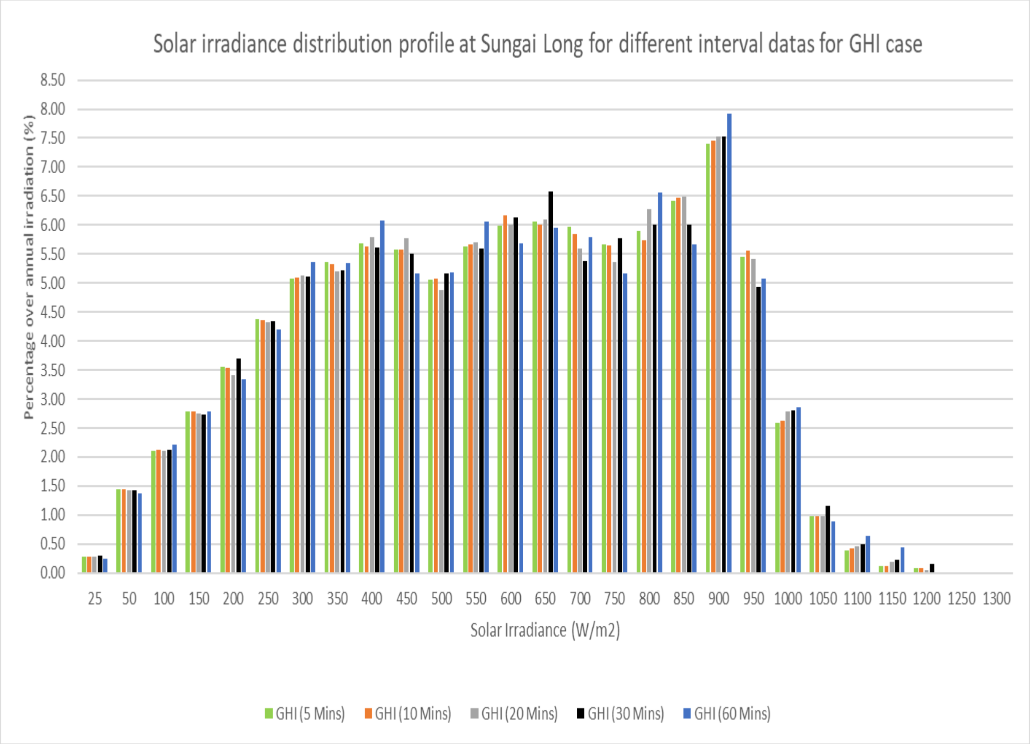


Figure 4.4: Sampled method of different solar irradiance distribution profiles at different interval data for GHI in Sungai Long 2020.

4.3 Investigation the effect of sampled method and averaged method on optimal ISR

4.3.1 Sampled method

The formula in Section 3.1.2 was implemented to obtain sampled data for various time intervals. The nominal value listed in Section 3.2 was used during the process of finding out the optimal ISR for different interval data. From Figure 4.5, it can be observed that the optimal ISR for GTI is smaller than GHI. This is due to the different distribution profiles. The trend of optimal ISR for GHI have slightly different only while the trend of optimal ISR has no changes for GTI as presented in Figure 4.5. From Figure 4.4, the distribution profiles for GHI at different intervals are quite similar for the GHI case. This will lead to the optimal ISR does not have much changes since the distribution profiles are quite the same. In a nutshell, the intervals do not give a clear change because the data is done sampled out and by probability the solar irradiance distribution profiles are quite the same. 1.85% difference in GHI and GTI are normally neglected in the industry but it can affect the optimal ISR by 0.09.

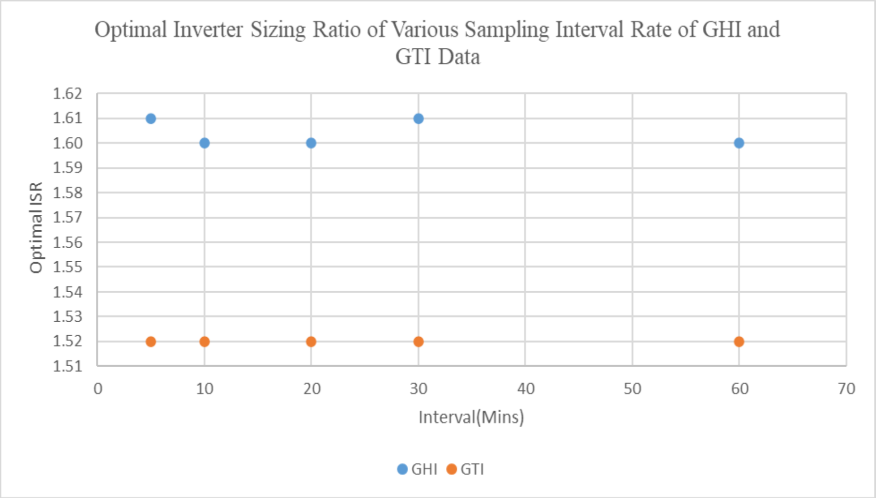


Figure 4.5: Optimal ISR of various sampled interval rate of GHI and GTI data.

4.3.2 Averaged method

Figure 4.6, Figure 4.7 and Figure 4.8 show different solar irradiance distribution profiles for GHI in Sungai Long 2020 for averaged and sampled methods at five, ten and twenty minutes thirty and sixty minutes intervals respectively. Figure 4.9 and Figure 4.10 show solar irradiance distribution profiles for GHI in Sungai Long 2020 for averaged and sampled methods at thirty and sixty minutes intervals respectively. When the solar irradiance more than 900 W/m^2, the percentage over annual irradiation for the averaged method is lower than the percentage over annual irradiation for sampled method. From Figure 4.6 to Figure 4.10, the percentage over annual irradiation at 900 W/m^2 or above for averaged method decreases as the interval increases. This is because the averaged method has been averaged out the high resolution solar irradiance into low resolution data. On the other hand, the distribution profiles for various time intervals for the sampled method are similar.

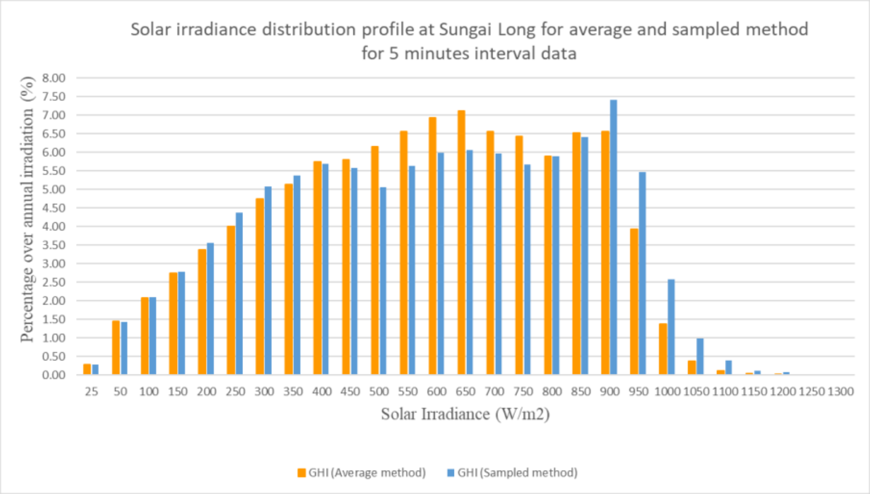


Figure 4.6: Different solar irradiance distribution profiles for averaged and sampled method at 5 Minutes interval for GHI in Sungai Long 2020.

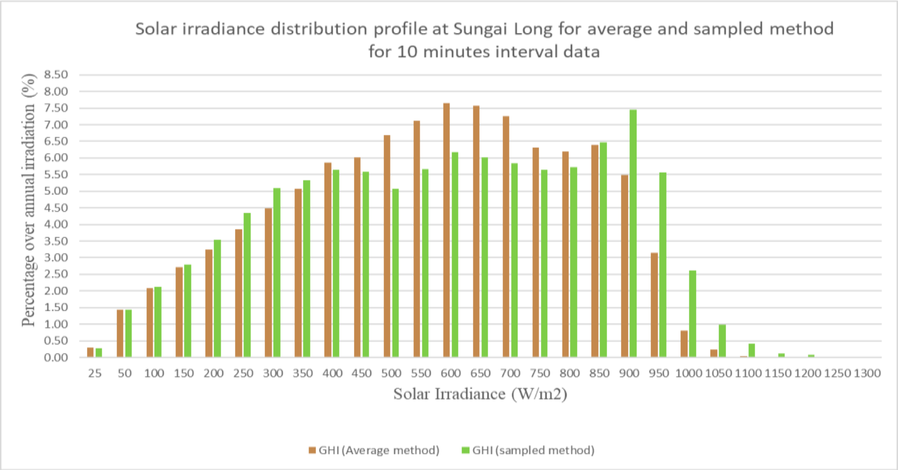


Figure 4.7: Different solar irradiance distribution profiles for averaged and sampled method at 10 Minutes interval for GHI in Sungai Long 2020.

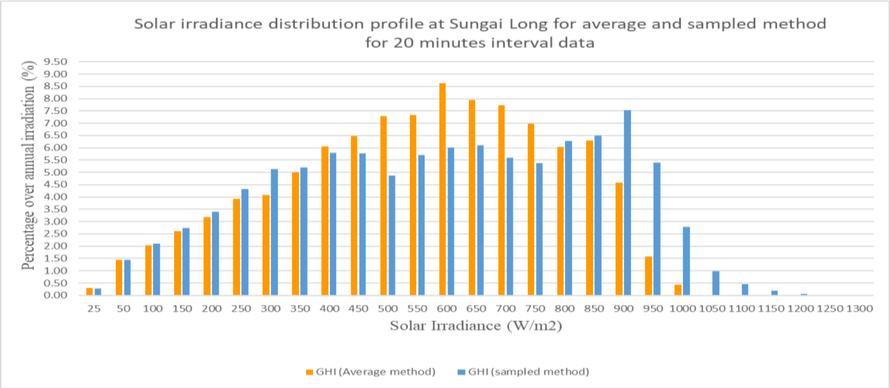


Figure 4.8: Different solar irradiance distribution profiles for averaged and sampled method at 20 Minutes interval for GHI in Sungai Long 2020.

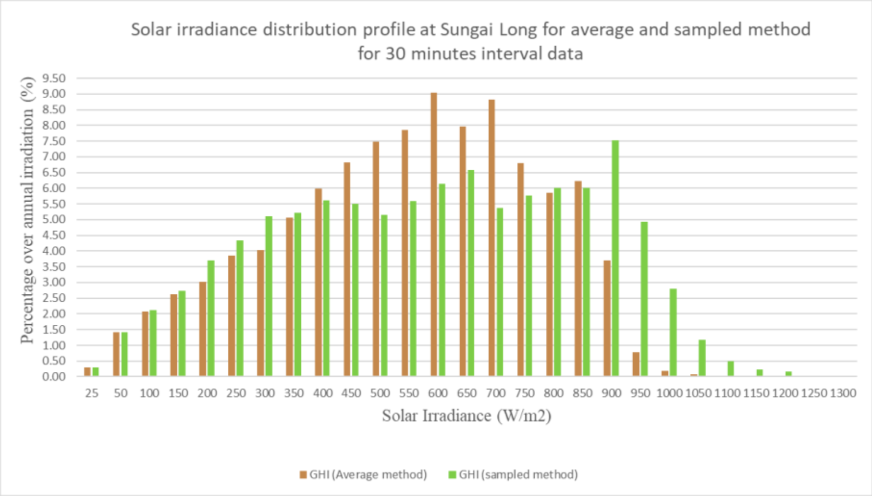


Figure 4.9: Different solar irradiance distribution profiles for averaged and sampled method at 30 Minutes interval for GHI in Sungai Long 2020.

