Master Level Thesis

European Solar Engineering School

No. 269, September 2020

Optimal Pitch Distance and Tilt Angle of PV Power Plant for Different Climate

Master thesis 15 credits, 2020
Solar Energy Engineering

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Course Code : EG3022

Examination date : 11 Sep 2020

ESES
EUROPEAN SOLAR
ENGINEERING SCHOOL

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Solar Energy Research Center

HÖGSKOLAN
DALARNA

MASTER THESIS

Dalarna University
Solar Energy
Engineering

Abstract

Finding the optimum inter-row spacing and installation tilt for tilted or ground mounted PV systems is a big issue in designing the large-scale PV systems. Increasing the array spacing leads to higher annual generated energy because of the reduced impact of row-shading, but on the other hand, it increases costs of land purchase/lease and wiring costs. Many compromises between performance and cost should be done to design an optimum large-scaled solar plant. One of the criteria in designing of solar power plants is reducing of LCOE, which reflects the cost of every unit of generated energy. Site locations have large impacts on the optimal design of pitch distance and title angles, but such impacts have not been studied extensively in the existing studies, so it is going to bridge this research gap in this thesis.

The main purpose of this research is to investigate the impact of climate conditions on the pitch distance and tilt angle for large-scale PV plant and finding the optimal pitch distance and tilt according to the least cost of production. The impact of climate and meteorological data on the self-shading loss and yield of energy are investigated through a simulation tool, which is PVsyst software here, in different tilt angles and distances between rows. The different climates can be considered by choosing site locations in different latitudes to cover all climate zones. Six cities in temperate climate, three cities in tropic climate and one city in polar climate have been selected. LCOE minimizing is a measure in finding the optimum tilt and pitch distance for a 1 MW solar system installed in different latitudes. In this study the type, size and cost of components have been assumed constant in different climate conditions. There is a wide range of variability in some economic indicators like interest rate and discount rate as well as the cost of land in different climates or even countries in the same climate; then to highlight the impacts of climate conditions on the optimal tilt and pitch distance, these parameters were assumed to be constant in this study.

The results show the optimal tilt of angles increases with getting far of equator in a range between 0° and 40° to capture more direct sunlight, and the optimal raw spacing grows in further locations to equator in a range between 4 m to 11 m to reduce self- shading loss. Moreover, the best module configuration for PV arrays (portrait or landscape) can be different in different climates.

Acknowledgment

Thanks God, the merciful, and the passionate, for giving us the strength, knowledge, ability, and opportunity to undertake this research study and complete it satisfactorily. We would like to thank our supervisor, Dr. Pei Huang, for his consistent support and guidance during the running of this project and his thoughtful comments and recommendations on this dissertation. Furthermore, we are grateful for the effort of all the teachers and staff in the Solar Energy Engineering Department at Dalarna University. Finally, we would like to thank our families for supporting us during the compilation of this dissertation.

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Abbreviations

Abbreviation	Description
LCOE	Levelized Cost of Electricity
PV	Photovoltaic
PVSyst	Photovoltaic system simulation software
NMOT	Nominal Module Operating Temperature
PSO	Particle Swarm Optimization
PSH	Peak Sun Hour
GTI	Global Tilted Irradiation/Irradiance
PR	Performance Ratio
STC	Standard Test Conditions
N	Northern hemisphere
S	Southern hemisphere
CEC	California Energy Commission efficiency
No.	Number
MPP	Maximum Power Point
MPPT	Maximum Power Point Tracker

Nomenclature

Symbol	Description	Unit
P_{max}	Maximum power	kW
V_{mpp}	Maximum power voltage	V
I_{mpp}	Maximum power current	A
V_{oc}	Open-circuit voltage	V
I_{sc}	Short-circuit current	A
V_{dcr}	Rated DC input voltage	V
$P_{MPPT,max}$	Maximum DC input power for each MPPT	kW
$V_{MPPT,min}$	Minimum MPPT input DC voltage	V
$V_{MPPT,max}$	Maximum MPPT input DC voltage	V
I_{in}	Input current maximum	A
$I_{ac,max}$	Maximum AC output current	A
2-P	2 modules in portrait	-
2-L	2 modules in landscape	-
3-L	3 modules in landscape	-
$V_{MAX\ (INV,\ DC)}$	Maximum voltage at the inverter input	V
$V_{INV,\ DC\ TURN\text{-}OFF}$	Inverter DC turn-off voltage	V
$V_{OC(MODULE)max}$	Maximum VOC in the coldest daytime temperature	V
N_{max}	Maximum number of modules	-
N_{min}	Minimum number of modules	-
$V_{MPP(MODULE)min}$	Minimum MPP module voltage	V
$I_{sc,module}$	Short circuit current of module	A
$I_{max\ input,\ inverter}$	Maximum input current of inverter	A

1 Introduction

Solar energy is becoming more popular as a source of energy in the world, because unlike the fossil fuels, it is an unlimited source of energy which helps to reduce greenhouse emissions [1]. The collection of sun energy is free, and it just needs to invest for required equipment which convert the solar energy to electricity [1]. A photovoltaic power station is a large-scale PV system designed to supply merchant power into the electricity grid [2]. Unlike building-mounted and other decentralized solar PV applications, they supply power at the utility level [2].

Finding the optimum inter-row spacing for tilted or ground mounted PV systems is a big issue in designing the large-scale PV systems. Increasing the array spacing leads to higher annual generated energy because of the reduced impact of row-shading, but on the other hand, it increases costs of land purchase/lease and wiring costs [3]. Selection the best tilt and orientation to install the modules results in higher yield of energy. Another important issue in designing of PV arrays is finding the optimum tilt angle. The tilt which panels produce the maximum amount of energy vary in different locations and times of the year. In fixed structures of solar systems, selecting a tilt which gives higher yield of energy, would be effective. Moreover, changing the tilt angle vary the row-shading loss too.

Reducing the levelized cost of electricity (LCOE) is purposed for finding the optimal tilt angle and distance between rows. While using higher efficiency technologies are costly, but they need smaller area [3] in comparison with less efficient modules to produce the same amount of energy. Considering the cost of the land, a well-designed solar plant can decrease the LCOE. It should be noticed that the designing a PV plant with the aim of decreasing the initial investment can result in higher maintenance and lost revenue due to lower yield of energy in future. As a result, it is a skill of plant designer to make compromises between efficient system and reasonable cost [4]

Design graphs are developed and presented as a means of visualizing the sensitivity of designed system. There are some potential applications of the design graphs. They help designers to design an optimized PV system based on the introduced pitch distance and title angle in different climates. They help people understand the impacts of location on the optimal pitch distance and tilt angles.

The main purpose of this research is to investigate the impact of climate conditions on the optimal pitch distance and tilt angle for large-scale PV plant with taking into consideration the influence of land cost. The different climates can be considered by choosing many latitudes to cover all climate zones. A 3D graph will be introduced as a result of this study. The dimensions of the 3D graph will be pitch, tilt and production cost, and every tilt and pitch distance which give the minimum cost of production will be proposed. This graph can be used to find the optimal tilt angle, and pitch distance for site location to according to a lowest LCOE.

1.1 Aim

A 1 MW system would be designed with the same geometric shape in different locations. For each location, the pitch distance and tilt should be optimized according to the least cost of production. The outcome of this research is a design graph which shows relation between LCOE, and optimal pitch distance and tilt in different climates.

The aims of this master thesis can be summarized in the following points:

- To investigate the impact of climates conditions on PV array structures.
- To optimize the pitch distance and tilt angle according to a least-cost production.

- To produce 3D graph can present LCOE against to a pitch distance and tilt tangle and show the optimal pitch distance and tilt angle according to least LCOE.

These three points form the goal and target of this research which have to be achieved. Where these objectives contribute and facilitate for designers to find out the impact of climate conditions on PV array structures through getting the optimal design according to a tilt angle and a pitch distance for achieving competitive renewable-energy price through lowest LCOE.

1.2 Method

The information resources include datasheets of selected equipment (Module, Inverter…), the solar radiation map, the weather data, the geographical maps etc. The most common tools for designing a solar system are PVsyst, Helioscope, Homer Pro…and the Excel program can be used for economic calculation.

In this study the type, size and cost of components will be considered constant in different climate conditions. There is a wide range of variability in some economic indicators like interest rate and discount rate as well as the cost of land in different climates or even countries in the same climate; then to highlight the impacts of climate conditions on the optimal tilt and pitch distance, these parameters were assumed to be constant in this study.

Figure 1.1 illustrates the flowchart of the full methodology, this flowchart can be divided into three different steps:

- Step 1: PVsyst is used to get the required parameters of PV power plant like annual yield, array area, and numbers of modules and inverters. These parameters are the inputs of the LCOE equation which are related to the PV power plant structure.
- Step 2: The economic indicators like interest rate are crossed with the PV plant´s parameter, from step 1, are used as variables of the LCOE equation. Excel is implemented to calculate the LCOE equation, through these calculations, the outputs of step 2 are managed and arranged into tables to preparing for step 3.
- Step 3: MATLAB is used to simulate the outputs of step 2, where the outputs are processed and drawn to produce the 3D graph which shows the LCOE variations against to tilt angle and pitch distance and the least LCOE are highlighted by different color according to optimal tilt angle and pitch distance.

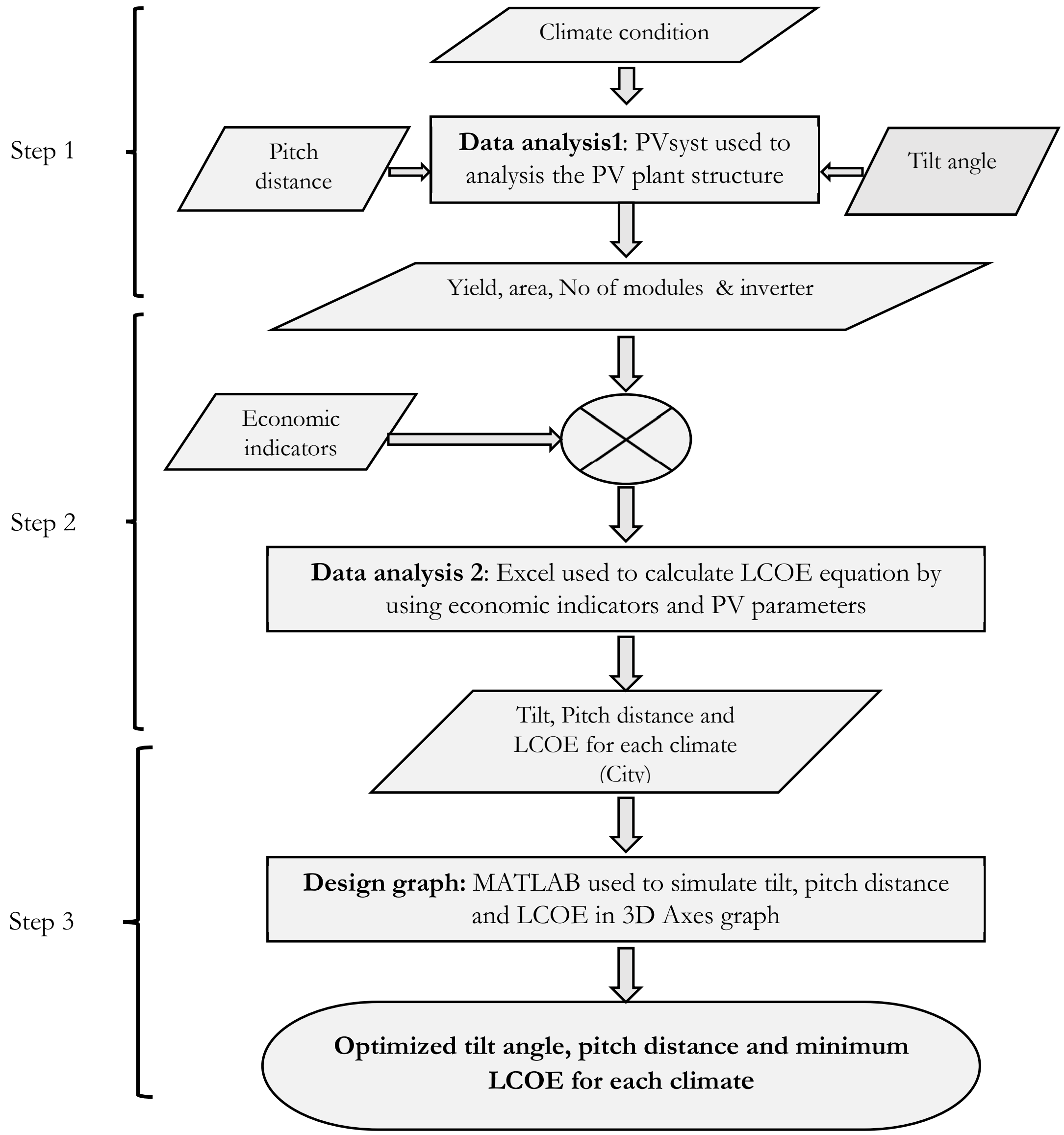


Figure 1.1 Flowchart methodology

The workplace of the study will be the main crucial variation in this research. The selected areas are the key figure for the objective of studying, where the final target of the research is to get the optimal pitch distance and tilt according to the climate.

There are three climate zones which should be considered in this research [5]:

- **Tropic zones** extend from the equator north to the tropic of Cancer at 23.5° north to the tropic of Capricorn at 23.5° south. This is a region of generally warm temperatures and lush tropical vegetation.
- **Temperate zones** extend from the tropics of Cancer and Capricorn to the arctic and antarctic circles, which are located at 66.5° north and south latitude respectively. These regions experience moderate temperatures and large temperature variations. The summers are hot and the winters cool.
- **Polar zones** extend from the arctic and antarctic circles to the poles. In these regions, temperatures are cold and vegetation sparse.

Latitudes between 23.55° and 23.5° N are called the tropics. Latitudes between 23.5° and 66.5° N/S are the temperate zones and between 66.5° and 90° N/S are the arctic (and antarctic) zones [6].

1.3 Previous work

Shading is considered as one of the major loss in photovoltaic energy generation [7]. The effects of mutual shading have been discussed as an important parameter in several studies. Volker et al. calculated the shading losses for standard and optimized photovoltaic modules [8]. The used method was changing the cell interconnections to increase the energy yield. It was concluded that using the optimized modules, the energy yield at the same area increased by 50 %.

Particle Swarm Optimization (PSO), as an optimization algorithm, has used for the design optimization of photovoltaic grid-connected systems [9]. The variables were the optimal number of the PV modules, the PV modules optimal tilt angle, the optimal placement of the PV modules within the available area and the optimal distribution of the PV modules among the inverters. The objective function of the proposed optimization process was the total net profit.

A technical and economical solution has developed to optimize a utility-scale grid connected solar photovoltaic park with an installed capacity of 24 MW [10]. Several influencing parameters such as configuration (landscape/portrait), inverter connection (central/string), structure type (fixed tilt/single-axis tracking), shading limit angle, and pitch distance analyzed individually and LCOE obtained for each case. The proposed solution with lower LCOE was employing a single-axis tracking system with a backtracking strategy as well as portrait configuration for modules. Moreover, the string inverter introduced as the best alternative to employ due to the better cost per unit of energy and easier replacement.

To reduce the impact of mutual shading, the parameters of inclination and row distance should be designed well. Jouri et al. studied the technical and economic consequences of mutual shading of PV systems on flat roofs [11]. The study has stated a significant decrease in generated energy occurs due to mutual shading, while the configuration which gave the maximum energy output was at a tilt angle of 0° and a row distance of 0 meters. Minimizing the payback time has considered as a target in this study.

Levelized cost of energy in utility scale PV system has investigated in some articles. Campbell M. studied the area related cost components for a tracker plant with annual production of 1 TWh and compared the required equipment and area for different technologies of PV modules [12]. Nuria et al. proposes a method to optimally minimize the distance between fixed PV panels without limiting the useful hours of energy production, for any angle of the sun and any latitude, then this method can be used everywhere [13]. The proposed method is based on the exact calculation of the shadows of the panels for any angle of the sun and for any latitude which makes it usable in every place. The method then has applied to a case study and has compared with traditional methods, concluding that the distance can be reduced by up to 40 % when the tilt angle of the panel is 60°.

A study suggests a simplified method to investigate the modules positioning impact on large-scale PV plant performances in northwest France through a case study [14]. The proposed method was an approximated way which simulate the impact of the module modality on large-scale PV plant considering a range of parameters including Ground Coverage Ratio (CGR), tilt angle and modules interconnection to translate them into French socio-economic indicators. Approximations have made using PVsyst software to estimate the electrical effect losses. Several configurations have defined to be implemented and simulated. Then the method has applicated and validated through a ground-mounted photovoltaic plant on located in France as a case study.

The impact of inverter structure in the performance of the PV power plants has been studied too [15]. The most used topologies of inverters are central and string structures. The result illustrated that PV plant using central layout presents the lower LCOE compared to string topology. The results also showed by increasing the inverter efficiency, the LCOE has decreased. A technical and economic comparison of different electrical collection grid configurations for large PV power plants has done based on a holistic approach that calculates the LCOE [16]. The results demonstrated that although some PV power plant configurations present higher performance ratio, but they are not necessarily the most cost-effective solutions because of used expensive technologies or the requirement of extra equipment.

This study tries to bridge the research gap in previous studies and to focus on finding a trade-off between cost and generated power, while the available area is not restricted. The impact of climate and meteorological data on the self-shading loss and yield of energy are investigated through a simulation tool in different tilt angles and distances between rows. LCOE minimizing is a measure in finding the optimum tilt and pitch distance for a 1 MW solar system which has installed in different latitudes.

1.4 Key concepts in this study

1.4.1. Large-scale PV power plant

While a roof-top solar system may consist of dozens of panels, a single large-scale PV power plant may have hundreds of thousand panels or even more [17]. Large-scale PV power plants may also be called solar farms, solar parks and solar power station. Solar farms operate as power plant that deliver the generated electrical energy to a customer site or electrical grid. They consist of ground-mounted solar panels installed in a large area [17]. PV modules are mounted on a structure which can be fixed in a specific orientation and tilt or track the sunlight to gain the maximum irradiation in year [4]. The key parameters in designing a large-scale PV power plant are:

- Radiation in the site
- Temperature and climate conditions
- Proper selection of component like modules, inverters, structures, cables
- Module degradation due to aging
- Near and far shading as well as self-shading
- Orientation and optimum angle of tilt
- Inter-row spacing
- Losses in PV system

1.4.2. Levelized cost of energy

The PV production of electricity is growing steadily from year to year, the market analysis for 2019 estimated 12 % increasing in production compared to 2018 to cumulative installed capacity above 620 GW where PV contributes about 3 % of the world production [18]. Solar photovoltaic (PV) power became as great potential for electricity source, the increasing of installation capacity for last two decades, where the capacity deployments, growth rates have been steadily increased in each successive year, so the price of solar system decreased significantly where the average of PV modules has been fallen from 4 $ per watt in 2007 to around 0.35 $ per watt in 2017 [19]. The steady increasing usage of PV power production as a large-scale renewable energy power generation introduced a critical question at a competitiveness of the PV energy generation cost with that of other sources, this leads to a common means of comparing the production cost with other sources is LCOE [20], so LCOE became as metric to compare the cost of energy production from PV to alternative traditional or other renewable sources to know the feasibility of PV projects and to measure the competitiveness of PV energy price with other energy sources.

1.4.3. Self-shading losses in PV arrays

The distance between the rows of a solar system should be designed appropriately to reduce the shading loss and increase the generated energy. Self-shading losses occur due to the partial shading of a row of PV modules in the rows behind. Just the first row located in the front does not have this problem. Self-shading between PV rows depends on different factors including the time of the day, distance between rows and configuration of the array [21]. The distance between rows should be estimated to have minimum shading losses. The pitch distance is affected by [22]:

- Latitude (sun path)
- Inclination of solar panels
- Configuration of PV modules on mounting structure
- Minimum space needed for operation and maintenance

Shading analysis is necessary in designing solar systems. There are several methods to analysis the impact of shading of near and far obstacles. The process of accurate shade analysis is based on on-site measurements and then the measured data are used to render the surrounding area as 2D or 3D model; most of these methods need mapping the horizon and combining it with sun path data [23].

These methods measure and estimate shading losses, but they usually do not present a separate estimation for self-shading. It is possible to study the impact of self-shading by some simulation software such as PVsyst [24]. It should be noticed that the energy yield of a PV system with fixed free-standing PV arrays decrease by self-shading losses.

1.4.4. PV modules

PV modules are the most important part in a solar system, which usually consist the main part of the initial investment. Today, different technologies are used in construction of modules which present a variety of efficiencies with different prices. Table 1.1 illustrates the common types of solar cells which are used today.

Table 1.1 The common types of solar panels [25]

Solar Cell Type	Efficiency-Rate	Advantages	Disadvantages
Monocrystalline Solar Panels	~20 %	High efficiency rate; optimized for commercial use; high life-time value	Expensive
Polycrystalline Solar Panels	~15 %	Lower price	Sensitive to high temperatures; lower lifespan & slightly less space efficiency
Thin-Film: Amorphous Silicon Solar Panels	~7-10 %	Relatively low costs; easy to produce & flexible	shorter warranties & lifespan
Concentrated PV Cell	~41 %	Very high performance & efficiency rate	Solar tracker & cooling system needed (to reach high efficiency rate)

Electrical performance of a PV module besides the semiconductor material is affected by two main parameters:

- Temperature:
  The increase of PV module operating temperature leads to drop in electrical efficiency. The output voltage reduces in higher module temperature, which causes less production. Some factors affect the yield potential of a solar power system which are ambient temperature, temperature coefficient of the actual panel and the type of installation [26].

- Solar irradiance:
  The higher solar irradiance causes the greater short circuit current and open circuit voltage, and as the result, the greater power generation. The increase in short circuit current in higher irradiance.

2 Design simulation method

2.1 Site Location

Different latitude has been selected in this study to create a designing table in a variety of climates. A step of 15° between latitudes has been chosen to cover different locations at the earth. It was tried to find a large city in selected latitude in both northern and southern hemisphere.

Tropical climate occurs 22.5° north and south of the equator. The temperature in this zone is high, and the sun can beat down from overhead once or twice each year directly [27]. Three cities have been selected in tropic climate which are Khartoum in Sudan (15° N, 30° E), Kampala in Uganda (0, 30° E) and Songo in Tanzania (15° S, 32° E).

From 23.5° N to 66.5° N and between 23.5° S and 66.5° S are the temperate zones, where there are clear four seasons [27]. Six cities have been selected in temperate climate which three of them are in northern hemisphere including Cairo in Egypt (30° N, 30° E), Turin in Italy (45° N, 7.4° E) and Petersburg in Russia (60° N, 30.36° E). The others are in southern hemisphere which are Durban in South Africa (30° S, 31° E), Dunedin in New Zealand (45° S, 170° E) and Rio Grande In Brazil (54° S, 68° W).

From 66.5° N to the north pole there is the Arctic, and from 66.5° S to the south pole, the Antarctic. In these arctic zones which called polar climate, the sun is above the horizon at midnight during part or all the summer and never rises at all during some days in the winter [27]. For polar climate, there was difficult to find a city exactly in desired latitude which was 75° in both hemispheres. So, it has decided to continue with Tromsø in Norway (69° N, 19° E) in northern hemisphere and there are not any residential places at the opposite side of the earth in southern hemisphere. Table 2.1 shows the selected cities for this study.

Table 2.1 Selected cities

No.	City	Country	Latitude	Longitude	Climate Type
1	Tromsø	Norway	69° N	19° E	Polar
2	Petersburg	Russia	60° N	30.36° E	Temperate
3	Turin	Italy	45° N	7.4° E	Temperate
4	Cairo	Egypt	30° N	30° E	Temperate
5	Khartoum	Sudan	15° N	30° E	Tropic
6	Kampala	Uganda	0	30° E	Tropic
7	Songo	Mozambique	15° S	32° E	Tropic
8	Durban	South Africa	30° S	31° E	Temperate
9	Dunedin	New Zealand	45° S	170° E	Temperate
10	Rio Grande	US	54° S	68° W	Temperate

The weather specifications in considered locations are sourced from Meteonorm 7.2 which includes information including average annual global horizontal irradiation, wind speed and temperature. Table 2.2 shows the value of the mentioned parameters in selected cities.

Since the peak solar radiation is 1 kW/m^2, the number of peak sun hours (PSH) can be calculated from horizontal global irradiation. For example, a location with 2 kWh/m^2 per day can receive 2 h of sun per day at 1 kW/m^2, then the PSH is equal to 2 h. The average annual PSH range between 2.01 h per day in Tromsø and 6.1 h per day in Khartoum. Each city has also a range of different peak sun hours during months of the year and the mentioned value in the table is just for average of PSH throughout the year. The highest PSH and annual horizontal global irradiation is in Khartoum located in 15° N latitude and Cairo in 30° N and Kampala at 0° are in second and third rank respectively.

The average monthly wind speed is between 1.29 m/s in Turin and 5.77 m/s in Tromsø and the average monthly temperature is between -3.2 °C in Tromsø and 35 °C in Khartoum. The mentioned values between parentheses for wind speed and temperature in Table 2.2 show the minimum and maximum average monthly of these parameters.