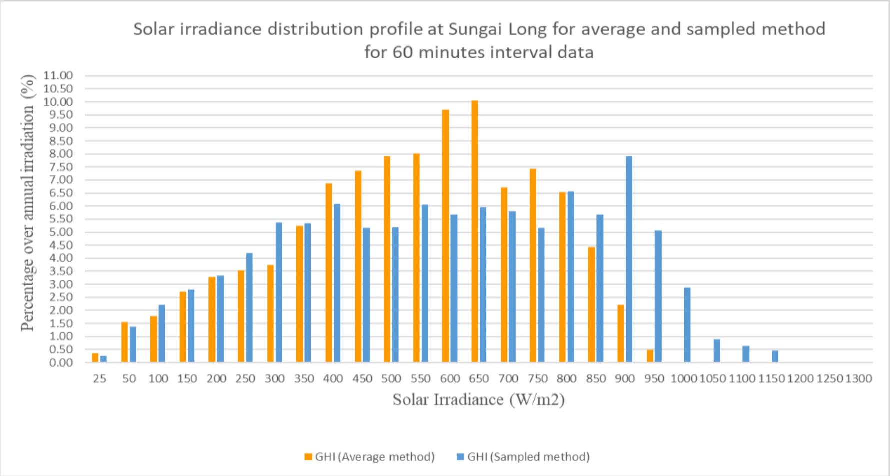


Figure 4.10: Different solar irradiance distribution profiles for averaged and sampled method at 60 Minutes interval for GHI in Sungai Long 2020.

The solar irradiance data was done averaged out for various intervals data. The nominal value listed in Section 3.2 was used during the calculation of the optimal ISR for different interval data. From Figure 4.11, it can be observed that the optimal ISR determined by the average method is higher than the optimal ISR determined by the sampled method. This is due to the different distribution profiles. From Figure 4.6 to Figure 4.10, the distribution profiles for both methods are not the same. This caused the optimal ISR to have a lot of changes since the distribution profiles are different. In conclusion, the average method of the solar irradiance data gives a clear change on the optimal since the data is done averaged out and it could not detect cases of short and rapid change of the high solar irradiance. Thus, the optimal ISR appears to be higher for averaged method.

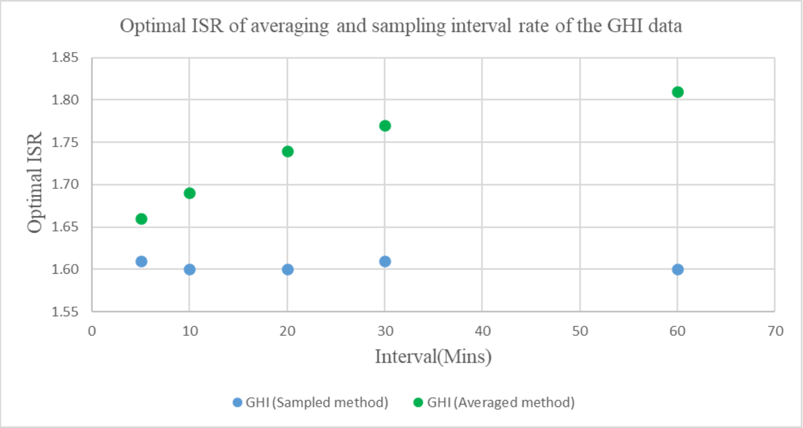


Figure 4.11: Optimal ISR of average and sampled interval rate of the GHI data.

4.4 Sensitivity analysis

The process of sample the 1-Minute solar irradiance data into 5-Minutes solar irradiance data was carried out. The 5-Minutes solar irradiance data was used by this study to perform sensitivity analysis such as degradation rates of the photovoltaic (PV) module, specific cost of the PV system and specific cost of the inverter. In all sensitivity analysis, the optimal ISR is selected based on minimum LCOE for PV plants that are planned to be used for 21 years. Table 4.1 shows the nominal value for specific parameters.

Table 4.1: The nominal value for specific parameters.

DC capacity (MW)	Specific cost of the inverter (RM/W)	Specific cost of the PV system (RM/W)	PR_{fixed}	O & M cost (RM/year)	Degradation rate (%/year)	Tariffs (RM/kWh)
10	0.52	2.20	0.92	200,000.00	0.5	0.28
50	0.40	1.90	0.92	500,000.00	0.5	0.22
100	0.32	1.70	0.92	600,000.00	0.5	0.20

4.4.1 Degradation rates of PV module

In this section, the sensitivity analysis of the degradation rates of the PV module was investigated. Figure 4.12 shows annual and cumulative clipped of electricity for a 10 MW plant at two different degradation rates. From Figure 4.12, it can be observed that the starting point (at the first year) of the annual clipped electricity for both degradation rates is different. The optimal ISR for degradation rates of 0.30% and 0.50% is 1.58 and 1.61 respectively. Hence, the amount of clipped electricity is different in the first year.

From Figure 4.12, it also can be seen that the annual clipped electricity for degradation rate of 0.30% is higher than annual clipped electricity for degradation rate of 0.50% starting from the 10th year. This is because the rates of decrement in total generated electricity for degradation rate of 0.50% is faster than the degradation rate of 0.30% after the 10th year. The higher the degradation rate, the lesser the total electricity yield, and thus the lower the amount of clipped electricity. Meanwhile, the gap between the cumulative clipped electricity for two different degradation rates is getting smaller as time increases until the 21st year. The difference between the annual clipped electricity for the two degradation rates is more obvious as time increases (especially after the 15th year since the unit is in term of MWh). Eventually, the cumulative annual clipped electricity for degradation rate of 0.30% exceeds the cumulative annual clipped electricity for degradation rate of 0.50% starting from the 21st year.

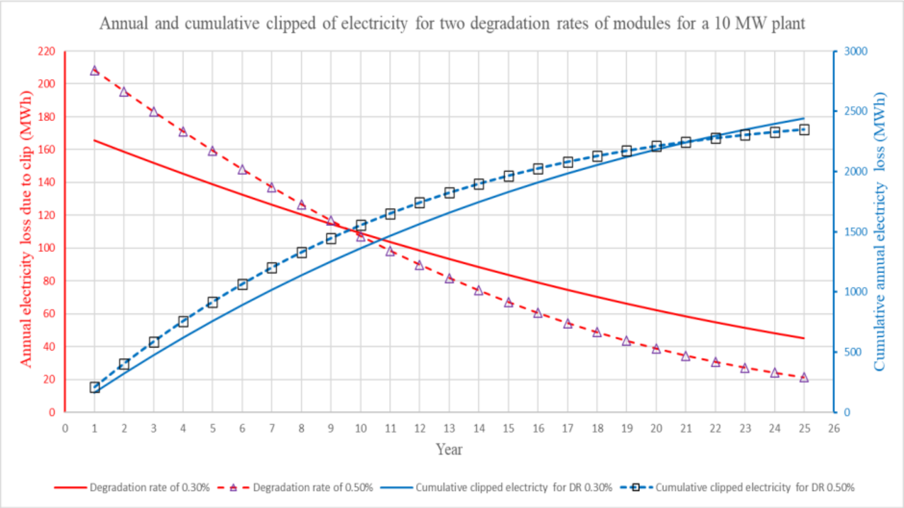


Figure 4.12: Annual and cumulative clipped of electricity for a 10 MW plant at two different degradation rates.

Figure 4.13 shows annual and cumulative clipped of electricity for 10 MW plant for the same optimal ISR at two different degradation rates. The ISR in Figure 4.13 is 1.58. The annual clipped electricity for degradation rate of 0.30% is higher than the annual clipped electricity for degradation rate of 0.50%. The higher the degradation rate, the lesser the total electricity yield. When total electricity yield is reduced, the clipped electricity is reduced. The cumulative clipped electricity for degradation rate of 0.30% is higher than cumulative clipped electricity for degradation rate of 0.50% since the annual clipped electricity for degradation rate of 0.30% is higher than the degradation rate of 0.50%.

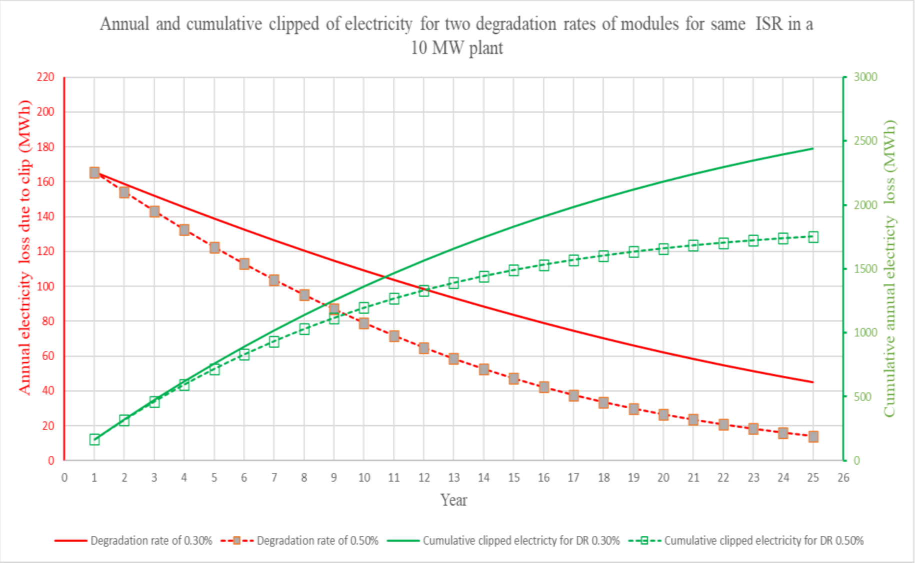


Figure 4.13: Annual and cumulative clipped of electricity for 10 MW plant for same optimal ISR at two different degradation rates.

The calculation below is to show the loss of income for 10 MW plant for GHI case for optimal ISR at different degradation rates. The calculation only determine the loss of income in 21 years only. The tariff is RM 280 per MWh.

Loss of profit (loss of tariffs)for DR of 0.30%

=Tariff price * Total electricity loss for 21 years (MWh)
= 280 * 2240
= RM 627,200

Loss of profit (loss of tariffs)for DR of 0.50%

=Tariff price * Total electricity loss for 21 years (MWh)
= 280 * 2246
= RM 628,880

By using Eqn. (3.14), the saving cost of the undersized inverter which included the clipped electricity for the 10 MW plant with a degradation rate of 0.30% and 0.50% is determined as 1.91 and 1.97 (in terms of RM in million) respectively. Similar to the 50 MW and 100 MW plant, the saving cost of the undersized inverter which included the clipped electricity are determined as

7.50 and 11.87 (in terms of RM in million) respectively. By using Eqn. (3.15), the net saving cost of the undersized inverter for a 10 MW plant with a degradation rate of 0.30% and 0.50% is determined as 1.28 and 1.34 (in terms of RM in million) respectively. The net saving cost of the undersized inverter for 50 MW and 100 MW plants are determined by Eqn. (3.15) and shown in Table 4.2. The net saving can calculate by using Eqn. (3.15). The alternative way to calculate the net saving of optimal ISR is shown below.

Net saving for optimal ISR for a 10 MW plant with degradation rate of 0.30%
= Saving of undersized inverter – Loss of profit
= 1.91 – 0.63
= 1.28 (RM in million)

Table 4.2: The loss of profit and net saving for optimal ISR at different degradation rates for GHI case.

Capacity (MW)	Degradation rate (%)	Optimal ISR	Saving of undersized inverter (RM in million)	Loss of profit/tariffs (RM in million)	Net saving (RM in million)
			Y21	Y21	Y21
10	0.30	1.58	1.91	0.63	1.28
	0.50	1.61	1.97	0.63	1.34
50	0.50	1.60	7.50	2.46	5.04
100	0.50	1.59	11.87	3.72	8.15

From Table 4.2, the total loss of profit in 21 years is less than the net saving from the undersized inverter. Figure 4.14 and Figure 4.15 show sensitivity analysis due to change of degradation rate for different capacity of the PV power plants for GHI and GTI respectively. From Figure 4.14, it can be observed that the trend of the optimal ISR increases with the degradation rate of the PV module per year increases. A similar trend can be seen in Figure 4.15 as well. This is because the higher the degradation rate, the lesser the total electricity yield. When total electricity yield is reduced, the total clipped electricity is reduced. Therefore, it allows a smaller size of the inverter (higher optimal ISR).

The optimal ISR for GTI as presented in Figure 4.15 is much smaller than GHI as presented in Figure 4.14. As mentioned in Section 4.1, it is very interesting that the total solar irradiation for GTI and GHI was differed by 1.85%, but the optimal ISR can be so much different, particularly due to the solar irradiance distribution profile. The higher the degradation rate of the PV module in practical cases, the higher the optimal ISR for that particular site. This trend can be used as a reference for any other sites in Malaysia. The industry players can refer to Figure 4.14 for GHI case to find out the optimal ISR at any degradation rates for 10 MW, 50 MW or 100 MW plant. If the industry player wants to find out the optimal ISR at degradation rates of 0.44% for 10MW from Figure 4.14, the optimal ISR is 1.60.

The trend of LCOE increased with degradation rate can be seen in both figures. The 100 MW PV power plant has the smallest LCOE as compared to the 10 MW PV power plant and 50 MW PV power plant. Nagar and Gidwani (2018) had found out that increasing the degradation rate will lead to the LCOE to be increasing. Figure 4.16 shows the article result from the paper of Nagar and Gidwani. One completed simulation result is shown in Appendix A.

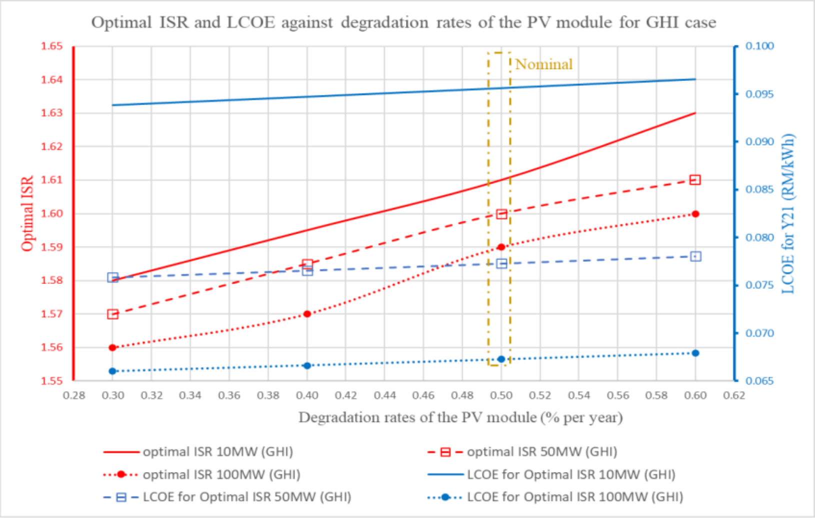


Figure 4.14: Sensitivity analysis due to change of degradation rates of PV module for 10 MW, 50 MW and 100 MW for GHI.

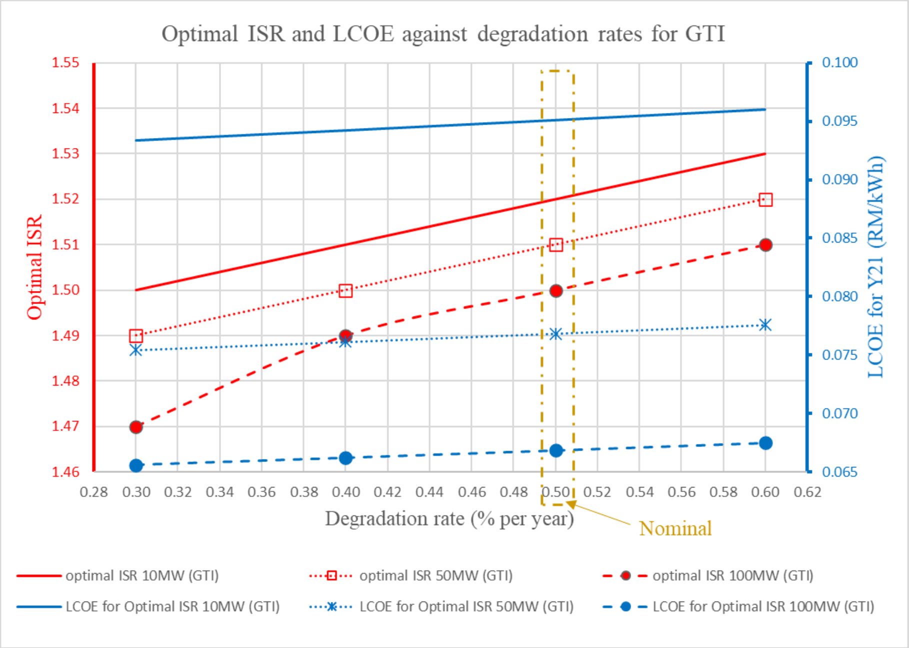


Figure 4.15: Sensitivity analysis due to change of degradation rates of PV module for 10 MW, 50 MW and 100 MW for GTI.

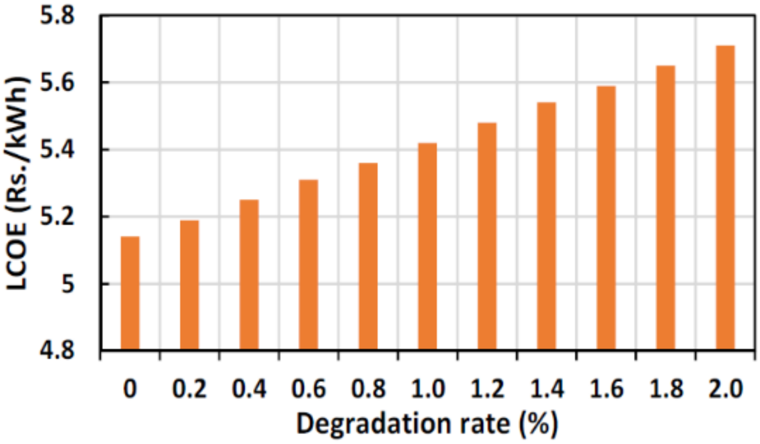


Figure 4.16: The graph of LCOE against degradation rates. (Nagar and Gidwani, 2018)

4.4.2 Fixed component of performance ratio (PR_{fixed})

In this section, the sensitivity analysis of the fixed component of performance ratio was investigated. Figure 4.17 shows the annual clipped of electricity for two PR_{fixed} for a 10 MW plant. The ISR in Figure 4.17 is 1.68. The reason the graph behaves in this kind of trend is due to different PR_{fixed} can cause different the total electricity yield along the project lifetime. From Eqn. (3.4), the higher the PR_{fixed}, the higher the PR. From Eqn. (3.3), the higher the PR, the higher the total electricity yield. When total electricity yield is increased, the total clipped electricity is increased. Thus, it allows a bigger size of the inverter (size refers to higher power rating, not the physical size). It also can be seen that the difference between the cumulative clipped electricity for the two PR_{fixed} for the same optimal ISR is more obvious as time increases.

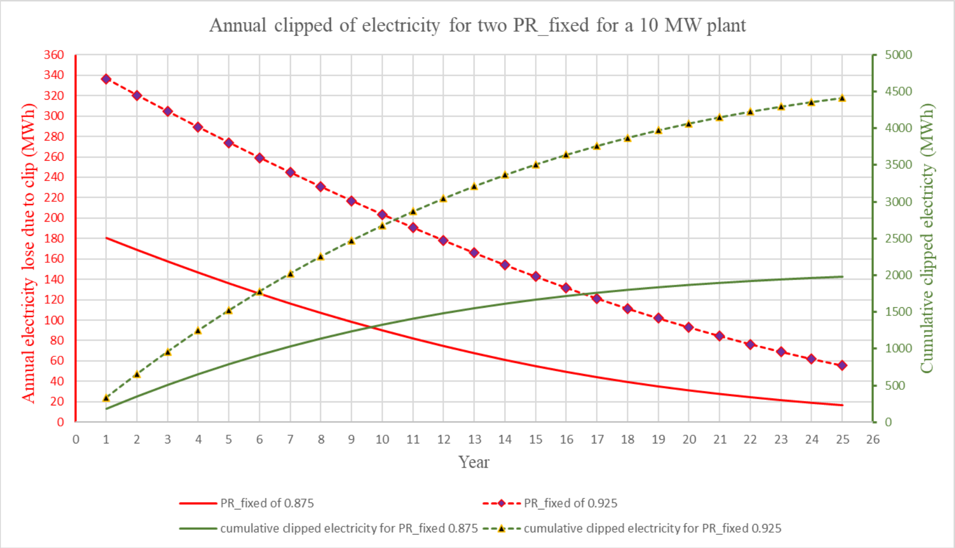


Figure 4.17: Annual clipped of electricity for two PR_{fixed} for a 10 MW plant.

The calculation below is to show the loss of profit for two different optimal ISR for 10 MW plant for GHI case at different PR_{fixed}. The tariff is RM 280 per MWh.

$Loss\ of\ profit\ with\ \ PR\_fixed\ of\ 0.875$

$=Tariff\ price\ *\ Total\ electricity\ loss\ for\ 21\ years(MWh)$

= 280 * 1897

= RM 531,160

$Loss\ of\ profit\ with\ \ PR\_fixed\ of\ 0.925$

$=Tariff\ price\ *\ Total\ electricity\ loss\ for\ 21\ years(MWh)$

= 280 * 2219

= RM 621,320

Eqn. (3.14) and Eqn. (3.15) were implemented to determine the saving for the undersized inverter and net saving from undersized inverter respectively. Table 4.3 shows saving and loss of profit for optimal ISR at different PR_{fixed} for GHI case. The net saving for 50 MW and 100 MW are also listed in Table 4.3.

Table 4.3: The amount of saving and loss of profit for optimal ISR at different PR_{fixed} for GHI case.

Capacity (MW)	PR_{fixed}	PR	Optimal ISR	Saving from undersized inverter (RM in million)	Loss of profit/tariffs (RM in million)	Net saving (RM in million)
				Y21	Y21	Y21
10	0.875	0.786	1.68	2.10	0.53	1.57
	0.925	0.830	1.60	1.95	0.62	1.33
50	0.925	0.831	1.59	7.42	2.42	5.00
100	0.925	0.832	1.58	11.75	3.67	8.08

From Table 4.3, it is found out that the total loss of profit in 21 years is less than the cost saved from the undersized inverter. This has proved the result of using the optimal ISR at minimum LCOE can save more money than the total loss of money due to clipped electricity. Figure 4.18 shows sensitivity analysis due to change of PR for 10 MW, 50 MW and 100 MW respectively. From Figure 4.18, it can be observed that the trend of optimal ISR decreases when PR increases. From Eqn. (3.4), the higher the PR_{fixed}, the higher the PR. The higher the PR, the higher the total electricity yield. When total electricity yield is increased, the total clipped electricity is increased. Therefore, it allows a bigger size of the inverter (lower optimal ISR). This trend also can be used as a reference for any other sites in Malaysia. The higher the PR applied in practical cases, the lower the optimal ISR for that particular site. Similarly to the sensitivity analysis of degradation rates, the industry players can extract the optimal ISR at any PR for the specific capacity of the PV plant. From Eqn. (3.13), the higher the total unclipped electricity yield, the lower the LCOE.

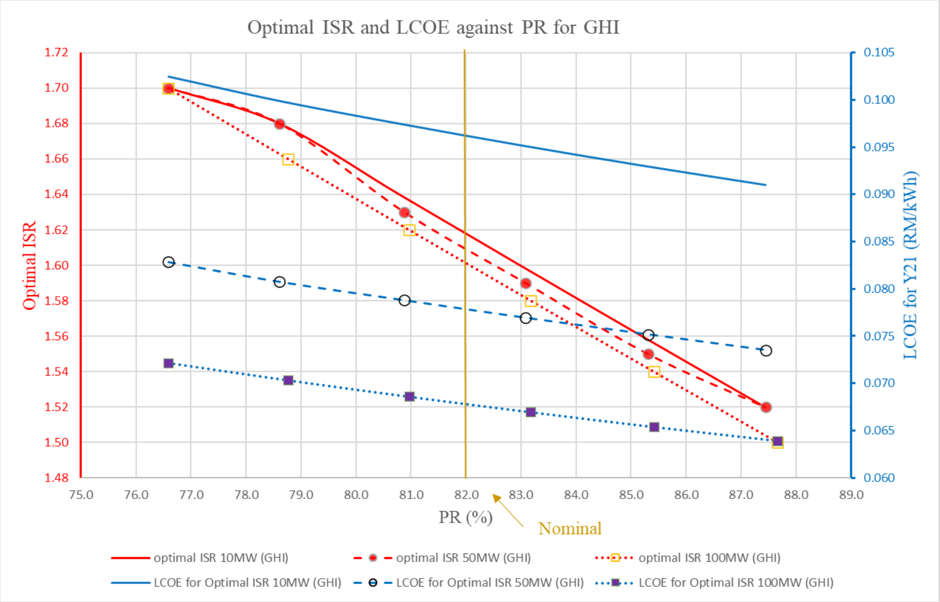


Figure 4.18: Sensitivity analysis due to change of PR for 10 MW, 50 MW and 100 MW.