Table 2.2 Weather specifications

No.	City	Average Annual Wind Speed [m/s]	Peak Sun Hour [PSH]	Monthly Mean Horizontal Global Irradiation [W/m^2]	Average Annual Temperature [°C]
1	Tromsø	4.3 (3.31, 5.77)	2.01	83.9	3.6 (-3.2, 12.6)
2	Petersburg	3.2 (2.6, 3.9)	2.80	108.3	5.8 (-6.2, 19)
3	Turin	1.7 (1.29, 2.10)	3.57	148.6	12.6 (1.8, 22.9)
4	Cairo	3.5 (2.9, 4.2)	5.27	219.6	22.4 (14.4, 29.5)
5	Khartoum	4.3 (3.3, 4.89)	6.10	254.3	30.4 (23.6, 35)
6	Kampala	2.7 (2.19, 3.29)	4.82	200.9	22.3 (20.7, 23.3)
7	Songo	2.1 (1.79, 2)	4.68	195.1	24 (21.7, 25.4)
8	Durban	3 (2.10, 3.8)	4.57	190.5	20.7 (17.7, 25)
9	Dunedin	3.5 (2.8, 4.29)	3.63	151.2	10.1 (4.6, 2,6)
10	Rio Grande	2 (1.6, 2.4)	4.63	193.0	23.8 (19.2, 26.8)

2.2 Main components

In this study, a 1 MW grid-connected PV array has been designed in the different latitudes. In order to make a comparison between the impact of the climate on the LCOE parameter, the same components have used in designing the solar system in all the selected cities.

I. PV Modules

Two poly-crystalline modules from different brands with the power of 280 W have selected for simulation of PV system. The considered brands are "Jinkosolar" and "Canadian Solar". The main features of the selected modules are mentioned in Table 2.3. Appendix A and Appendix B show the datasheet of these modules.

Table 2.3 Specifications of modules

Module Type	**Jinkosolar JKM280PP-60**		**Canadian Solar CS3K-275**	
Test Condition	STC	NMOT	STC	NMOT
P_{max}	280 W	208 W	280 W	206 W
V_{mpp}	32.3 V	30.1 V	31.2 V	28.5 V
I_{mpp}	8.69 A	6.91 A	8.98 A	7.23 A
V_{oc}	39.4 V	30.1 V	37.9 V	35.3 V
I_{sc})	9.20 A	7.99 A	9.47 A	7.64 A
Module Efficiency STC (%)	17.11 %		16.85 %	
Operating Temperature (℃)	-40 ℃ ~ +85 ℃		-40°C ~ +85°C	

II. Inverter

A PV inverter is a type of electrical converter which converts the direct current (DC) output of a photovoltaic (PV) solar panel into a utility frequency alternating current (AC) that can be connected an electrical grid or used by a local. Two types of inverters have investigated for the designing solar system. The first is a 100 kW inverter of "ABB" and the other is a 60 kW of "Canadian Solar". Table 2.4 shows the main feature of these inverters. Appendix C and Appendix D show the datasheet of these inverters.

Table 2.4 Specifications of inverters

Inverter Type	**ABB string inverters PVS-100-TL**	**CANADIAN SOLAR CSI-60KTL-GI-H**
Rated Output Power:	100 kW	60 kW
Maximum Input Power DC:	125 kW	72 kW
V_{dcr}	620 V	
$P_{MPPT,max}$	17.5 kW	22.5 kW
MPPT input DC voltage range, ($V_{MPPTmin}$...$V_{MPPTmax}$) at P_{acr}	480…850 V	526...850 V
Rated Efficiency (EURO/CEC)	98.2 %	98.5 %
I_{in}	216 A	178 A (44.5 A per MPPT)
$I_{ac,max}$	145 A	72.2 A
Number of Maximum Power Point (MPP) Trackers	6	4
Number of DC input pairs for each MPPT	4	3

III. Components combination

The different combination of these two types of modules with two types of selected inverters has simulated in this study. Table 2.5 shows the result of simulation including the number of required components, the yearly yield and the annual production for designing a 1 MW PV system in St. Petersburg in Russia. The tilt of orientation has considered 45° and the PV's are south faced.

To design a 1 MW PV system, 3570 modules of 280 W are needed. 17 sheds with the shed space of 7 meters in a portrait configuration which every shed include two rows of 105 modules have considered in this design. The inverter can be undersized; 8 inverters in the size of 100 kW or 14 inverters of 60 kW are compatible with the selected size of PV modules.

Using Canadian Solar Inc. brand for both module and inverter, the array short circuit current is greater than the inverter maximum input current, then it can increase the risk of damage for inverters. Using Canadian Solar Inc. inverter in the size of 60 kW, a greater number of inverters should be used, which reduces the reliability of system and increase the cost of system [28]. As ABB inverter can support more numbers of MPP tracker inputs and higher number of DC input pairs for each MPPT and it has wider MPPT input DC voltage range, it can be a suitable component for designing a solar system in different climates. Moreover, the less numbers of inverters needed using ABB (100 kW) which probably reduces the investment cost of inverter too.

Table 2.5 Different combination of two types of selected modules and inverters

Combination 1		**No**	**Pros & Cons**
Module type	Jinkosolar (280 W)	3570	+ Compatible with different climates + Higher reliability + More numbers of MPP tracker inputs, wider MPPT input DC voltage range
Inverter type	ABB (100 kW)	8	
Yield (kWh/kWyear)	948		
Production (MWh/year)	948		
Combination 2		**No**	**Pros & Cons**
Module type	Jinkosolar (280 W)	3570	+ High yield of energy – More numbers of inverters, less reliability, more cost
Inverter type	Canadian solar (60 kW)	14	
Yield (kWh/kWyear)	951		
Production (MWh/year)	951		
Combination 3		**No**	**Pros & Cons**
Module type	Canadian solar (280 W)	3570	+ Higher reliability + More numbers of MPP tracker inputs, wider MPPT input DC voltage range – Less yield of energy
Inverter type	ABB (100 kW)	8	
Yield (kWh/kWyear)	945		
Production (MWh/year)	944		
Combination 4		**No**	**Pros & Cons**
Module type	Canadian solar (280 W)	3570	+ High yield of energy – More numbers of inverters, less reliability, more cost – $I_{sc,module} > I_{max\ input,\ inverter}$, higher risk of inverter damage
Inverter type	Canadian solar (60 kW)	14	
Yield (kWh/kWyear)	950		
Production (MWh/year)	950		

Since this study aims to investigate the impacts of climate on tilt angle and pitch distance, the same type of components is selected for designing a large-scale PV system in different latitudes. Then it is important to find the components that their technical specifications would be suitable and compatible in various weather conditions and solar irradiance levels. The selected components are Jinkosolar (280 W) due to higher efficiency for modules and ABB (100 kW) for inverters which have good operation in different weather conditions. The number of 3570 modules with the power 280 W and 8 inverters in the size of 100 kW to design a 1 MW solar system are needed.

2.3 Levelized cost of electricity calculations

Equation 2.1 has used to calculate LCOE is given as following [19]:

$$\mathrm{LCOE} = \frac{\mathrm{INV} + (\mathrm{C} * \mathrm{n}) - \mathrm{RV}}{\sum_{i=1}^{i=n} \frac{\mathrm{Y} * (1 - \mathrm{DR})^{i-1}}{(1 + \mathrm{IR})^{i}}} \qquad \textit{Equation 2.1}$$

INV: Initial investment

C: Annual cost
RV: Residual value
Y: First year yield
DR: Degradation rate
IR: Interest rate
i: Years
n: Lifetime of project.

Main inputs of LCOE
The initial investment, the annual cost, energy production, and the economic indicators are the major inputs of the LCOE equation.

Initial investment

- The initial investment is the total cost of the PV project can summaries by:
- PV array components like modules, inverters, and monitor tools.
- Infrastructure and interactions of PV grid
- Area cost which becomes the main concern in the initial cost especially to fall off modules and inverters price nowadays.

Annual cost
The annual cost is related to operation and maintenance. This cost covers all related expenses like cleaning site, land leases, replacing defects components, sales marketing, etc.

First-year yield
The energy production determines by the annual production over the lime time of the project which discounted according to the degradation rate. The first-year yield (the first-year energy production) is the ratio kilowatt-hours generated to kilowatt peak of capacity per year (kWh/kW) [18]. The first-year yield is affected by many factors like the amount of ration in a year, system orientation, degradation rate, and losses due to soiling, inverters, and wiring [20].

Residual Value
The present value of the asset of the project at the end of project life. This value is deducted from the investment cost because the residual value considers as income cashflow. The residual value has a significant influence if the project has a short cycle-life [18].

Interest rate
The interest rate is the ration of loan which added as an interest to the borrowed loan, and usually, the interest rate is an annual percentage from the loan. interest rate is a function of price inflation and discount rate. The variation of interest rate influences on LCOE significantly, where a 1 % change in interest rate leads to 3.73 % of LCOE.

Different scenarios
Small changes in input variables lead to a large change in LCOE values so it is important to pay attention when the input variables assumptions are made to calculate LCOE for comparing with other technologies [20]. Table 2.6 shows the varying in LCOE according to changing the inputs variables, where the initial cost and first-year production are constant while degradation, lifetime project, discount rate, and annual cost are variables in three different cases [29].

Table 2.6 Sensitivity according to input variables changings

Input variables	Case 1	Case 2	Case 3
First-year yield [kWh/kW]	Constant	Constant	Constant
Initial cost [$]	Constant	Constant	Constant
Degradation Rate [%]	1	0.5	0.3
Project lifetime [year]	15	25	40
Annual cost [$/kWh]	0.03	0.01	0.005
Discount rate [%]	9	7	5
LCOE [$/kWh]	0.23	0.13	0.09

Financing Parameters
According to Sveriges Riksbank (Swedish central bank), Table 2.7 summaries the economic indicators for the first quarter in 2020.

Table 2.7 Economic indicators according to Sveriges Riksbank for the first quarter in 2020

Indicators	Percentage
Interest rate	4 %
Inflation rate	2 %
Discount rate	2 %
VAT	25 %

In addition to economic indicators, the initial investment, annual cost, and residual value are required to calculate LCOE, see Table 2.8.

Table 2.8 Estimated prices for initial investment and annual cost [29] [30] [31]

Items	No.	Amount [€]	Description
Module	3750	273000	Monocrystalline 0.3 (€/W) Polycrystalline 0.26 €/W)
Inverter	8	56000	For power < 100 kW is 0.07 (€/W)
Electrical installation material		16450	5 % of total equipment cost
Mounting/Installation work		32900	10 % of total equipment cost
Land lease			1.892 €/m^2

2.4 Selection of modules' arrangement

After site selection, the amount of available area without shading and the number of modules that could be installed there should be determined. The required space is determined according to the dimension of equipment, vehicular access, security fences, and other needed structures. The number of modules can be calculated considering the required space between rows for cleaning and maintenance and to minimize the self-shading loss.

Solar panels can be installed in either portrait or landscape configuration. The best configuration can be selected according to higher energy production in the smallest area which gives the minimum amount of LCOE. According to the shape of area and optimal tilt angle, the selection of either landscape or portrait which gives the possibility of installing more modules and at the higher yield of energy is critical.

2.4.1. Landscape versus portrait

There are two main issues that suggest the optimal orientation for a solar system [32]. The first one is making decision about the number of PV modules that can be installed in a specific length. More modules can lead to higher yield of energy. Figure 2.1 shows the number of modules which can be fit in in both landscape and portrait. More modules fit in portrait configuration in each row length.

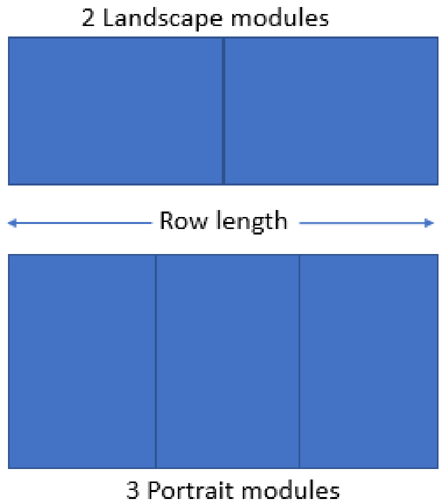


Figure 2.1 *Number of modules per row*

The second issue is the number of modules which can be installed in a specific height considering the amount of shading caused by a row of modules. The PV modules row spacing depends on the sun elevation in the selected latitude, the panels height and the angle of mounting. Figure 2.2 illustrates the number of modules in a specific height.