4.4.3 Sensitivity analysis on operation and maintenance (O & M) cost

In this section, the O & M cost were adjusted in this study to investigate its effect on LCOE and optimal ISR. The saving for the undersized inverter which included clipped electricity and net saving from undersized inverter were determined by using Eqn. (3.14) and Eqn. (3.15) respectively. Table 4.4 shows the saving of the undersized inverter and loss of profit for different PV capacity and O & M cost.

Table 4.4: The saving of the undersized inverter and loss of profit for different PV capacity and O & M cost.

Capacity (MW)	O & M cost (RM/year)	Optimal ISR	Saving which included clipped electricity (RM in million)	Loss of profit/tariffs (RM in million)	Net saving (RM in million)
			Y21	Y21	Y21
10	180,000.00	1.61	1.97	0.63	1.34
50	400,000.00	1.60	7.50	2.46	5.04
100	500,000.00	1.59	11.87	3.72	8.15

Figure 4.19 shows optimal ISR and LCOE against O & M cost. Changing the O & M cost does not affect the amount of clipped electricity or generated electricity. Based on Eqn. (3.13), the higher the O & M cost, the higher the LCOE if the amount of unclipped electricity and capital cost remains constant. The trend of optimal ISR for 100 MW plants does not change at all unlike the trend of optimal ISR for 10 MW and 50 MW plants have slightly changed. Based on Eqn. (3.16), the capital cost for 100 MW is very high since the cost is calculated based on RM per watt. The ratio of O & M cost is a very small portion of the investment. This caused the O & M cost to have less influence on the LCOE. Since the LCOE does not affect much by the O & M cost, the optimal ISR is also not affected much by O & M cost as it is selected based on the lowest LCOE. Industry players can refer to the trend and value of the optimal ISR in Figure 4.19.

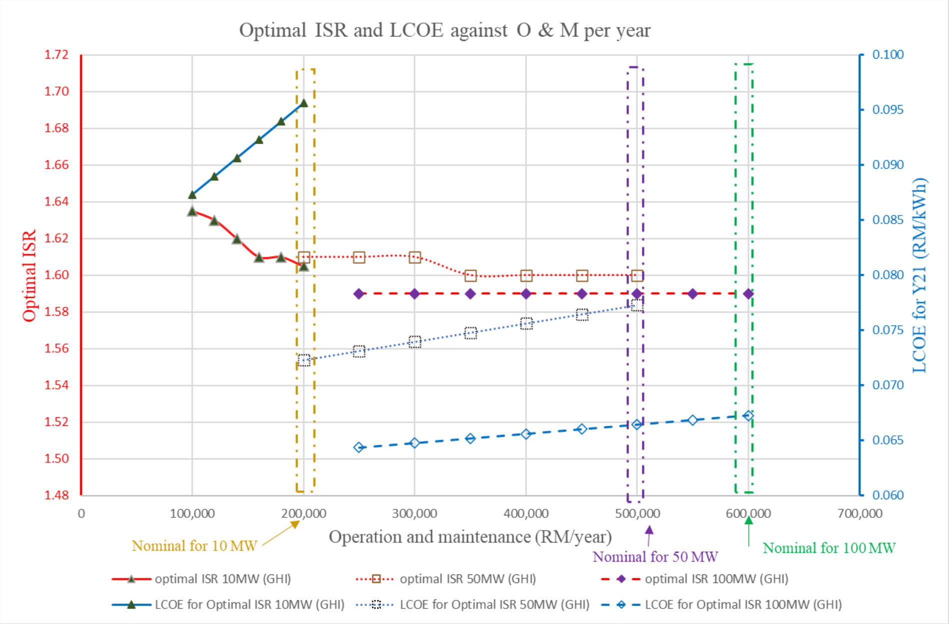


Figure 4.19: Optimal ISR and LCOE against O & M cost.

4.4.4 Sensitivity analysis on specific costs of the PV system and the inverter

4.4.4.1 Specific cost of the PV system with the fixed specific cost of the inverter

In this section, the specific cost of an inverter remains constant and the specific cost of the PV system was adjusted in this study to investigate its effect on LCOE and optimal ISR. The saving for the undersized inverter which included clipped electricity and net saving from undersized inverter were determined by Eqn. (3.14) and Eqn. (3.15) respectively. Table 4.5 shows the amount of saving of the undersized inverter and loss of profit for specific cost of the PV system with the fixed specific cost of the inverter for the GHI case. The result in Table 4.5 has successfully verified that the selected optimal ISR can save more cost than the total loss of money in 21 years.

Table 4.5: The amount of saving of the undersized inverter and loss of profit for specific cost of the PV system with the fixed specific cost of the inverter for GHI case.

Capacity (MW)	Specific cost of the PV system (RM/W)	Optimal ISR	Saving which included clipped electricity (RM in million)	Loss of profit/tariffs (RM in million)	Net saving (RM in million)
			Y21	Y21	Y21
10	2.20	1.605	1.97	0.63	1.34
50	1.90	1.600	7.50	2.46	5.04
100	1.70	1.590	11.87	3.72	8.15

Figure 4.20 shows optimal ISR and LCOE against changing of specific cost of the PV system. Based on Eqn. (3.16), an increment in the specific cost of the PV system causes the capital cost to be increased. Based on Eqn. (3.13), the LCOE at optimal ISR increases as the capital cost increases. Hence, the LCOE at optimal ISR increases as the specific cost of the PV system increases. The optimal ISR is affected as it is chosen at the lowest LCOE. The higher the specific cost of the PV system applied in practical cases, the lower the optimal ISR. The industry players also can extract the value of optimal ISR from Figure 4.20.

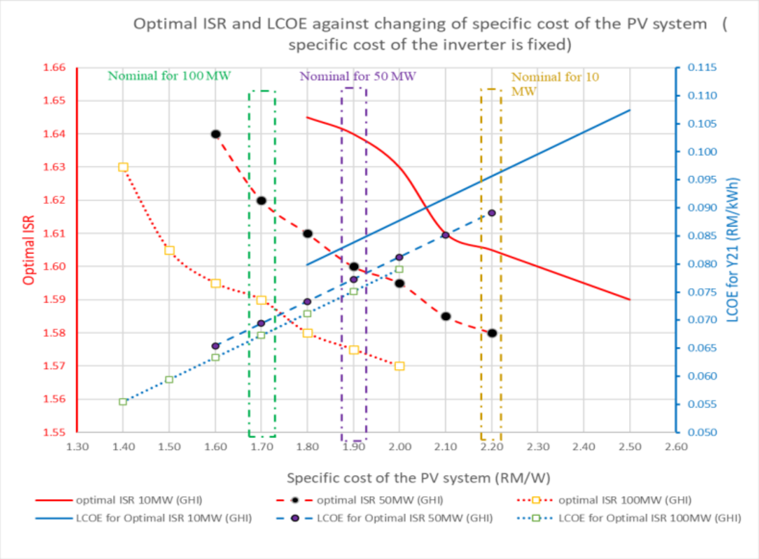


Figure 4.20: Optimal ISR and LCOE against changing of specific cost of the PV system. (Specific cost of inverter is fixed)

4.4.4.2 Specific cost of the PV system change with the specific cost of the inverter.

In this section, the study on the specific cost of the PV system change with the specific cost of the inverter was carried out. The saving for the undersized inverter which included clipped electricity and net saving from undersized inverter were determined by Eqn. (3.14) and Eqn. (3.15) respectively. Table 4.6 shows the saving of the undersized inverter and loss of profit for the specific cost of the PV system change with the specific cost of the inverter for the GHI case. The calculation has shown that the selected optimal ISR is able to save more money than the total loss of money due to clipped electricity in 21 years.

Table 4.6: The saving of the undersized inverter and loss of profit for Specific cost of the PV system change with specific cost of the inverter for GHI case.

Capacity (MW)	Specific cost of the PV system (RM/W)	Specific cost of the inverter (RM/W)	Optimal ISR	Saving which included clipped electricity (RM in	Loss of profit/tariffs (RM in million)	Net saving (RM in million)

				million)		
				Y21	Y21	Y21
10	2.20	0.70	1.67	2.81	0.95	1.86
50	1.90	0.70	1.75	15.00	4.16	10.84
100	1.70	0.60	1.74	25.52	6,75	18.76

Figure 4.21 shows optimal ISR and LCOE against the specific cost of the inverter for the GHI case. From Figure 4.21, it can be seen that the trend of the optimal ISR increases as the inverter price increases. From Eqn. (3.14), the saving of the undersized inverter which included the clipped electricity rises when the specific cost of the inverter rises. Based on Eqn. (3.16), the capital cost rises as the specific cost of the PV system rises. From Eqn. (3.13), the increment of LCOE will happen when the capital cost increases. The optimal ISR is affected by LCOE since it is chosen based on the lowest LCOE. When the specific cost of the inverter is more expensive, it allows higher optimal ISR for saving cost. The investors can refer the Figure 4.21 to obtain the optimal ISR for this sensitivity analysis.

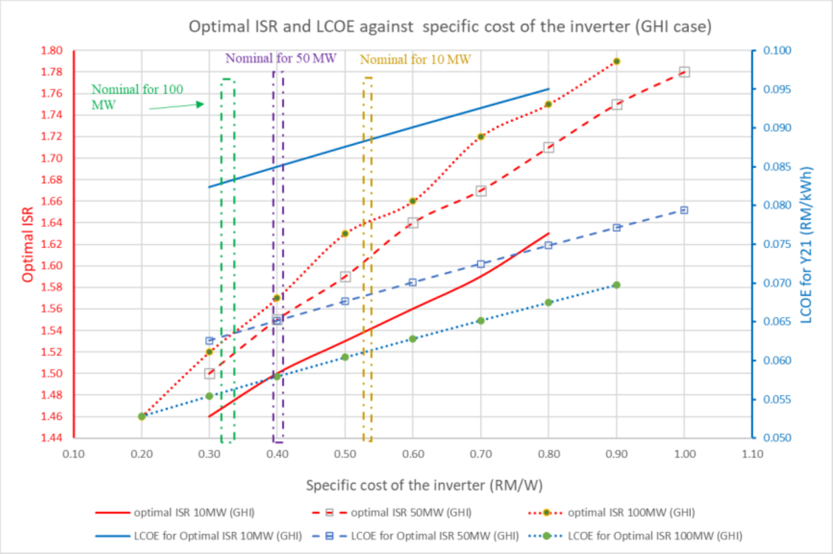


Figure 4.21: Optimal ISR and LCOE against specific cost of the inverter for GHI case.

Figure 4.22 shows optimal ISR and LCOE against the specific cost of the PV system for the GHI case. From Figure 4.22, it can be seen that the trend of optimal ISR increases when the specific cost of the PV system increases. The effect of changing the specific cost of the inverter on the optimal ISR is inverse of the effect of changing the specific cost of the PV system with the fixed specific cost of the inverter on optimal ISR. This can be observed by comparing Figure 4.20 and Figure 4.22.

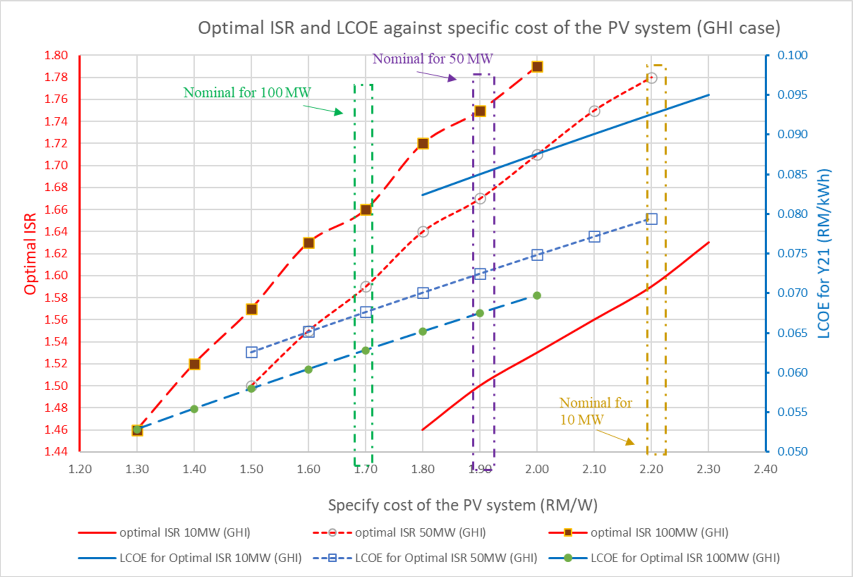


Figure 4.22: Optimal ISR and LCOE against specific cost of the PV system for GHI case.

4.4.4.3 Change of specific cost of the inverter with the fixed specific cost of the PV system

In this section, the study on the change of specific cost of the inverter with the fixed specific cost of the PV system was performed. The Eqn. (3.14) and Eqn. (3.15) were used to calculate the saving for the undersized inverter which included clipped electricity and net saving from undersized inverter respectively. Table 4.7 shows the specific cost of the inverter with the fixed specific cost of the PV system The results have successfully shown that the selected optimal ISR is able to save more cost in 21 years. This can be observed in Table 4.7 as the loss of profit is much less than the net saving cost of the undersized inverter.

Table 4.7: The saving of the undersized inverter and loss of profit for specific cost of the inverter with the fixed specific cost of the PV system for GHI case.

Capacity (MW)	Specific cost of the inverter (RM/W)	Optimal ISR	Saving which included clipped electricity (RM in million)	Loss of profit/tariffs (RM in million)	Net saving (RM in million)
			Y21	Y21	Y21
10	0.50	1.61	1.89	0.58	1.31
50	0.40	1.61	7.58	1.57	6.01
100	0.30	1.59	11.13	2.23	8.90

Figure 4.23 shows optimal ISR and LCOE for the different specific costs of the inverter with the fixed specific cost of the PV system for GHI case. Based on Eqn. (3.14), the saving of the undersized inverter which included the clipped electricity increases as the specific cost of the inverter increases. From Eqn. (3.16), the value of the capital cost is only affected by the saving of the undersized inverter which included the clipped electricity since the specific cost of the PV system remains constant in this section. In this section, the capital cost decreases as the specific cost of the PV system increases unlike in Section 4.4.4.2. Based on Eqn. (3.13), the LCOE decreases as the capital cost decreases. The optimal ISR is affected as it is chosen at the lowest LCOE. When the specific price of the inverter is higher, it allows higher optimal ISR for saving cost. The trend of LCOE decreases as the specific cost of the inverter rises.

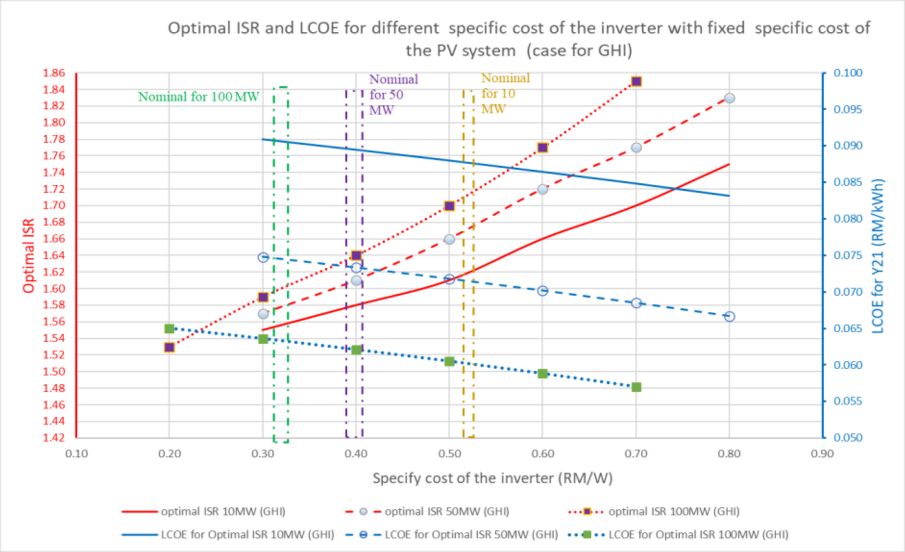


Figure 4.23: Optimal ISR and LCOE for different specific cost of the inverter with fixed specific cost of the PV system for GHI case.

4.5 Comparison of all sensitivity analysis

Sections 4.4.1, 4.4.2 and 4.4.4.1 were compared. Figure 4.24 shows the results for 3 sensitivity analysis for 10 MW. The 3-sensitivity analysis is degradation rate, PR and changing of specific cost of the PV system with the fixed specific cost of the inverter. It can be observed that the trend of optimal ISR increases as the degradation rate increases. The increment of PR caused the optimal ISR to decrease dramatically. The optimal ISR decreases as the specific cost of the PV system with fixed inverter price increases. The case for changing the PR has more influence on optimal ISR as compared to the degradation rate and specific cost of the PV system with the fixed specific cost of the inverter.

From Figure 4.24, the LCOE decreases linearly when the degradation rate increases. The LCOE declines linearly as the specific cost of the PV system with the fixed specific cost of the inverter increases. The LCOE decreases linearly as the PR increases.

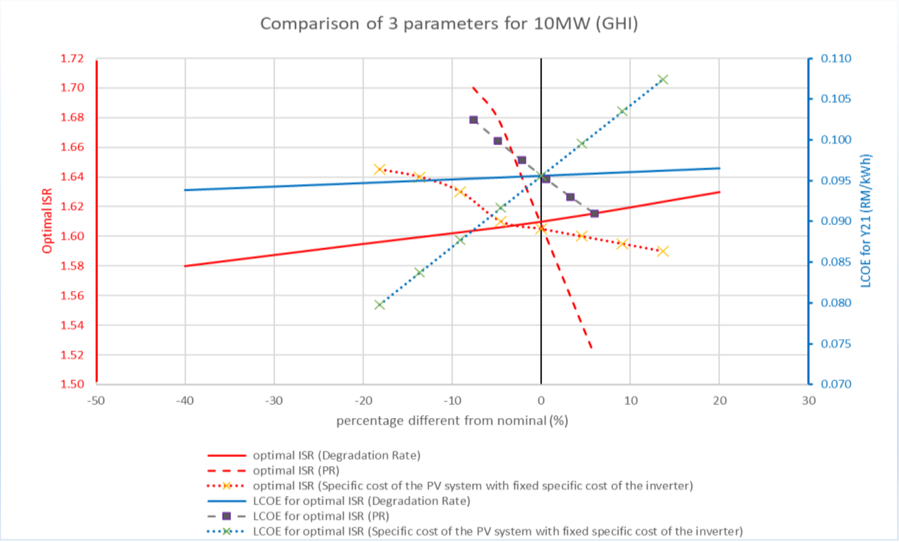


Figure 4.24: The result for degradation rate, PR and change specific cost of the PV system with fixed specific cost of the inverter for 10 MW.

Sections 4.4.3, 4.4.4.2 and 4.4.4.3 were compared. Figure 4.25 shows the results for the other 3 sensitivity analysis for 10 MW. The 3-sensitivity analysis is changed the specific cost of the PV system with the specific cost of the inverter, change the specific cost of the inverter with the fixed specific cost of the PV system and O & M cost. It can be observed that the trend of optimal ISR increases as the nominal value increases for the two cases. The two cases are change the specific cost of the PV system with the specific cost of the inverter and change the specific cost of the inverter with the fixed specific cost of the PV system. The increment of O & M cost caused the optimal ISR to decrease.

Besides that, the LCOE increases linearly when the specific cost of the inverter increases. The LCOE declines linearly as the specific cost of the PV system with the fixed specific cost of the inverter increases. The LCOE increases linearly as the O & M cost increases.

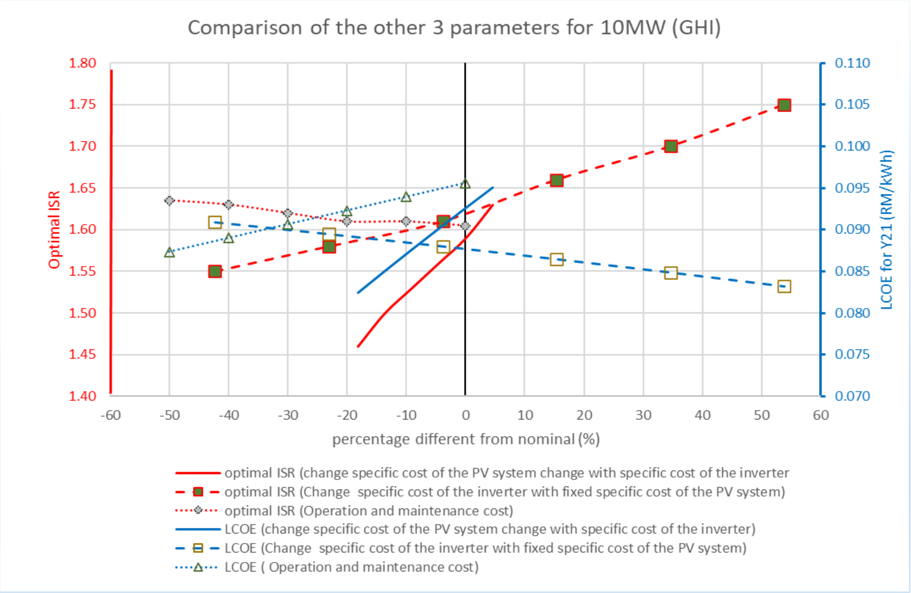


Figure 4.25: The result for change specific cost of the PV system with specific cost of the inverter, change specific cost of the inverter with fixed specific cost of the PV system with and O & M cost for 10 MW.

The industry players can refer to the trend from Figure 4.24 and Figure 4.25 to estimate percentage changes on the optimal ISR and LCOE will be changed if the parameter is different from the nominal value. Moreover, the higher gradient parameter is the item very sensitive to the changes, the industry needs to pay attention. The industry needs to pay attention to the case of changing of the specific cost of the PV system together with the change of the specific cost of the inverter.

4.6 Comparison result on the best and the worst case scenerios

In this section, the parameters were set as the same as Section 3.5 for best and worst-case scenarios. Table 4.8 shows the parameters, optimal ISR and LCOE for the 10 MW plant for the two cases. It can be observed that the optimal ISR at the best-case scenario is much lower than the worst-case scenario. The optimal ISR for the optimistic case is simulated with a low degradation rate and high PR_{fixed} which caused the clipped electricity to be increased. Thus, it allows a smaller size of the inverter (lower optimal ISR). The LCOE for the optimistic case is lesser than the LCOE for the pessimistic case. This is because the amount of unclipped electricity in the pessimistic case is lesser than in the optimistic case. Moreover, the capital cost in the pessimistic case is higher than the optimistic case. From Eqn. (3.13), the LCOE increases as the capital cost increases and the amount of unclipped electricity decreases. In a nutshell, the recommended range of optimal ISR for a 10 MW plant is from 1.50-1.80 in the tropics. The reason for choosing this range is because this project does not take into account of the inflation rate of the currency. The inflation rate of the currency has influence on the optimal ISR. Hence, the recommended range for the optimal ISR is slightly smaller as compared to the range of optimal ISR from 1.44-1.84.

Table 4.8: The parameters, optimal ISR and LCOE for 10 MW plant for the two cases.