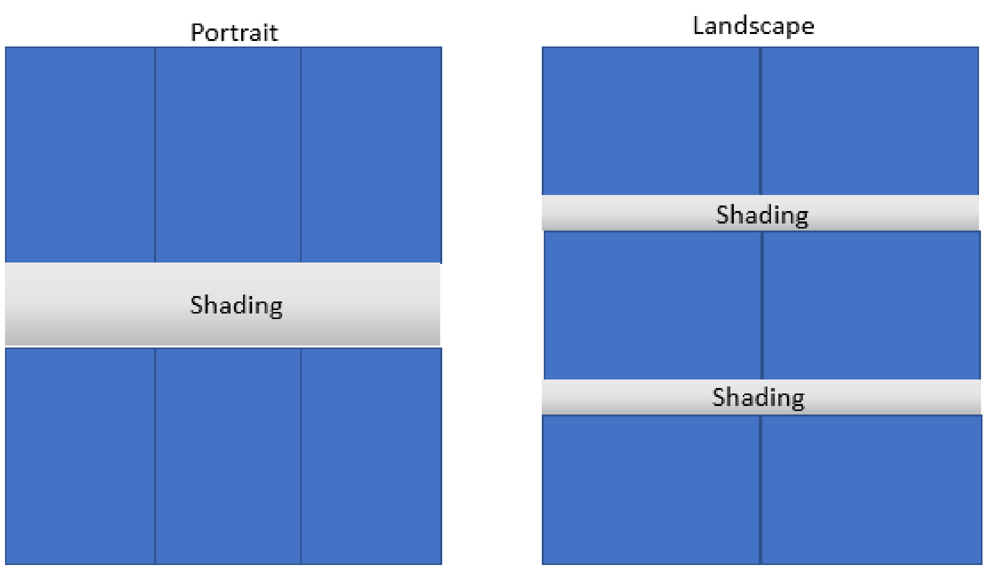


Figure 2.2 Number of modules according to shading in a specific height

In summary, taking decisions about optimum arrangement should be based on system efficiency and less LCOE.

2.4.2. Different configurations

In this study, three configurations for each city will be proposed which are:

- 2 modules in portrait (2-P)
- 2 modules in landscape (2-L)
- 3 modules in landscape (3-L)

2-P Configuration:

To arrange 3570 modules in two rows in portrait configuration, 17 sheds which each of them included two modules in height and 105 modules in width are used. Figure 2.3 shows an example of this system.

Figure 2.3 2-P Configuration

2-L Configuration:

To arrange 3570 modules in landscape configuration, 17 sheds which each of them included two modules in height and 105 modules in width (Figure 2.4).

Figure 2.4 2-L Configuration

3-L Configuration:

To arrange 3570 modules in landscape configuration, 10 sheds which each of them included three modules in height and 119 modules in width (Figure 2.5).

Figure 2.5 3-L Configuration

2.4.3. Configuration selection

To select the best configuration for every city, Kampala is introduced as an example and other cities will be done in a similar way. The pitch distance is defined in a way in three configurations which gives the same yield of energy and shading loss, then LCOE will be calculated for every configuration. The configuration with the least LCOE is considered as best to simulate in other tilts and pitch distances. According to Table 2.9 Configuration selection in Kampala, 2-P configuration is considered as suitable arrangement in Kampala.

Table 2.9 Configuration selection in Kampala

Configuration	**2-P**	**2-L**	**3-L**
Shed	17	17	10
X	105	105	119
Y	2	2	3
Pitch distance(m)	4	3	4
Area (m^2)	7276	8800	7800
Yield (kWh/kWyear)	1466	1466	1466
Shading loss (%)	~0	~0	~0
LCOE	2.172	2.184	2.176

Table 2.10 shows the selected configuration for each city considering yield of energy, shading loss, area which results the minimum LCOE.

Table 2.10 Selected configuration

No.	City	Latitude	Climate Type	Suggested Configuration
1	Tromsø	69° N	Polar	3 L
2	Petersburg	60° N	Temperate	3 L
3	Turin	45° N	Temperate	3 L
4	Cairo	30° N	Temperate	2 P
5	Khartoum	15° N	Tropic	3 L
6	Kampala	0	Tropic	2 P
7	Songo	15° S	Tropic	3 L
8	Durban	30° S	Temperate	2 P
9	Dunedin	45° S	Temperate	3 L
10	Rio Grande	54° S	Temperate	3 L

2.5 Simulation method

Many compromises between performance and cost should be done to design an optimum large-scaled solar plant. In this part, some of the effective parameters in designing a solar plant are explained. The important criterion in designing of most solar power plants is reducing of LCOE, which reflects the cost of every unit of generated energy. Specific of the site location such as irradiation, weather data, shading, and sun position should be considered to make a balance between cost and yield. The quality of the designed system should be kept as well as considering reducing the cost of the system. Designing a cheaper system can lead to the higher operation cost and lower revenue due to lower yield in the future.

Using a simulation software helps the designer to investigate the impact of different climates, different kinds of components, and different layouts of the system on the yield and required land area in order to reduce the LCOE. The used software in this study is PVsyst which today is used by most of the solar system designers for component sizing and simulation. It is possible to simulate the impact of shading of rows and change the tilt of angles and the distance between rows and every time get the performance ratio of the system, the annual energy production and yield. Moreover, it is possible to study the impact of configuration and the distance between rows on the required land area.

2.5.1. Inputs

- **Solar resources and weather:**
  Higher average annual global tilted irradiation/irradiance (GTI) leads to the greater energy yield per installed kW. Shading situation should be minimized because it reduces the irradiation received and makes a loss in generated energy. The source used for weather specifications and solar resources is Meteonorm 7.2.

- **Area:**
  The area required depends on different factors including the technology chosen for PV modules, the space required for cleaning and maintenance, and the pitch distance regarding inter-row shading. The latitude of the site effects on determining the area.

- **Climate:**
  Three different climates in both the southern and northern hemispheres have considered in this study. The risk of damage by some climate situations should be

kept low for the solar system. High wind speed, flooding, snow-covered on modules, air pollution, and high temperature can damage the system and reduce its efficiency.

- **Orientation:**
  The best direction for PV system installation in the northern hemisphere is the south-facing slope and in the southern hemisphere is the north-facing slope.

- **Land cost:**
  Large-scaled PV arrays usually are installed in cheaper land. The cost of purchase or lease land should be considered if the land has not owned by the solar system owner. This parameter participates in LCOE calculation.

- **Tilt angle:**
  The best tilt angle for every location is the tilt which maximizes the total annual irradiation. This tilt depends on latitude for a fixed mounted solar system and can be determined by thumb of rule or using some simulation software's. Higher tilt angles can reduce the soiling losses and on the other hand, high tilted modules cause more shading on modules in the behind row which result less production [4]. The tilt angles used in this study for simulation are in a range of at least four angles with the 5° step.

- **Pitch distance:**
  Shading losses can be reduced by increasing the distance between rows, but the area needed will increase too which result to higher land cost. Then it is necessary to compromise between the production and cost. The pitch distance used in this study for simulation are at least four pitch distances with the step of 1 meter.

2.5.2. Electrical PV array design

- **PV module sizing**
  There are some criteria should be considered in selection of PV modules which some of them have mentioned in following:

  ➢ Maximum and minimum number of modules in a string:

  The number of modules in strings must be chosen in a way that the string voltage does not go above the DC voltage input range of inverter and if it did, the inverter could be damaged. The maximum number of modules in a string is defined by the maximum voltage at the inverter input ($V_{MAX\ (INV,\ DC)}$) which occurs at the lowest temperature during open circuit operation. The open-circuit voltage is the highest voltage of the module which occur in the coldest temperature in site location. Equation 2.2 shows the calculation of maximum number of modules (N_{max})

  $$V_{\mathrm{OC(MODULE),max}} \times N_{max} < V_{MAX\ (INV,DC)} \quad \text{Equation 2.2}$$

  The lowest module voltage is at highest operating module temperature and it should not drop under the minimum MPP voltage of inverter. The minimum number of modules in a string (N_{min}) can be calculated using theEquation 2.3.

  $$V_{MPP(MODULE)\ min} \times N_{min} > V_{MPP(INV\ min)} \quad \text{Equation 2.3}$$

  ➢ Number of strings:

  The maximum input current of inverter and the maximum PV array current determine the permitted number of strings a PV array.

- **Inverter Sizing**
  The choice of optimal power for inverters is important in designing a solar plant. Oversizing of an inverter can waste the investment and under sizing can lead to lower yield of energy, because the generated power in high levels of irradiation is limited due to limitation in the maximum input power of inverter. Finding a formula to estimate the best size of inverter is not easy and it can vary for different location. According to the rule of thumb, the size of inverter can be 20 % higher or lower than the size of PV array, but it sometimes does not lead to the best design.

  Site specifications such as irradiance profile and tilt of modules are important in optimal sizing of inverters. Some of the important factors in sizing of inverter has come in following [4]:
    - The maximum V_{OC} in the coldest daytime temperature ($V_{OC(MODULE)\ max}$) must be less than the maximum inverter DC input voltage ($V_{MAX\ (INV,\ DC)}$).
    - The maximum PV array(s) current should be less with input current of inverter.
    - The minimum V_{OC} in the hottest daytime temperature must be greater than the inverter DC turn-off voltage ($V_{INV,\ DC\ TURN\text{-}OFF}$).
    - The MPP range of inverter must include PV array MPP points at different temperatures.
    - The ambient temperature range and irradiation profiles in the site location.
    - Economics and cost-effectiveness.

2.5.3. Output

- **Shading loss:**
  Shading is created because of different causes including far trees, mountain, buildings and self-shading between rows of modules. The shading should be analyzed using the full sun path diagram for a site location [4]. In this study, it is assumed that the area is shading free and the only shading loss in the system is inter-row shading.

- **Performance ratio (PR):**
  PR is a measure to show the performance of a solar system considering environmental factors such as temperature, irradiation, climate changes etc. and usually expressed by percentage. Higher PR means more solar irradiation is converted to useful energy by solar system.

- **Specific yield of energy:**
  The specific yield of energy is the total generated energy in a year per kW installed. It participates in LCOE calculation and it is used to compare the operation of the system with different technologies. It depends on total annual irradiation, the efficiency of modules, and losses in the system.

- **Yield production:**
  The generated energy by a solar system in one year.

- **LCOE:**
  LCOE refers to the cost of generated solar energy during the lifetime of the system considering the cost of components, land, operation, maintenance, construction, taxes, insurance, and other financial parameters.

2.5.4. Uncertainties and limitations in simulation

- **Uncertainties in the meteorological data**
  The meteorological data is the main uncertainties for the simulation. There are four predefined meteo database in PVsyst which are Meteonorm 7.2, NASA-SSE, PVGIS TMY and NREL/NSRDB TMY and also it is possible to import our measured data file in the software. Poorly measured or processed data causes significant deviations of the results. Using data from trustable sources is recommended [33].

  The most common uncertainties in meteo data are [33]:
    - The yearly variability, with a gaussian distribution,
    - The quality of the data recording, the skill and care of the operators, positioning, calibration and drift of the sensors, perturbations like shadings, covered sensors by dirt or snow on, etc.
    - The presence of a not negligible horizon for terrestrial measurements,
    - The location difference (distance of measuring station) for terrestrial measurements,
    - The quality of used models for interpreting the satellite data,
    - The evolution of the climate. For example, it supposed to be around 5 % increase in the irradiation since the beginning of the 21st century in Europe.
- **Uncertainties in Simulation process:**
  Uncertainties in the simulation process should be considered too. Most important of them are [33]:
    - PV modules model and parameters, which is the main uncertainty after meteo,
    - Inverter efficiency, which, which is negligible,
    - Soiling and module quality loss, which depend on the site conditions,
    - Long term degradation, which is not compatible with the P90 evaluation concept,
    - Custom other contributions, which handling with is unknown in the present.

- **Economic approximation**
  The financial calculations contain significant uncertainty due to use of guide cost figures for components, operation, electrical installation material, installation work, and mounting. These figures can be a good estimation for initial investment of a solar system but is not accurate. The most variable parameter is land lease which is even different in different cities of a country. Moreover, the economic indicators including interest rate, discount rate, inflation rate, and VAT, which are used in calculation of LCOE, are variable in different countries.

  In this project to study the impact of climate condition on tilt angle and pitch distance, the economical parameters have considered the same in different countries. Then as shown in table 2.3.2, the used indicators for all locations have selected according to Sweden. Furthermore, the used cost for land lease in this study is according to information in Sweden.

3 Results

In this section, the obtained results are analyzed, discussed, and commented minutely according to the PV plant structure for each location.

3.1 Optimal design in Khartoum city

3.1.1. Impact of variable pitch distance to annual yield and LCOE

The tilt angle has to be kept constant in this case, where the fixed tilt has been chosen to achieve the optimal angle according to analyzing and studying the PV array for each project site (chosen city).

Table 3.1 illustrates the change of LCOE and annual yield due to the changes in pitch distance. This was executed by keeping the tilt angle is fixed at 15°. In this situation, the tilt angle is the optimal one to achieve the lowest value of LCOE for the PV array.