Cases	Capital cost (RM in million)	Nominal degradation rate (%/year)	Nominal PR_{fixed}	Specific cost of the PV system (RM/W)	Specific inverter cost (RM/W)	Optimal ISR	LCOE for Y21 (RM/kWh)
Optimistic	16.78	0.30	0.975	1.80	0.30	1.44	0.077
Pessimistic	19.21	0.60	0.850	2.30	0.80	1.84	0.102

4.7 Summary

The summary of the trend on changing the parameters from Section 4.4.1 to 4.4.4.3 on optimal ISR and LCOE can be observed in Table 4.9.

Table 4.9: The effect of changing the parameters on optimal ISR and LCOE for Y21.

Type of parameters	When parameter	Effect on optimal ISR	Effect on LCOE for Y21 (RM/kWh)
Degradation rate	Increased	Increased	Increased
	Decreased	Decreased	Decreased
PR_{fixed}	Increased	Decreased	Decreased
	Decreased	Increased	Increased
Operation and maintenance (O & M) cost	Increased	Decreased	Increased
	Decreased	Increased	Decreased
Specific cost of the PV system with fixed specific cost of inverter	Increased	Decreased	Increased
	Decreased	Increased	Decreased
Specific cost of the PV system changes with specific cost of the inverter.	Increased	Increased	Increased
	Decreased	Decreased	Decreased
Change of specific cost of the inverter with fixed specific cost of the PV system	Increased	Increased	Decreased
	Decreased	Decreased	Increased

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The objectives of this project were achieved. The influence of the sensitivity analysis on optimal inverter sizing ratio (ISR) was investigated. The two cases of sensitivity analysis which is changing the specific cost of the photovoltaic (PV) system with the specific cost of the inverter and the specific cost of the inverter with the fixed specific cost of the PV system has a great influence on the optimal ISR. The analysis shows that the capital cost of a large-scale PV system can be significantly saved using the optimal ISR to downsize the inverter capacity. The advantage of using the optimal ISR is to obtain a higher return of investment and a shorter payback period of the project. All the optimal ISR is assumed can be used for 21 years. The results from this study can give guidelines on choosing the right ISR for the PV industry players while the trend of the lines plotted through the sensitivity analysis can be used as a reference for projects operating in the tropics. The recommended range for the optimal ISR for a 10 MW plant is from 1.50-1.80 in the tropics.

In addition, the influence of using various sampled interval data on the optimal ISR was studied. The sampled intervals do not give a clear change because the data is done sampled out and the solar irradiance distribution profiles are quite the same. Besides achieving the objectives, the averaged method was used to investigate its influence on the optimal ISR. The averaged intervals give a clear change on the optimal ISR because it could not reveal the cases of short and quick changes of the data. Thus, the optimal ISR determined by the averaged method is higher than the optimal ISR determined by the sampled method.

Lastly, the study on the effect of using two types of irradiance data to determine the optimal ISR was studied. The optimal ISR determined by using global tilted irradiance (GTI) data is lower than the optimal ISR determined by using global horizontal irradiance (GHI) data. This is due to the distribution profile issue. Although annual GTI and GHI only differ by 1.85%, the distribution profile is quite different.

5.2 Recommendations for Future Work

Firstly, the landing cost for the PV system can be taken into account in the future study. Moreover, the sensitivity analysis on tariffs can be conducted to study the influence on the net saving of undersized inverter and determine the income.

In addition, the solar irradiance data obtain from the ground-mounted weather station is expensive. Investigation on optimal ISR determined by ground-mounted weather station data for several sites in the tropical area could be studied. There is the possibility of extrapolating the optimal ISR to other sites that do not have high resolution solar irradiance database but the optimal ISR is obtained from the low-resolution database from a trend or relationship for various resolution databases. This can be achieved if more solar irradiance data from the ground-mounted weather station in Malaysia or tropical areas are studied.

REFERENCES

Bellini, E., 2020. *Five bidders set to secure 490 MW in Malaysia's third solar auction*. [online] Available at: <https://www.pv-magazine.com/2020/01/09/five-bidders-set-to-secure-490-mw-in-malaysias-third-solar-auction/> [Accessed 9 April 2021].

Blaabjerg, F., Sangwongwanich, A. and Yang, Y., eds., 2018. *Flexible Power Control of Photovoltaic Systems*. [e-book] Advances in Renewable Energies and Power Technologies. Imene Yahyaoui. Available at: https://doi.org/10.1016/B978-0-12-812959-3.00006-X. [Accessed 30 August 2020].

Chen, S., 2011. Optimum inverter sizing in consideration of irradiance pattern and PV incentives. *2011 Twenty-Sixth Annual IEEE Applied Power Electronics Conference and Exposition: (APEC 2011) ; Fort Worth, Texas, USA, 6 - 11 March 2011.* Piscataway, NJ: IEEE , pp. 982–988.

Chen, S., Li, P., Brady, D. and Lehman, B., 2013. Determining the optimum grid-connected photovoltaic inverter size. *Solar Energy,* [e-journal] 87, pp. 96–116. http://dx.doi.org/10.1016/j.solener.2012.09.012.

David, F. and Robert, M., 2019. *Q1/Q2 2019 Solar Industry Update. [e-book].* <https://www.nrel.gov/docs/fy19osti/74585.pdf>.

Fischer, M., 2020. *ITRPV 11th ed. Apr 2020 report presentation and key findings*. [online]. <https://itrpv.vdma.org/documents/27094228/29066965/ITRPV020200Presentation/eb855894-bbfd-e9fa-b368-592c186986b6> [Accessed 9 June 2020].

Grid Connected PV System. n.d. [online] Available at: <https://www.alternative-energy-tutorials.com/solar-power/grid-connected-pv-system.html>. [Accessed 28 August 2020].

John, W., 2018. *Solar module lifetime predictions are getting better*. [online] Available at: <https://www.pv-magazine.com/2018/12/10/solar-module-lifetime-predictions-are-getting-better/>.[Accessed 10 March 2021].

Kathie, Z., 2018. *Why array oversizing makes financial sense*. [online] Available at: <https://new.abb.com/docs/librariesprovider117/default-document-library/solar-inverters/solar_power_world-article.pdf?sfvrsn=80a7614_4> [Accessed 9 May 2020].

Khatib, T., Yasin, A., Mohammad, A. and Ibrahim, A., 2017. *On the effectiveness of optimally sizing an inverter in a grid-connected photovoltaic power system.* 14th International Conference on Smart Cities: Improving Quality of Life Using ICT & IoT (HONET-ICT), Irbid, 2017, pp. 48-52, doi: 10.1109/HONET.2017.8102220

Lai, K. and Lim, B., 2019a. Optimal Inverter Sizing Ratio For Photovoltaic Power Plants In Malaysia. 11th International Conference on Applied Energy 2019, Västerås, Sweden, 5, paper ID: 774.

Lai, K. and Lim, B., 2019b. Comparative Study for Time-specific Ross Coefficient and Overall Ross Coefficient for Estimation of Photovoltaic Module Temperature. *2019 IEEE Conference on Sustainable Utilization and Development in Engineering and Technologies (CSUDET)* pp. 251–256. http://dx.doi.org/10.1109/CSUDET47057.2019.9214602.

Liew, J., 2018. *Hoping to take a bite at the RM2 billion solar pie*. [online] Available at: https://www.theedgemarkets.com/article/hoping-take-bite-rm2-billion-solar-pie [Accessed 12 April 2021].

Lorente, D. G., Pedrazzi, S., Zini, G., Dalla, R. A. and Tartarini, P., 2014. Mismatch losses in PV power plants. *Solar Energy,* [e-journal] 100, pp. 42–49. http://dx.doi.org/10.1016/j.solener.2013.11.026.

Martin, J., 2020a. *Malaysia eyes pandemic recovery with 1GW new solar tender*. [online] Available at: <https://www.pv-tech.org/malaysia-eyes-pandemic-recovery-with-1gw-new-solar-tender/> [Accessed 12 April 2021].

Martin, S., 2020b. *Module Price Index: July 2020:A new boom, or the same old?* [online] Available at: <https://www.pv-magazine.com/module-price-index/> [Accessed 6 September 2020].

Mermoud, A., 2010. *Modeling Systems Losses in PVsyst.* Institute of the Environmental Sciences Group of energy–PVsyst, Universitè de Genève.

Mostefaoui, M., ed., 2018. *Importance cleaning of PV Modules for Grid-Connected PV Systems in a desert environment.* Piscataway, NJ: IEEE. Available at: Mansouri, Khalifa (HerausgeberIn). <http://ieeexplore.ieee.org/servlet/opac?punumber=8363020>.

Nagar, R. R. and Gidwani, L., 2018. Levelized Cost of Electricity with Degradation of 10 MW Grid-Connected Photovoltaic Power Plant in Kalwakurthy, India. In: *2018 3rd International Innovative Applications of Computational Intelligence on Power, Energy and Controls with their Impact on Humanity (CIPECH).* Ghaziabad, India, 1/11/2018 - 2/11/2018: IEEE, pp. 50–55.

Paiva, G. M., Pimentel, S. P., Marra, E. G. and Alvarenga, B. P., 2017. Analysis of inverter sizing ratio for PV systems considering local climate data in central Brazil. *IET Renewable Power Generation,* [e-journal] 11(11), pp. 1364–1370. http://dx.doi.org/10.1049/iet-rpg.2016.0918.

PV-Manufacturing ., n.d. *Glass-Glass PV module.* [online] Available at: <https://pv-manufacturing.org/glass-glass-modules/#:~:text=Due%20to%20an%20increased%20reliability,85%25%20of%20the%20nameplate%20capacity.> [Accessed 12 April 2021].

Reich, N. H., Mueller, B., Armbruster, A., van Sark, W. G. J. H. M., Kiefer, K. and Reise, C., 2012. Performance ratio revisited: is PR > 90% realistic? *Progress in Photovoltaics: Research and Applications,* [e-journal] 20(6), pp. 717–726. http://dx.doi.org/10.1002/pip.1219.

Salih, S. and Taha, M., 2013. Photovoltaic Modules Simulation with Shading Effect. *Proceeding at center of desert conference.,* University of Anbar- Iraq , [e-journal] 2.

Samaiden, n.d. [online] Available at: <https://samaiden.com.my/renewable-energy/solar-energy/large-scale-solar/>. [Accessed 15 April 2021].

Tawa, H., Saiki, H., Ota, Y., Araki, K., Takamoto, T. and Nishioka, K., 2020. Accurate Output Forecasting Method for Various Photovoltaic Modules Considering Incident Angle and Spectral Change Owing to Atmospheric Parameters and Cloud Conditions. *Applied Sciences*, [e-journal] 10(2), p. 703–703. http://dx.doi.org/10.3390/app10020703.

Tsoutsos, T., Savvakis, N., Kanakis, I., Papadakis, G., Kyriakarakos, G., Schwartz, B., 2011. TEMPERATURE EFFECT ON PV PERFORMANCE EXPERIMENTAL RESULTS FROM A 2.18 KWP THIN FILM PV SYSTEM. 26th Photovoltaic Solar Energy Conference and Exhibition.

Urrejola, E., Antonanzas, J., Ayala, P., Salgado, M., Ramírez-Sagner, G., Cortés, C., Pino, A. and Escobar, R., 2016. Effect of soiling and sunlight exposure on the performance ratio of photovoltaic technologies in Santiago, Chile. *Energy Conversion and Management,* [e-journal] 114, pp. 338–347. http://dx.doi.org/10.1016/j.enconman.2016.02.016.

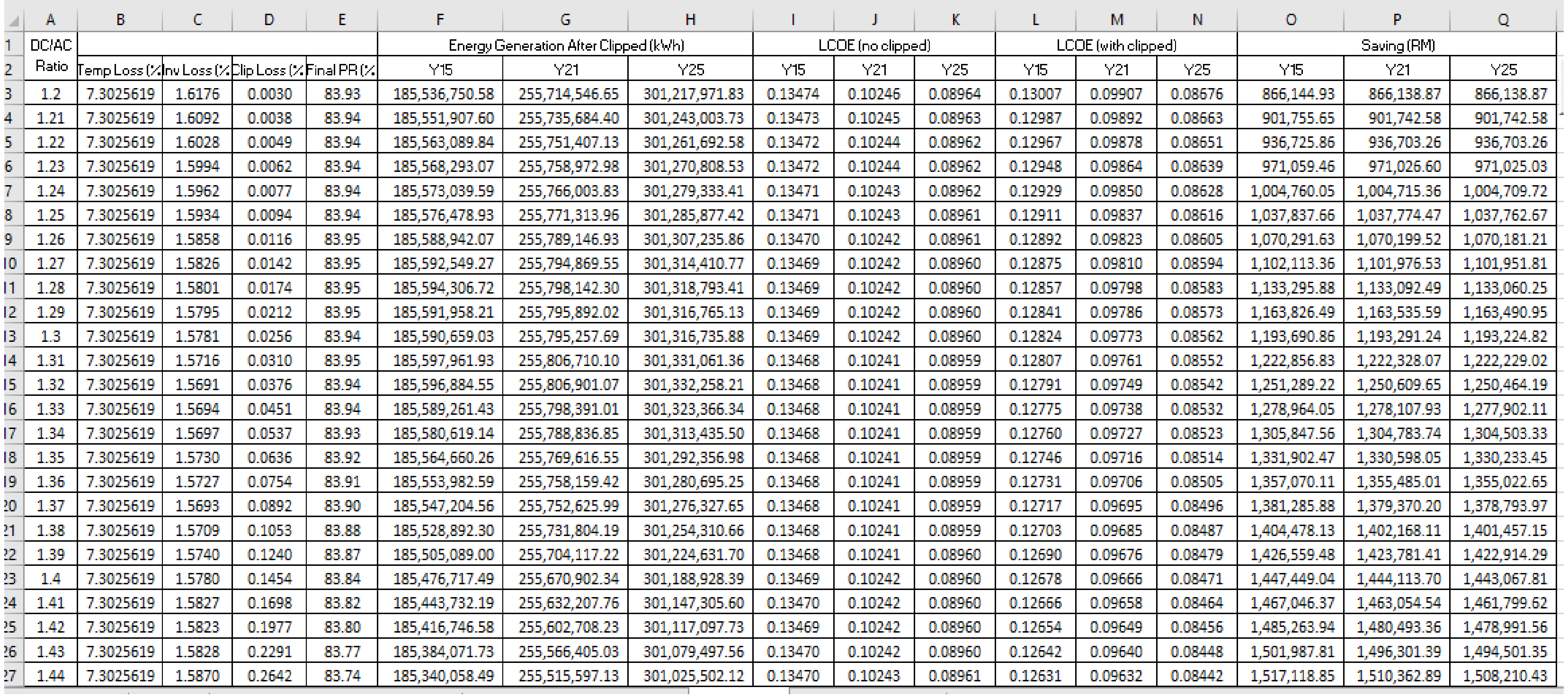
Väisänen, J., Kosonen, A., Ahola, J., Sallinen, T. and Hannula, T., 2019. Optimal sizing ratio of a solar PV inverter for minimizing the levelized cost of electricity in Finnish irradiation conditions. *Solar Energy,* [e-journal] 185, pp. 350–362. http://dx.doi.org/10.1016/j.solener.2019.04.064.

Zhu, J., Bründlinger, R., Mühlberger, T., Betts, T. R. and Gottschalg, R., 2011. Optimised inverter sizing for photovoltaic systems in high-latitude maritime climates. *IET Renewable Power Generation,* [e-journal] 5(1), p. 58–58. http://dx.doi.org/10.1049/iet-rpg.2009.0162.

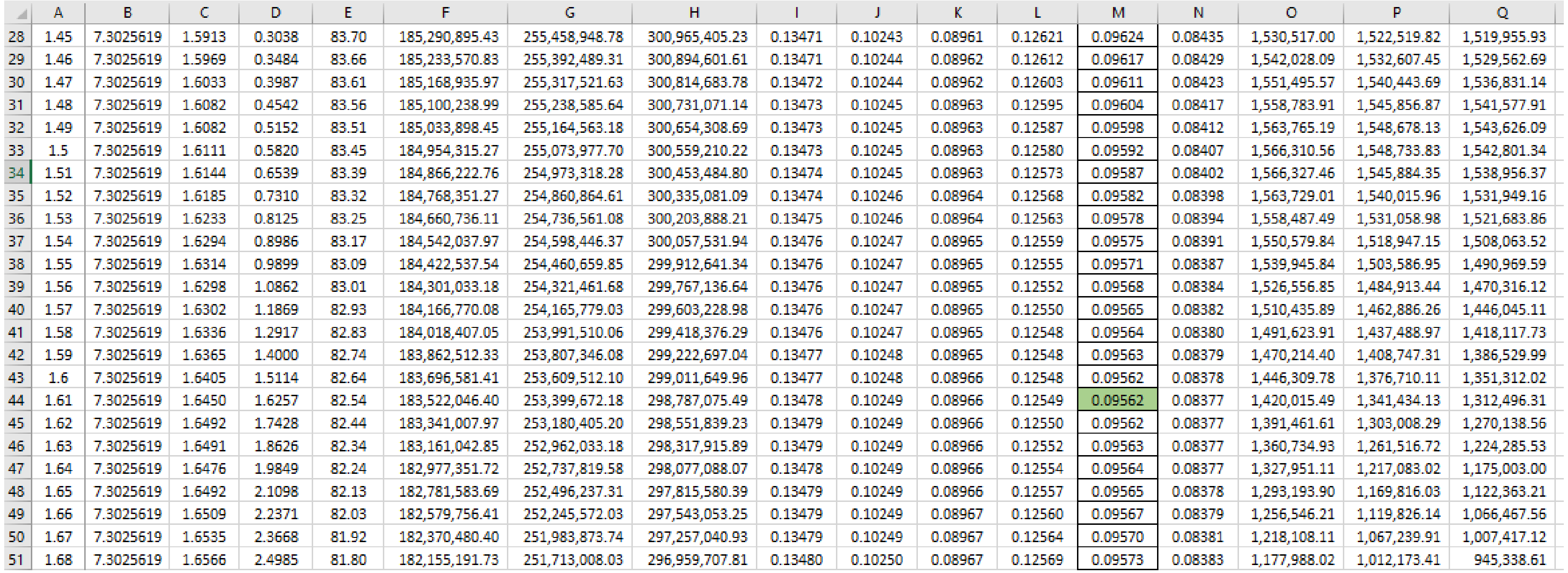
APPENDICES

APPENDIX A: Result from one simulation.

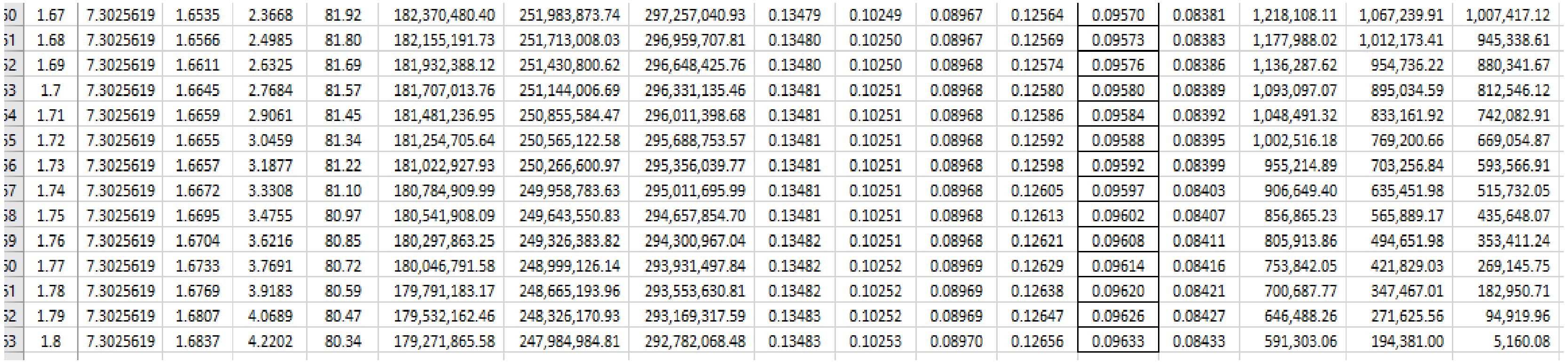
Result for degradation rate of the PV module = 0.50% in Section 4.4.1.



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
1	DC/AC Ratio					Energy Generation After Clipped (kWh)			LCOE (no clipped)			LCOE (with clipped)			Saving (RM)		
2		Temp Loss (%	Inv Loss (%	Clip Loss (%	Final PR (%	Y15	Y21	Y25	Y15	Y21	Y25	Y15	Y21	Y25	Y15	Y21	Y25
3	1.2	7.3025619	1.6176	0.0030	83.93	185,536,750.58	255,714,546.65	301,217,971.83	0.13474	0.10246	0.08964	0.13007	0.09907	0.08676	866,144.93	866,138.87	866,138.87
4	1.21	7.3025619	1.6092	0.0038	83.94	185,551,907.60	255,735,684.40	301,243,003.73	0.13473	0.10245	0.08963	0.12987	0.09892	0.08663	901,755.65	901,742.58	901,742.58
5	1.22	7.3025619	1.6028	0.0049	83.94	185,563,089.84	255,751,407.13	301,261,692.58	0.13472	0.10244	0.08962	0.12967	0.09878	0.08651	936,725.86	936,703.26	936,703.26
6	1.23	7.3025619	1.5994	0.0062	83.94	185,568,293.07	255,758,972.98	301,270,808.53	0.13472	0.10244	0.08962	0.12948	0.09864	0.08639	971,059.46	971,026.60	971,025.03
7	1.24	7.3025619	1.5962	0.0077	83.94	185,573,039.59	255,766,003.83	301,279,333.41	0.13471	0.10243	0.08962	0.12929	0.09850	0.08628	1,004,760.05	1,004,715.36	1,004,709.72
8	1.25	7.3025619	1.5934	0.0094	83.94	185,576,478.93	255,771,313.96	301,285,877.42	0.13471	0.10243	0.08961	0.12911	0.09837	0.08616	1,037,837.66	1,037,774.47	1,037,762.67
9	1.26	7.3025619	1.5858	0.0116	83.95	185,588,942.07	255,789,146.93	301,307,235.86	0.13470	0.10242	0.08961	0.12892	0.09823	0.08605	1,070,291.63	1,070,199.52	1,070,181.21
10	1.27	7.3025619	1.5826	0.0142	83.95	185,592,549.27	255,794,869.55	301,314,410.77	0.13469	0.10242	0.08960	0.12875	0.09810	0.08594	1,102,113.36	1,101,976.53	1,101,951.81
11	1.28	7.3025619	1.5801	0.0174	83.95	185,594,306.72	255,798,142.30	301,318,793.41	0.13469	0.10242	0.08960	0.12857	0.09798	0.08583	1,133,295.88	1,133,092.49	1,133,060.25
12	1.29	7.3025619	1.5795	0.0212	83.95	185,591,958.21	255,795,892.02	301,316,765.13	0.13469	0.10242	0.08960	0.12841	0.09786	0.08573	1,163,826.49	1,163,535.59	1,163,490.95
13	1.3	7.3025619	1.5781	0.0256	83.94	185,590,659.03	255,795,257.69	301,316,735.88	0.13469	0.10242	0.08960	0.12824	0.09773	0.08562	1,193,690.86	1,193,291.24	1,193,224.82
14	1.31	7.3025619	1.5716	0.0310	83.95	185,597,961.93	255,806,710.10	301,331,061.36	0.13468	0.10241	0.08959	0.12807	0.09761	0.08552	1,222,856.83	1,222,328.07	1,222,229.02
15	1.32	7.3025619	1.5691	0.0376	83.94	185,596,884.55	255,806,901.07	301,332,258.21	0.13468	0.10241	0.08959	0.12791	0.09749	0.08542	1,251,289.22	1,250,609.65	1,250,464.19
16	1.33	7.3025619	1.5694	0.0451	83.94	185,589,261.43	255,798,391.01	301,323,366.34	0.13468	0.10241	0.08959	0.12775	0.09738	0.08532	1,278,964.05	1,278,107.93	1,277,902.11
17	1.34	7.3025619	1.5697	0.0537	83.93	185,580,619.14	255,788,836.85	301,313,435.50	0.13468	0.10241	0.08959	0.12760	0.09727	0.08523	1,305,847.56	1,304,783.74	1,304,503.33
18	1.35	7.3025619	1.5730	0.0636	83.92	185,564,660.26	255,769,616.55	301,292,356.98	0.13468	0.10241	0.08959	0.12746	0.09716	0.08514	1,331,902.47	1,330,598.05	1,330,233.45
19	1.36	7.3025619	1.5727	0.0754	83.91	185,553,982.59	255,758,159.42	301,280,695.25	0.13468	0.10241	0.08959	0.12731	0.09706	0.08505	1,357,070.11	1,355,485.01	1,355,022.65
20	1.37	7.3025619	1.5693	0.0892	83.90	185,547,204.56	255,752,625.99	301,276,327.65	0.13468	0.10241	0.08959	0.12717	0.09695	0.08496	1,381,285.88	1,379,370.20	1,378,793.97
21	1.38	7.3025619	1.5709	0.1053	83.88	185,528,892.30	255,731,804.19	301,254,310.66	0.13468	0.10241	0.08959	0.12703	0.09685	0.08487	1,404,478.13	1,402,168.11	1,401,457.15
22	1.39	7.3025619	1.5740	0.1240	83.87	185,505,089.00	255,704,117.22	301,224,631.70	0.13468	0.10241	0.08960	0.12690	0.09676	0.08479	1,426,559.48	1,423,781.41	1,422,914.29
23	1.4	7.3025619	1.5780	0.1454	83.84	185,476,717.49	255,670,902.34	301,188,928.39	0.13469	0.10242	0.08960	0.12678	0.09666	0.08471	1,447,449.04	1,444,113.70	1,443,067.81
24	1.41	7.3025619	1.5827	0.1698	83.82	185,443,732.19	255,632,207.76	301,147,305.60	0.13470	0.10242	0.08960	0.12666	0.09658	0.08464	1,467,046.37	1,463,054.54	1,461,799.62
25	1.42	7.3025619	1.5823	0.1977	83.80	185,416,746.58	255,602,708.23	301,117,097.73	0.13469	0.10242	0.08960	0.12654	0.09649	0.08456	1,485,263.94	1,480,493.36	1,478,991.56
26	1.43	7.3025619	1.5828	0.2291	83.77	185,384,071.73	255,566,405.03	301,079,497.56	0.13470	0.10242	0.08960	0.12642	0.09640	0.08448	1,501,987.81	1,496,301.39	1,494,501.35
27	1.44	7.3025619	1.5870	0.2642	83.74	185,340,058.49	255,515,597.13	301,025,502.12	0.13470	0.10243	0.08961	0.12631	0.09632	0.08442	1,517,118.85	1,510,362.89	1,508,210.43