Table 3.1the effects of the fixed tilt angle with variable pitch distance to LCOE, annual yield, performance, near shading, and production for Khartoum city

Tilt angle	°	15			
Pitch distance	m	3	4	5	6
Area	m^2	6169	7960	9552	11343
Yield	kWh/kWyear	1699	1819	1832	1836
Production	MWh/year	1699	1818	1831	1835
Near Shading	%	9.2	1.8	1.0	0.8
PR	%	73	78	79	79
LCOE	€.cent/kWh	1.867	1.755	1.752	1.760

Figure 3.1 describes the impact of pitch distance on LCOE. Through this graph, LCOE has the highest value 1.867 €.cent/kWh at 3 m of pitch distance due to high near shading 9.2 % by modules panels, then LCOE decreases with increase the pitch distance up to 5 m which achieves the optimal one. Increasing the pitch distance more than 5 m (the optimal one) leads¨to LCOE increase again; that is because more area is needed without notable improvement in the yield, thus more expense will be added to the capital investment.

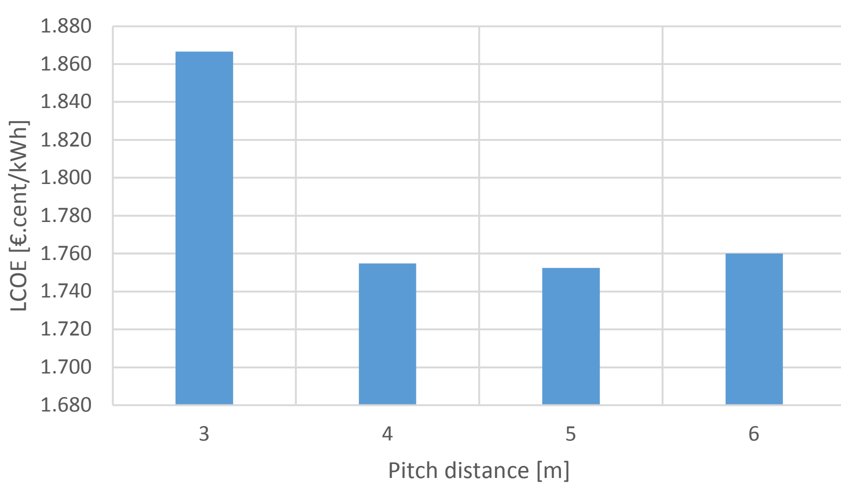


Figure 3.1 LCOE changes against pitch distance for Khartoum city

Figure 3.2 illustrates yield changes against the PV array area at the optimal tilt which is 15°. The graph shows that the yield has the lowest value when the area responds to 3 m of pitch distance, this means 3 m of pitch distance accompanied with highest near shading (irradiation loss) 9 %, this loss causes the lower yearly yield. After 3 m of pitch distance, the yield increases steeply due to decreasing the irradiation loss up to 2 %. After this sharp rise, the yield increases slightly with increasing the PV array area where the near shading appears to be diminishing slightly (see Table 3.1).

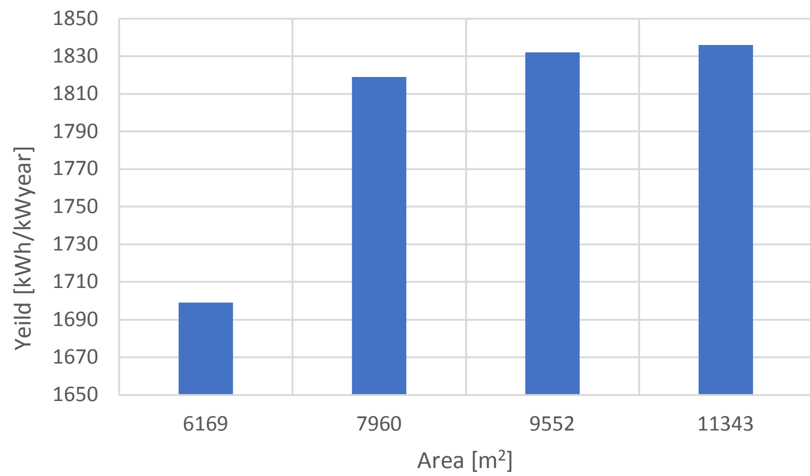


Figure 3.2 Yielded changes against PV array area for Khartoum city

The annual yield is one of the important parameters of LCOE equation which has a great influence to reduce LCOE. Through Figure 3.3, LCOE decreases form 1.867 €.cent/kWh to 1.755 €.cent/kWh suddenly due to increasing the yield from 1699 kWh/kWyear to 1819 kWh/kWyear. After that LCOE has not significant changes according to small changes of yield.

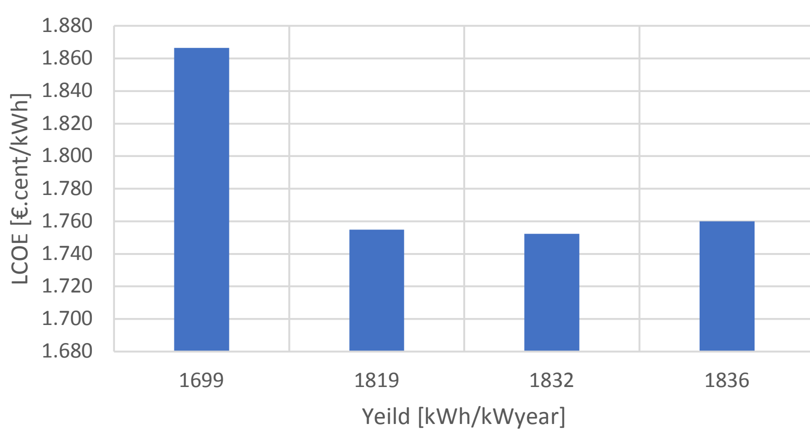


Figure 3.3 LCOE changes against annual yield for Khartoum city

3.1.2. Impact of variable tilt angle to annual yield and LCOE

Table 3.2 illustrates the LCOE and yield characteristics resulting from tilt changes when the pitch distance was considered to be constant at 5 m. During the simulation process, it was observed that the variation of tilt angles has not much impact on LCOE since the variation of PV modules' tilt angle doesn't significantly affect the annual output (yield) in range $\pm 10°$ of tilt angle (see Figure 3.4).

Table 3.2 the effects of the fixed pitch distance with variable tilt angle to LCOE, annual yield, performance, and production for Khartoum city

Pitch distance	m	5			
Tilt	°	10	15	20	25
Area	m^2	9552	9552	9552	9552
Yield	kWh/kWyear	1826	1832	1821	1800
Production	MWh/year	1825	1831	1821	1799
Near Shading	%	0.5	1.0	1.8	0.8
PR	%	79	79	78	78
LCOE	€.cent/kWh	1.758	1.752	1.763	1.784

Figure 3.4 illustrates the yield changes against the tilt angle for Khartoum city. The annual yield has no big changes according to tilt angle changes, where the near shading (around 1 %), this means the tilt angle can receive the optimal annual yield in range 10° up to 25° while the pitch distance constant at 5 m.

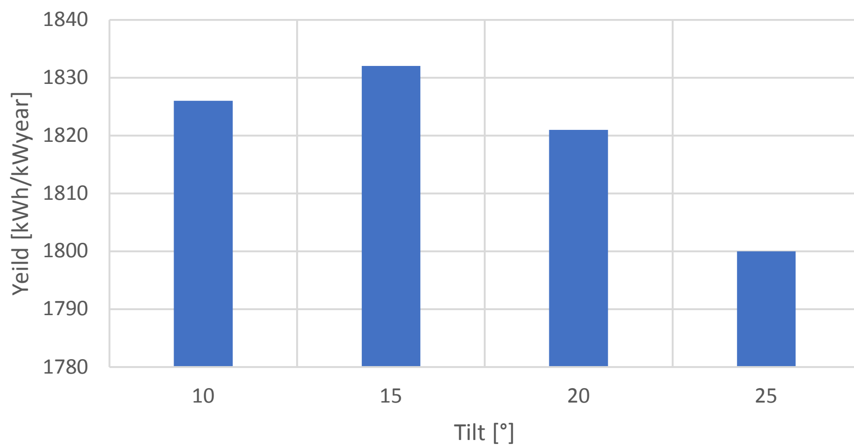


Figure 3.4 Yield changes against tilt angle for Khartoum city

The variation of tilt angle has not a great influence on LCOE when this variation takes place around the optimal tilt angle considering the pitch distance fixed at the optimal one. Figure 3.5 shows that LCOE has small changes when the tilt angle variations range between 10° and 25°.

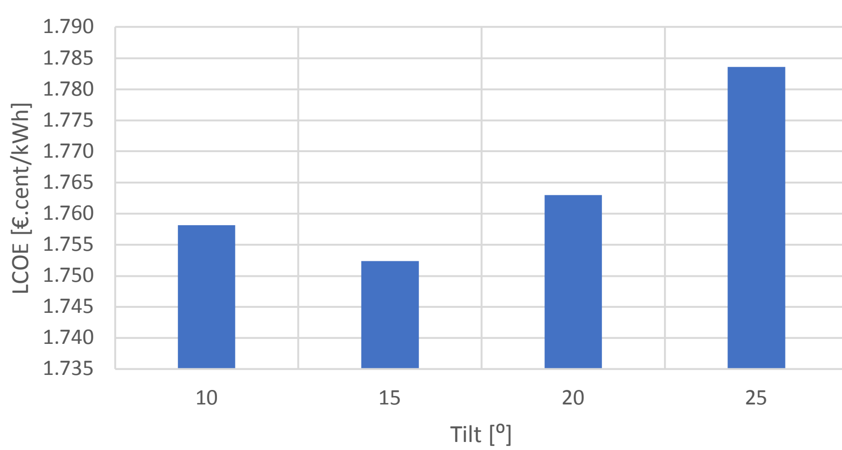


Figure 3.5 LCOE changes against tilt angle for Khartoum city

3.1.3. Optimal tilt and pitch distance

Table 3.3 summarizes the design results of LCOE by €.cent/kWh under different combination scenarios of tilt angle and pitch distance. Through this table, the deviations of LCOE are very small especially when the pitch distance equals to 4, 5, and 6 m where PRs, in these cases, are very close and the near shading is around 1 %, (see Table 3.3). Also, there is a small difference between the best design (5 m, 15°) and the worst one (3 m, 25°) which equals to 0.189 €.cent/kWh.

Table 3.3 LCOE by €.cent/kWh according to variations of tilt angle and pitch distance for Khartoum city

Pitch distance [m] / Tilt [°]	3	4	5	6
10	1.841	1.755	1.758	1.768
15	1.867	1.755	**1.752**	1.760
20	1.900	1.771	1.763	1.766
25	1.941	1.800	1.784	1.784

Figure 3.6 shows the 3-dimensional diagram indicating the comparison of characteristics between LCOE and both pitch distance and tilt angle. It is well stated that LCOE increases by increasing the pitch distance. Similarly, the lower LCOEs are situated around the optimal tilt angle 15°, then LCOE increases with the deviation of tilt angle form the optimal one, whether by increasing or decreasing. The red line corresponds to the selected optimal parameters such as 5 m of pitch distance and 15° of PV panel tilt angle which corresponds to the LCOE of 1.752 €.cent/kWh.

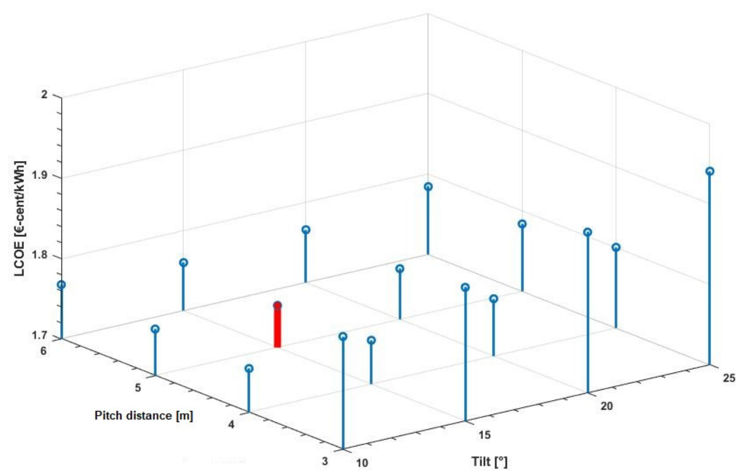


Figure 3.6 3D-variation of LCOE against tilt and pitch distance for Khartoum city

In previous paragraphs, the spotlight has been focused on Khartoum city results minutely, while the rest of the results had been managed in the same processing way according to the followed methodology in this thesis (see Figure 1.1).