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
28	1.45	7.3025619	1.5913	0.3038	83.70	185,290,895.43	255,458,948.78	300,965,405.23	0.13471	0.10243	0.08961	0.12621	0.09624	0.08435	1,530,517.00	1,522,519.82	1,519,955.93
29	1.46	7.3025619	1.5969	0.3484	83.66	185,233,570.83	255,392,489.31	300,894,601.61	0.13471	0.10244	0.08962	0.12612	0.09617	0.08429	1,542,028.09	1,532,607.45	1,529,562.69
30	1.47	7.3025619	1.6033	0.3987	83.61	185,168,935.97	255,317,521.63	300,814,683.78	0.13472	0.10244	0.08962	0.12603	0.09611	0.08423	1,551,495.57	1,540,443.69	1,536,831.14
31	1.48	7.3025619	1.6082	0.4542	83.56	185,100,238.99	255,238,585.64	300,731,071.14	0.13473	0.10245	0.08963	0.12595	0.09604	0.08417	1,558,783.91	1,545,856.87	1,541,577.91
32	1.49	7.3025619	1.6082	0.5152	83.51	185,033,898.45	255,164,563.18	300,654,308.69	0.13473	0.10245	0.08963	0.12587	0.09598	0.08412	1,563,765.19	1,548,678.13	1,543,626.09
33	1.5	7.3025619	1.6111	0.5820	83.45	184,954,315.27	255,073,977.70	300,559,210.22	0.13473	0.10245	0.08963	0.12580	0.09592	0.08407	1,566,310.56	1,548,733.83	1,542,801.34
34	1.51	7.3025619	1.6144	0.6539	83.39	184,866,222.76	254,973,318.28	300,453,484.80	0.13474	0.10245	0.08963	0.12573	0.09587	0.08402	1,566,327.46	1,545,884.35	1,538,956.37
35	1.52	7.3025619	1.6185	0.7310	83.32	184,768,351.27	254,860,864.61	300,335,081.09	0.13474	0.10246	0.08964	0.12568	0.09582	0.08398	1,563,729.01	1,540,015.96	1,531,949.16
36	1.53	7.3025619	1.6233	0.8125	83.25	184,660,736.11	254,736,561.08	300,203,888.21	0.13475	0.10246	0.08964	0.12563	0.09578	0.08394	1,558,487.49	1,531,058.98	1,521,683.86
37	1.54	7.3025619	1.6294	0.8986	83.17	184,542,037.97	254,598,446.37	300,057,531.94	0.13476	0.10247	0.08965	0.12559	0.09575	0.08391	1,550,579.84	1,518,947.15	1,508,063.52
38	1.55	7.3025619	1.6314	0.9899	83.09	184,422,537.54	254,460,659.85	299,912,641.34	0.13476	0.10247	0.08965	0.12555	0.09571	0.08387	1,539,945.84	1,503,586.95	1,490,969.59
39	1.56	7.3025619	1.6298	1.0862	83.01	184,301,033.18	254,321,461.68	299,767,136.64	0.13476	0.10247	0.08965	0.12552	0.09568	0.08384	1,526,556.85	1,484,913.44	1,470,316.12
40	1.57	7.3025619	1.6302	1.1869	82.93	184,166,770.08	254,165,779.03	299,603,228.98	0.13476	0.10247	0.08965	0.12550	0.09565	0.08382	1,510,435.89	1,462,886.26	1,446,045.11
41	1.58	7.3025619	1.6336	1.2917	82.83	184,018,407.05	253,991,510.06	299,418,376.29	0.13476	0.10247	0.08965	0.12548	0.09564	0.08380	1,491,623.91	1,437,488.97	1,418,117.73
42	1.59	7.3025619	1.6365	1.4000	82.74	183,862,512.33	253,807,346.08	299,222,697.04	0.13477	0.10248	0.08965	0.12548	0.09563	0.08379	1,470,214.40	1,408,747.31	1,386,529.99
43	1.6	7.3025619	1.6405	1.5114	82.64	183,696,581.41	253,609,512.10	299,011,649.96	0.13477	0.10248	0.08966	0.12548	0.09562	0.08378	1,446,309.78	1,376,710.11	1,351,312.02
44	1.61	7.3025619	1.6450	1.6257	82.54	183,522,046.40	253,399,672.18	298,787,075.49	0.13478	0.10249	0.08966	0.12549	0.09562	0.08377	1,420,015.49	1,341,434.13	1,312,496.31
45	1.62	7.3025619	1.6492	1.7428	82.44	183,341,007.97	253,180,405.20	298,551,839.23	0.13479	0.10249	0.08966	0.12550	0.09562	0.08377	1,391,461.61	1,303,008.29	1,270,138.56
46	1.63	7.3025619	1.6491	1.8626	82.34	183,161,042.85	252,962,033.18	298,317,915.89	0.13479	0.10249	0.08966	0.12552	0.09563	0.08377	1,360,734.93	1,261,516.72	1,224,285.53
47	1.64	7.3025619	1.6476	1.9849	82.24	182,977,351.72	252,737,819.58	298,077,088.07	0.13478	0.10249	0.08966	0.12554	0.09564	0.08377	1,327,951.11	1,217,083.02	1,175,003.00
48	1.65	7.3025619	1.6492	2.1098	82.13	182,781,583.69	252,496,237.31	297,815,580.39	0.13479	0.10249	0.08966	0.12557	0.09565	0.08378	1,293,193.90	1,169,816.03	1,122,363.21
49	1.66	7.3025619	1.6509	2.2371	82.03	182,579,756.41	252,245,572.03	297,543,053.25	0.13479	0.10249	0.08967	0.12560	0.09567	0.08379	1,256,546.21	1,119,826.14	1,066,467.56
50	1.67	7.3025619	1.6535	2.3668	81.92	182,370,480.40	251,983,873.74	297,257,040.93	0.13479	0.10249	0.08967	0.12564	0.09570	0.08381	1,218,108.11	1,067,239.91	1,007,417.12
51	1.68	7.3025619	1.6566	2.4985	81.80	182,155,191.73	251,713,008.03	296,959,707.81	0.13480	0.10250	0.08967	0.12569	0.09573	0.08383	1,177,988.02	1,012,173.41	945,338.61



50	1.67	7.3025619	1.6535	2.3668	81.92	182,370,480.40	251,983,873.74	297,257,040.93	0.13479	0.10249	0.08967	0.12564	0.09570	0.08381	1,218,108.11	1,067,239.91	1,007,417.12
51	1.68	7.3025619	1.6566	2.4985	81.80	182,155,191.73	251,713,008.03	296,959,707.81	0.13480	0.10250	0.08967	0.12569	0.09573	0.08383	1,177,988.02	1,012,173.41	945,338.61
52	1.69	7.3025619	1.6611	2.6325	81.69	181,932,388.12	251,430,800.62	296,648,425.76	0.13480	0.10250	0.08968	0.12574	0.09576	0.08386	1,136,287.62	954,736.22	880,341.67
53	1.7	7.3025619	1.6645	2.7684	81.57	181,707,013.76	251,144,006.69	296,331,135.46	0.13481	0.10251	0.08968	0.12580	0.09580	0.08389	1,093,097.07	895,034.59	812,546.12
54	1.71	7.3025619	1.6659	2.9061	81.45	181,481,236.95	250,855,584.47	296,011,398.68	0.13481	0.10251	0.08968	0.12586	0.09584	0.08392	1,048,491.32	833,161.92	742,082.91
55	1.72	7.3025619	1.6655	3.0459	81.34	181,254,705.64	250,565,122.58	295,688,753.57	0.13481	0.10251	0.08968	0.12592	0.09588	0.08395	1,002,516.18	769,200.66	669,054.87
56	1.73	7.3025619	1.6657	3.1877	81.22	181,022,927.93	250,266,600.97	295,356,039.77	0.13481	0.10251	0.08968	0.12598	0.09592	0.08399	955,214.89	703,256.84	593,566.91
57	1.74	7.3025619	1.6672	3.3308	81.10	180,784,909.99	249,958,783.63	295,011,695.99	0.13481	0.10251	0.08968	0.12605	0.09597	0.08403	906,649.40	635,451.98	515,732.05
58	1.75	7.3025619	1.6695	3.4755	80.97	180,541,908.09	249,643,550.83	294,657,854.70	0.13481	0.10251	0.08968	0.12613	0.09602	0.08407	856,865.23	565,889.17	435,648.07
59	1.76	7.3025619	1.6704	3.6216	80.85	180,297,863.25	249,326,383.82	294,300,967.04	0.13482	0.10251	0.08968	0.12621	0.09608	0.08411	805,913.86	494,651.98	353,411.24
60	1.77	7.3025619	1.6733	3.7691	80.72	180,046,791.58	248,999,126.14	293,931,497.84	0.13482	0.10252	0.08969	0.12629	0.09614	0.08416	753,842.05	421,829.03	269,145.75
61	1.78	7.3025619	1.6769	3.9183	80.59	179,791,183.17	248,665,193.96	293,553,630.81	0.13482	0.10252	0.08969	0.12638	0.09620	0.08421	700,687.77	347,467.01	182,950.71
62	1.79	7.3025619	1.6807	4.0689	80.47	179,532,162.46	248,326,170.93	293,169,317.59	0.13483	0.10252	0.08969	0.12647	0.09626	0.08427	646,488.26	271,625.56	94,919.96
63	1.8	7.3025619	1.6837	4.2202	80.34	179,271,865.58	247,984,984.81	292,782,068.48	0.13483	0.10253	0.08970	0.12656	0.09633	0.08433	591,303.06	194,381.00	5,160.08