3.2 Optimal design in all cities and analysis the impacts of climate on the optimal design

As the distance of the site location increases from the equator in both directions (north and south), the pitch distance and tilt angle increase accordingly. This is logical due to the decrease in the height of the path of the sun in the sky. Through *Table 3.4*, the results can illustrate and explain the influences of climate regions on the optimal design of PV array:

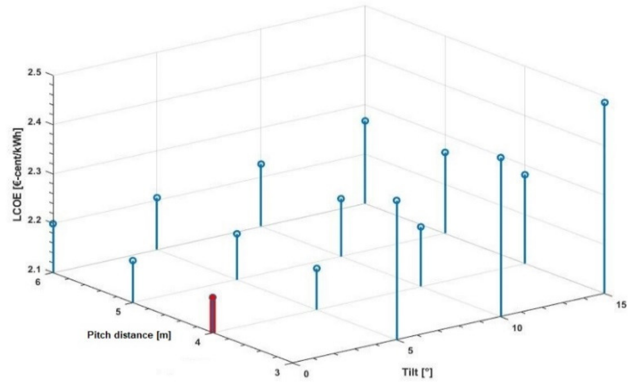
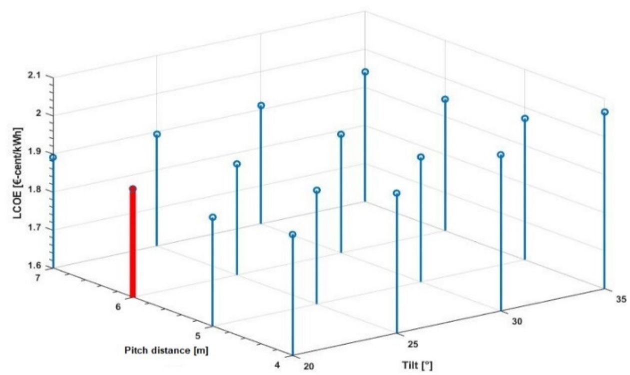
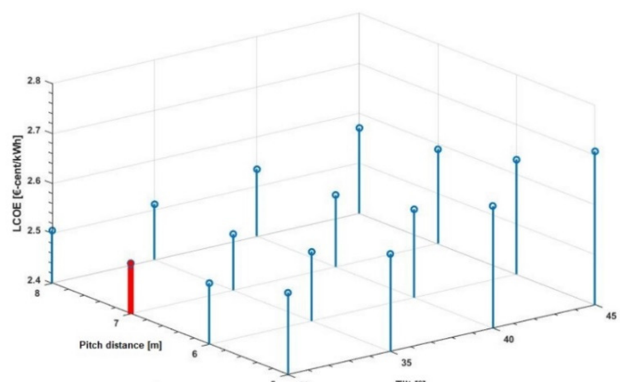
- In the tropic zone, the optimal tilt is equal to the latitude of the site location exact or in the range -5° accompanied with relative small optimal pitch distance due to there are no big differences in the solar irradiation in the seasons over the year, this means the PV array needs less area compared to other climate zones.
- In the temperate zone, the optimal tilt is less than the latitude of the site location in the range 10° up to 25°, while the optimal pitch distance increases as increasing the latitude in both directions north and south due to the seasonal variation of solar height over the horizon and too big differences in solar irradiation between the summer and winter, thus the PV array needs more area thus more expense increase LCOE.
- In the polar zone, both the optimal tilt angle and pitch distance continue to increase, although that the optimal tilt angle is equal to less than the latitude of site location around 30° due to the solar irradiation is almost negligible during the winter season, thus more area is needed, this leads to higher LCOE.
- Although the step of pitch distance is 1 m, the PV array area increases significantly which equals to the number of rows multiplied by the number of modules in one row, here lies the importance of achievement of the least possible area to reduce the expenses in the capital investment, thus obtain the lowest LCOE.

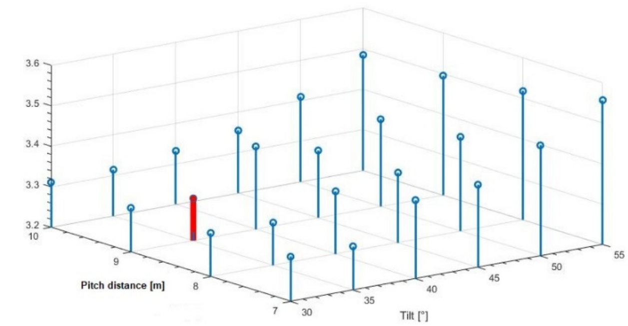
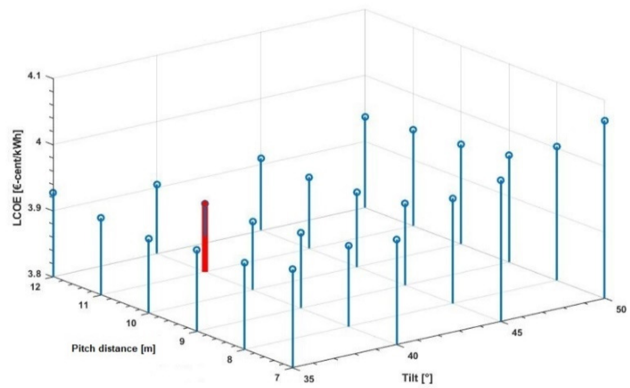
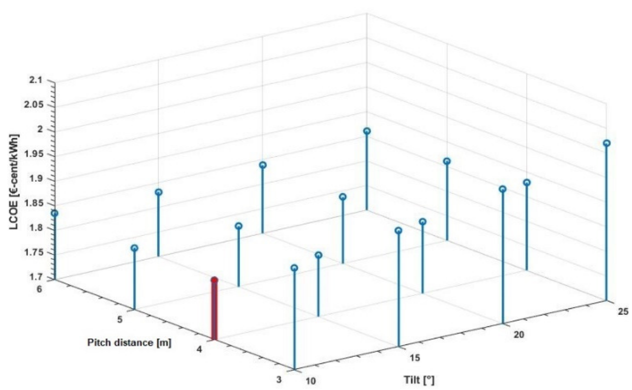
Table 3.4 summary of information and simulation results for all cities

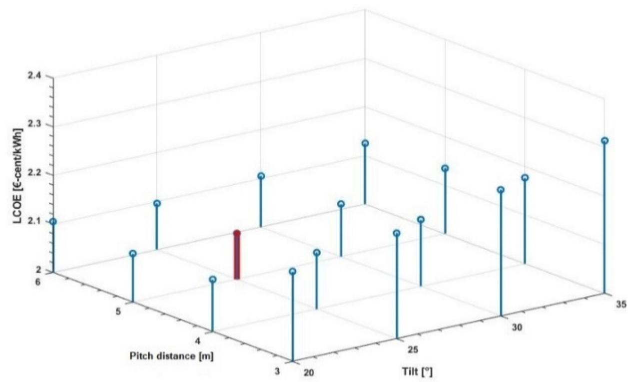
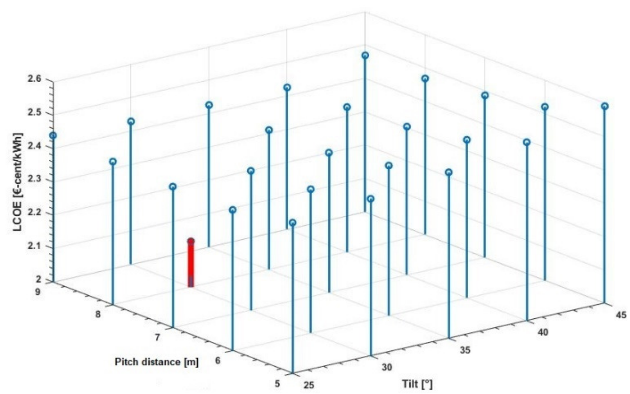
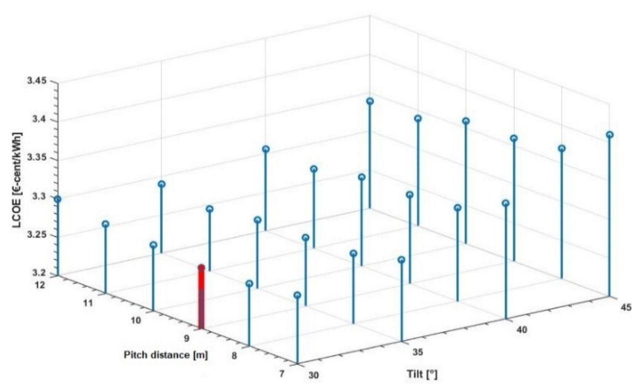
City	Pitch distance [m]	Tilt [°]	LCOE [€.cent/kWh]	PR [%]	Yield [kWh/kWyear]	Production [MWh/year]	Area [m²]
Tromsø	11	40	3.903	88	855	855	20497
St. Petersburg	10	35	3.304	86	996	997	16915
Turin	7	30	2.501	85	1301	1300	13333
Cairo	6	20	1.885	82	1710	1709	10700
Khartoum	5	15	1.752	79	1832	1831	9552
Kampala	4	0	2.172	83	1466	1465	8988
Songo	4	10	1.821	82	1753	1752	7960
Durban	6	25	2.094	82	1539	1539	10700
Dunedin	8	30	2.138	86	1532	1532	15124
Rio Grande	9	30	3.279	88	1005	1005	16915

The next figures show the 3D graph and the small difference between the rest of the studied locations and their most important specifications.

Table 3.5 3D-variation of LCOE against tilt and pitch distance in all locations excluding Khartoum city

No	3D graph	Specifications
1	 *Figure 3.7 3D variation of LCOE against tilt and pitch distance for Kampala city*	1. The optimal tilt angle is 0° and pitch distance is 4 m and LCOE equal to 2.172 €.cent/kWh. 2. LCOE increases with tilt and pitch distance. 3. LCOE is a bit high despite the small PV array area due to the low annual yield.
2	 *Figure 3.8 3D variation of LCOE against tilt and Pitch distance for Cairo city*	1. The optimal tilt angle is 20° and pitch distance is 6 m and LCOE equal to 1.885 €.cent/kWh. 2. LCOE is quite low due to the high annual yield and small pitch distance.
3	 *Figure 3.9 3D variation of LCOE against tilt and pitch distance for Turin city*	1. The optimal tilt angle is 30° and pitch distance is 7 m and LCOE equal to 2.501 €.cent/kWh. 2. LCOE increase is due to the lower yield slightly.

No	3D graph	Specifications
4	 *Figure 3.10 3D variation of LCOE against tilt and pitch* distance *for St. Petersburg city*	1. The optimal tilt angle is 35° and pitch distance is 10 m and LCOE equal to 3.304 €.cent/kWh. 2. LCOE is high due to the low annual yield and the high pitch distance.
5	 *Figure 3.11 3D variation of LCOE against tilt and pitch distance for Tromsø city*	1. The optimal tilt angle is 40° and pitch distance is 11 m and LCOE equal to 3.903 €.cent/kWh. 2. The optimal tilt is lower than the latitude of location by 29° due to the irradiation in the winter season is negligible.
6	 *Figure 3.12 3D variation of LCOE against tilt and pitch distance for Songo city*	1. The optimal tilt angle is 10° and pitch distance is 4 m and LCOE equal to 1.821 €.cent/kWh. 2. The optimal tilt angle is slightly small one due to the city location is in the equatorial zone where the inclination of radiation is very small slightly.

No	3D graph	Specifications
7	 *Figure 3.13 3D variation of LCOE against tilt and pitch distance for Durban city*	1. The optimal tilt angle is 25° and pitch distance is 6 m and LCOE equal to 2.094 €.cent/kWh. 2. LCOE is higher than one of Cairo city due to lower annual yield.
8	 *Figure 3.14 3D variation of LCOE against tilt and pitch distance for Dunedin city*	1. The optimal tilt angle is 30° and pitch distance is 8 m and LCOE equal to 2.138 €.cent/kWh. 2. LCOE is lower than Turin´s one as an equivalent city in the northern hemisphere due to higher annual yield.
9	 *Figure 3.15 3D variation of LCOE against tilt and pitch distance for Dunedin city*	1. The optimal tilt angle is 30° and pitch distance is 9 m and LCOE equal to 3.279 €.cent/kWh. 2. The optimal tilt is lower than the latitude of location due to the irradiation, in the winter season, is ineffective.

Appendix E contains all tables for LCOE by €.cent/kWh according to variations of tilt angle and pitch distance for Khartoum city for the 9 cities.

4 Discussion

- **Finding the optimal tilt angle in different ways**

The global tilted irradiation (GTI) shows the amount of irradiation received by the module installed at a specific tilt angle. The optimal tilt angle, that maximizes the total annual irradiation, varies by latitude and sun position. Simulation software (PVsyst in this study) can be used to calculate the GTI and suggest an optimum tilt in fixed-tilted PV arrays for whole seasons in each location.

According to the rules of thumb, the minimum angle of 10°…15° is suggested to avoid settlement of dust and dirt. Moreover, the tilt angle against the horizontal can be considered equal to the latitude of the installation site, but in areas with latitude higher than 30°, the tilt angle is usually considered about 5° and 20° less than the latitude [22]. The suggested optimal tilt angles in this study in different latitudes, have compared with the optimal tilt angle suggested by PVsyst and rules of thumb in Table 4.1.

Table 4.1 Optimal tilt angles in different latitudes

#	City	Latitude	Optimal tilt suggested in this study [°]	Optimal tilt suggested by Pvsyst [°]	Optimal tilt suggested by rules of thumb [°]
1	Tromsø	69° N	40	45	50 … 65
2	Petersburg	60° N	35	45	40 … 55
3	Turin	45° N	30	40	25 … 40
4	Cairo	30° N	20	26	30
5	Khartoum	15° N	15	20	15
6	Kampala	0°	0	0	0
7	Songo	15° S	10	20	15
8	Durban	30° S	25	26	30
9	Dunedin	45° S	30	40	25 … 40
10	Rio Grande	54° S	30	45	45 … 50

Modules installed in the higher tilt angles have lower soiling losses, because module's surface can be cleaned by natural flow of rainwater and snow slides off easily, but on the other hand modules with higher tilt create more shading on modules behind them which decrease the energy yield According to Table 4.1, suggested tilts in this study, which minimize the LCOE, in most area are about 5° to 15° less than the suggested tilts by PVsyst, which have calculated just considering highest energy production. Furthermore, optimal tilt gained of rules of thumb are closer to the values calculated in PVsyst than suggested tilt in this study, which seems this approximation is based on higher produced energy in similar way to PVsyst. Suggestion of lower tilt in this study is due to other parameters together with annual yield of energy are effective in LCOE calculation which in total leads to less values for modules inclination.

Considering the cost of cleaning and weather condition for solar system installed in Kampala and Songo, which have the optimal tilt less than 15°, an investigation for the need of increase in inclination can be done in future works.

- **Finding the optimal pitch distance**

The row spacing between two modules is defined as the distance between one edge of one of them to another. Theoretically, there are some formulas which suggest the minimum pitch distance without or with a few shadings between module rows [13] [34]. The minimum distance in these formulas related to the height of sun, the declination and the dimension of modules. The pitch distance increases in higher tilt angles and when the height of sun reduces [35]. Designing based on the rule of thumb is to space the rows in a way that there is no shading (or the annual shading loss less than 1 %) at solar noon in winter solstice in the northern hemisphere and summer solstice in the southern hemisphere [4].

In this study, the criteria to find the optimal row spacing has been the least LCOE, so it needs a tradeoff between area required and yield of energy which both can impact on cost of produced energy. Figure 4.1 shows the density of annual produced energy in different latitudes. The highest density is for cities located in tropic zone and these values decrease while going toward north and south poles. Keeping shading loss less than 1 % in temperate and polar zones needs a noticeable rise in the area which rises the land cost and at the result leads to an increase in LCOE.

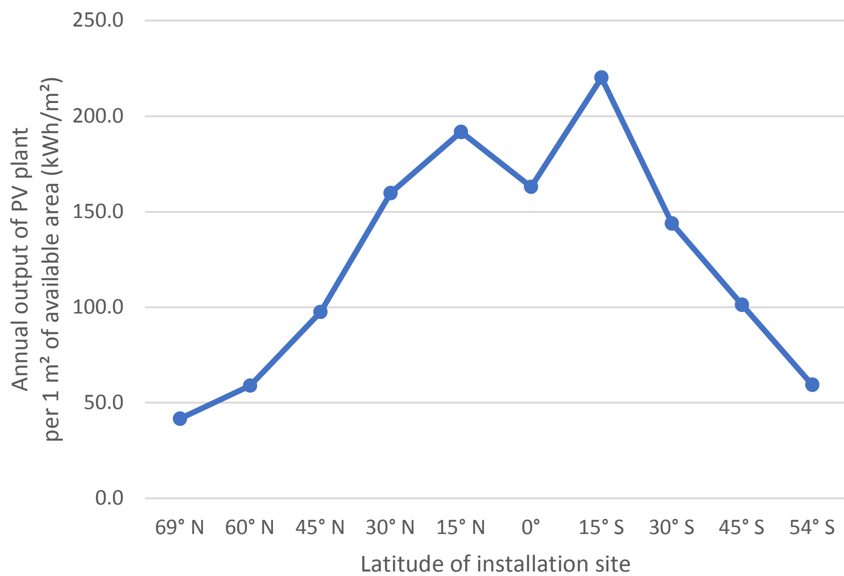


Figure 4.1 Annual output of PV plant per 1 m² of available area (kWh/m²) and annual shading loss in different climates in the optimal pitch distance and tilt

There is a peak in latitude 15° S, which is because of the least area required for this location and relatively high production in this city (*Table 3.4*). There is a valley in Figure 4.1, which has occurred in latitude 0°. According to mentioned weather specification in Table 2.2 , the monthly mean horizontal global irradiation in Kampala city (latitude 0°) is less than Khartoum (latitude 15° N) and almost equal to Songo (latitude 15° S). Moreover, the produced energy in the city located in 0° is lower than cities in latitudes 15° N and 15° S (according to *Table 3.4*), which even lower area required in this city in comparison with city in 15° N cannot compensate that.

- **Impact of module configuration on pitch distance selection**

In solar plant with the selected configuration of 2-P, the height of array is 3.34 m and in 3-L configuration, it is 3.04 m. That means in designed system for Kampala with the tilt of zero degree, the row spacing is limited considering the height of array. Since the configuration selected for Kampala is 2-P, around 0.65 m has considered for maintenance and cleaning which means the least possible space between rows should be higher than 4 m. The selected cleaning method can determine the least space required between rows for cleaning and maintenance.

- **Trend of least LCOE in different climates**

The least cost of produced energy is in the 15° S latitude and it rises with going toward poles. Figure 4.2 illustrates trend of LCOE and area required for installation of 1 MW solar plant in different climates. For Kampala, the area required is lower than Khartoum, but LCOE is higher because of less yield of energy in this city.

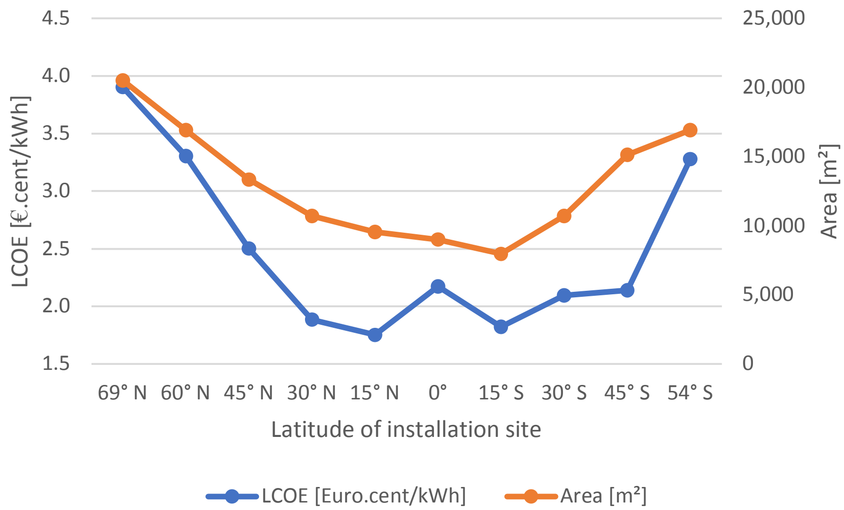


Figure 4.2 LCOE and area required for different climates

- **Impact of the climate on the optimal tilt and pitch distance**

Figure 4.3 demonstrates the suggested optimal solar module inclination and inter row spacing in large scale PV plants in different climates. Tilt angle and pitch distance should be increased by getting far from equator line in either northern or southern hemisphere continuously. The maximum difference in calculated values for the same latitude in northern and southern hemisphere is 5° for optimal tilt and 1 m for optimal pitch distance.

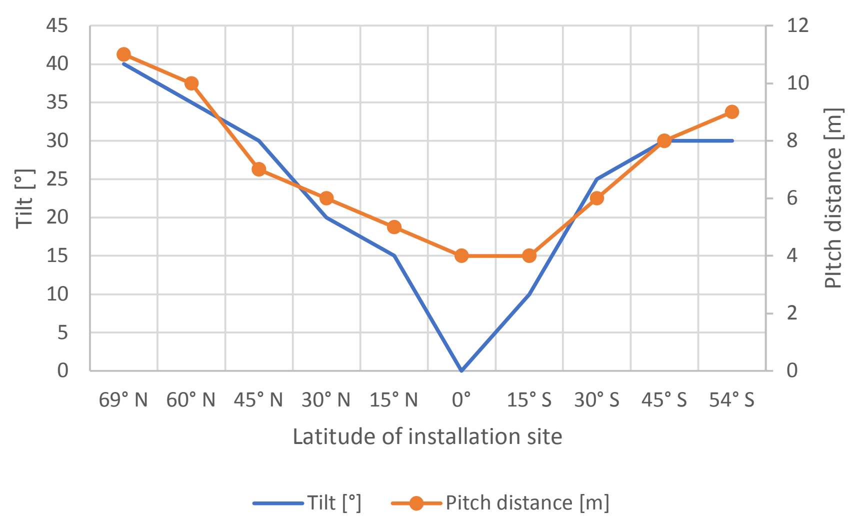


Figure 4.3 Optimal tilt angle and pitch distance in large-scale PV plant in different climates

The tilt angle of modules in a solar plant affects the amount of solar radiation received. Low tilt angles are suggested for countries near the equator because the sun is higher in the sky and PV panels can capture the direct sunlight in low tilt angles. On the other hand, the sun is lower in sky in higher latitudes and the suggested tilt angle increases by getting close to south and north polar in order to receive more direct. The space between rows of modules are least in lower latitude, because the amount of row-shading loss is not high in lower tilt. But in further locations to equator, the space increases to reduce row-shading power loss.

5 Conclusions

In this study, a framework has been developed to optimize the tilt angle and pitch distance in large scale PV plant. The considered criteria for optimization is the least LCOE and the impact of different climate conditions on the optimal values has been investigated. In method used, 10 site locations in different latitudes with about 15° step selected to cover a range of different climates. At first a 1 MW solar plant have been designed as components used would be suitable in every climate. In order to focus on the impact of climates, the type and number of components were considered the same in the selected sites. Then it has been decided which module configurations work better in each site. In each location, simulation was done for several tilt angles and pitch distances in PVsyst program and the LCOE was calculated in each condition considering the area required and produced energy gained of PVsyst. At the end the tilt and pitch distance which leads to the least LCOE in each site was introduced as the optimal values in this study. Financial parameters and land lease cost were assumed constant for all sites to gain better knowledge of climate effect.

The major findings of this study can be summarized as following:

- The optimal tilt of angles increases with getting far of the equator line in a range between 0° and 40°.
- The optimal raw spacing grows by getting far of the equator to reduce self- shading loss in a range between 4 m to 11 m. The minimum space between rows is determined according to the dimension of equipment, vehicular access, security fences and other needed structures.
- The configuration of modules affects on area required and yield of energy.

In this study, financial parameters and land lease cost were assumed constant for all sites to gain better knowledge of climate effect. Moreover, the type, number and cost of components were considered the same in the selected sites. The following cases can be suggested to be studied in future works:

- Different technologies of solar modules produce different amount of energy per 1 m^2. The impact of using various technologies on the optimal tilt and pitch distance and power density in large-scale PV array in various climates can be studied in future works.
- Since self-cleaning feature in some modules can decrease the maintenance cost, its impact on LCOE can be investigated.
- The impact of changing the module inclination twice a year in the seasons summer and winter on the optimal tilt angle and row spacing in different climates can be noticeable.
- An investigation for the need of increase in inclination in the areas with suggested tilt angles less than 15° in order to decrease the cleaning costs will be considerable.

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Appendix A
Jinkosolar 280 W module datasheet

www.jinkosolar.com

JinKO Solar
Building Your Trust in Solar

Eagle 60P
260-280 Watt
POLY CRYSTALLINE MODULE

Positive power tolerance of 0~+3%

ISO9001:2008、ISO14001:2004、OHSAS18001 certified factory.
IEC61215、IEC61730 certified products.

(5BB)

KEY FEATURES

5 Busbar Solar Cell:
5 busbar solar cell adopts new technology to improve the efficiency of modules , offers a better aesthetic appearance, making it perfect for rooftop installation.

High Power Output:
Polycrystalline 60-cell module achieves a power output up to 280Wp.

PID RESISTANT:
Eagle modules pass PID test, limited power degradation by PID test is guaranteed for mass production.

Low-light Performance:
Advanced glass and surface texturing allow for excellent performance in low-light environments.

Severe Weather Resilience:
Certified to withstand: wind load (2400 Pascal) and snow load (5400 Pascal).

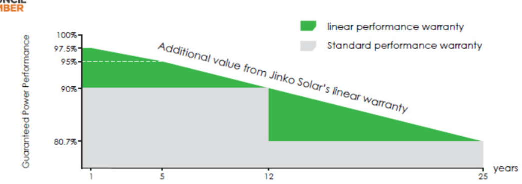
Durability against extreme environmental conditions:
High salt mist and ammonia resistance certified by TUV NORD.

Temperature Coefficient:
Improved temperature coefficient decreases power loss during high temperatures.

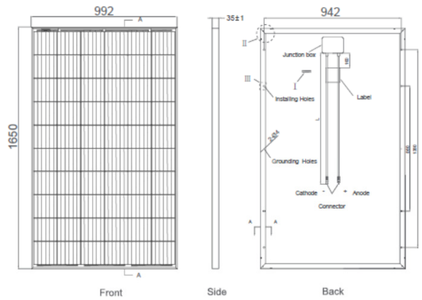
PV CYCLE · CE · POSITIVE QUALITY · CLEAN ENERGY COUNCIL MEMBER

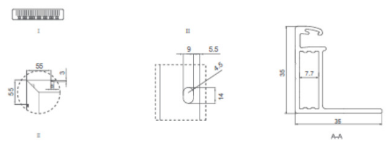
LINEAR PERFORMANCE WARRANTY

10 Year Product Warranty • 25 Year Linear Power Warranty



Engineering Drawings



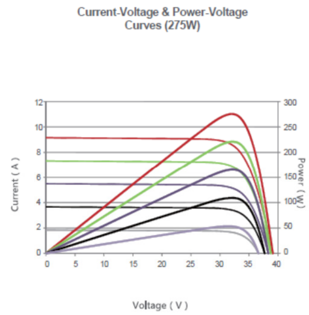


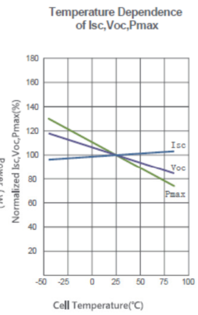
Packaging Configuration

(Two pallets=One stack)

30pcs/pallet, 60pcs/stack, 840 pcs/40'HQ Container

Electrical Performance & Temperature Dependence





Mechanical Characteristics

Cell Type	Poly-crystalline 156×156mm (6 inch)
No.of cells	60 (6×10)
Dimensions	1650×992×35mm (65.00×39.05×1.37 inch)
Weight	19.0 kg (41.9 lbs)
Front Glass	3.2mm, Anti-Reflection Coating, High Transmission, Low Iron, Tempered Glass
Frame	Anodized Aluminium Alloy
Junction Box	IP67 Rated
Output Cables	TÜV 1×4.0mm², Length: 900mm or Customized Length

SPECIFICATIONS

Module Type	JKM260PP-60		JKM265PP-60		JKM270PP-60		JKM275PP-60		JKM280PP-60	
	STC	NOCT	STC	NOCT	STC	NOCT	STC	NOCT	STC	NOCT
Maximum Power (Pmax)	260Wp	193Wp	265Wp	197Wp	270Wp	200Wp	275Wp	204Wp	280Wp	208Wp
Maximum Power Voltage (Vmp)	31.1V	28.7V	31.4V	29.0V	31.7V	29.4V	32.0V	29.8V	32.3V	30.1V
Maximum Power Current (Imp)	8.37A	6.71A	8.44A	6.78A	8.52A	6.80A	8.61A	6.85A	8.69A	6.91A
Open-circuit Voltage (Voc)	38.1V	35.2V	38.6V	35.3V	38.8V	35.4V	39.1V	35.4V	39.4V	35.6V
Short-circuit Current (Isc)	8.98A	7.31A	9.03A	7.36A	9.09A	7.38A	9.15A	7.44A	9.20A	7.99A
Module Efficiency STC (%)	15.88%		16.19%		16.50%		16.80%		17.11%	
Operating Temperature(℃)	-40℃~+85℃									
Maximum system voltage	1000VDC (IEC)									
Maximum series fuse rating	20A									
Power tolerance	0~+3%									
Temperature coefficients of Pmax	-0.40%/℃									
Temperature coefficients of Voc	-0.31%/℃									
Temperature coefficients of Isc	0.06%/℃									
Nominal operating cell temperature (NOCT)	45±2℃									

STC: Irradiance 1000W/m² Cell Temperature 25°C AM=1.5

NOCT: Irradiance 800W/m² Ambient Temperature 20°C AM=1.5 Wind Speed 1m/s

* Power measurement tolerance: ± 3%

Appendix B
CanadianSolar 280 W module datasheet

NEW

CanadianSolar

KuPower

HIGH EFFICIENCY POLY^GEN 3 MODULE

CS3K-275 | 280 | 285 | 290P

(1000 V / 1500 V)

With Canadian Solar's industry leading black silicon cell technology and the innovative LIC (Low Internal Current) module technology, we are now able to offer our global customers high power poly modules up to 290 W.

The KuPower poly modules with a dimension of 1675 × 992 mm, close to our 60 cell modules, have the following unique features:

- **Higher** power classes for equivalent module sizes
- **High** module efficiency up to 17.45 %
- **LOW** hot spot temperature risk
- **LOW** temperature coefficient (Pmax): -0.39 % / °C
- **LOW** NMOT (Nominal Module Operating Temperature): 43 ± 2 °C

More power output thanks to low NMOT: 43 ± 2 °C

Low power loss in cell connection

Safer: lower hot spot temperature

Heavy snow load up to 6000 Pa, wind load up to 4000 Pa*

1500 V

Low BoS cost with 1500 V_{DC} system voltage

*For detailed information, please refer to Installation Manual.

*Black frame product can be provided upon request.

25 years linear power output warranty

10 years product warranty on materials and workmanship

PRODUCT CERTIFICATES*

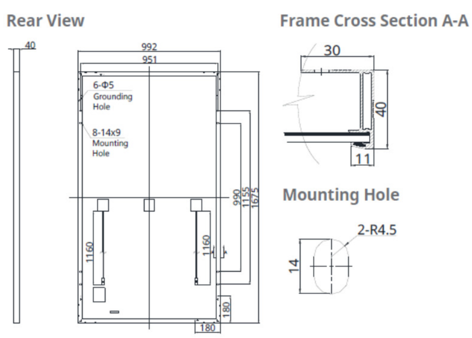
IEC 61215 / IEC 61730: 2005 & 2016: VDE / CE

CEC AU (Expected by end of Aug, 2017)

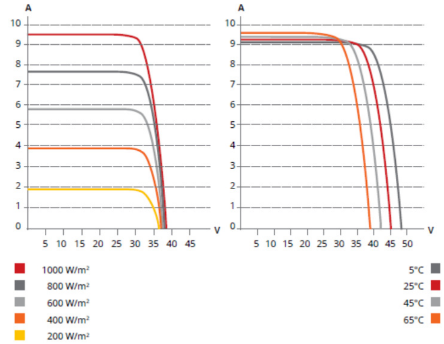
UL 1703: CSA

* Please contact your local Canadian Solar sales representative for the specific product certificates applicable in your market.

ENGINEERING DRAWING (mm)



CS3K-280P / I-V CURVES



ELECTRICAL DATA | STC*

CS3K	275P	280P	285P	290P
Nominal Max. Power (Pmax)	275 W	280 W	285 W	290 W
Opt. Operating Voltage (Vmp)	31.0 V	31.2 V	31.4 V	31.6 V
Opt. Operating Current (Imp)	8.88 A	8.98 A	9.08 A	9.18 A
Open Circuit Voltage (Voc)	37.7 V	37.9 V	38.1 V	38.3 V
Short Circuit Current (Isc)	9.38 A	9.47 A	9.56 A	9.64 A
Module Efficiency	16.55%	16.85%	17.15%	17.45%
Operating Temperature	-40°C ~ +85°C			
Max. System Voltage	1000 V (IEC / UL) or 1500 V (IEC)			
Module Fire Performance	TYPE 1 (UL 1703) or CLASS C (IEC 61730)			
Max. Series Fuse Rating	30 A			
Application Classification	Class A			
Power Tolerance	0 ~ + 5 W			

* Under Standard Test Conditions (STC) of irradiance of 1000 W/m², spectrum AM 1.5 and cell temperature of 25°C. Measurement uncertainty: ±3 % (Pmax).

ELECTRICAL DATA | NMOT*

CS3K	275P	280P	285P	290P
Nominal Max. Power (Pmax)	203 W	206 W	210W	214W
Opt. Operating Voltage (Vmp)	28.3 V	28.5 V	28.7 V	28.9 V
Opt. Operating Current (Imp)	7.18 A	7.23 A	7.32 A	7.41 A
Open Circuit Voltage (Voc)	35.1 V	35.3 V	35.5 V	35.7 V
Short Circuit Current (Isc)	7.58 A	7.64 A	7.72 A	7.79 A

* Under Nominal Module Operating Temperature (NMOT), irradiance of 800 W/m², spectrum AM 1.5, ambient temperature 20°C, wind speed 1 m/s.

MECHANICAL DATA

Specification	Data
Cell Type	Poly-crystalline, 156.75 × 78.38 mm
Cell Arrangement	120 [2 × (10 × 6)]
Dimensions	1675 × 992 × 40 mm (65.9 × 39.1 × 1.57 in)
Weight	18.5 kg (40.8 lbs)
Front Cover	3.2 mm tempered glass
Frame	Anodized aluminium alloy
J-Box	IP68, 3 diodes
Cable	4.0 mm² (IEC), 12 AWG (UL) ,1160 mm
Connector	T4 series or MC4 series
Per Pallet	27 pieces
Per Container (40' HQ)	756 pieces

TEMPERATURE CHARACTERISTICS

Specification	Data
Temperature Coefficient (Pmax)	-0.39 % / °C
Temperature Coefficient (Voc)	-0.31 % / °C
Temperature Coefficient (Isc)	0.05 % / °C
Nominal Module Operating Temperature	43±2 °C

PARTNER SECTION

The aforesaid datasheet only provides the general information on Canadian Solar products and, due to the on-going innovation and improvement, please always contact your local Canadian Solar sales representative for the updated information on specifications, key features and certification requirements of Canadian Solar products in your region.

Please be kindly advised that PV modules should be handled and installed by qualified people who have professional skills and please carefully read the safety and installation instructions before using our PV modules.

CANADIAN SOLAR INC. c/o Canadian Solar Australia 1 Pty Ltd, 165 Cremorne Street, Richmond, VIC 3121, Australia
support@canadiansolar.com, www.canadiansolar.com/au

* Manufactured and assembled in China.

Appendix C
ABB 100 kW Inverter datasheet

ABB

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SOLAR INVERTERS

ABB string inverters
PVS-100/120-TL

—
PVS-100/120-TL three-phase outdoor string inverter

The PVS-100/120-TL is ABB's cloud connected three-phase string solution for cost efficient decentralized photovoltaic systems for both ground mounted and large commercial applications.

This platform, for extreme high power string inverters with power ratings up to 120 kW, maximizes the ROI for decentralized ground mounted and large rooftop applications. With six MPPT energy harvesting is optimized even in shading situations.

Extreme power with high integration level
The extreme high power module up to 120 kW saves installation resources as less units are required. Due to its compact size further savings are generated in logistics and in maintenance. Thanks to the integrated DC/AC disconnection, 24 string connections, fuses and surge protection no additional boxes are required.

Ease of installation
The horizontal and vertical mounting possibility creates flexibility for both ground mounted and rooftop installations. Covers are equipped with hinges and locks that are fast to open and reduce the risk of damaging the chassis and interior components when commissioning and performing maintenance actions.

Standard wireless access from any mobile device makes the configuration of inverter and plant easier and faster. Improved user experience thanks to a build in User Interface (UI) enables access to advanced inverter configuration settings.

The installer mobile APP, available for Android/iOS devices, further simplifies multi-inverter installations.

The design supports both copper and aluminum cabling even up to 185 mm² cross section to minimize the energy losses.

Fast system integration
Industry standard Modbus/SUNSPEC protocol enables fast system integration. Two ethernet ports enable fast and future proof communication for PV plants.

ABB plant portfolio integration
Monitoring your assets is made easy as every inverter is capable to connect to ABB plant portfolio manager to secure your assets and profitability in long term.

Design flexibility and shade tolerance
The double stage conversion topology and six MPPT guarantee maximum flexibility for the system design on rooftops or hilly ground.
With this technological choice energy harvesting is optimized even in shading situations.

Highlights
- 6 independent MPPT
- Transformerless inverter
- 120 kW for 480 Vac and 100 kW for 400 Vac
- Wi-Fi as standard for configuration
- Two ethernet ports for plant level communication
- Large set of specific grid codes available which can be selected directly in the field
- Double stage topology for a wide input range
- Both vertical and horizontal installation
- Separate wiring compartment for fast swap and replacement
- IP66 Environmental protection
- Maximum efficiency up to 98.9%

ABB string inverters
PVS-100/120-TL
100 to 120 kW

Technical data and types

Type code	PVS-100-TL	PVS-120-TL
Input side		
Absolute maximum DC input voltage ($V_{max,abs}$)	1000V	
Start-up DC input voltage (V_{start})	420V (400...500 V)	
Operating DC input voltage range ($V_{dcmin}...V_{dcmax}$)	360...1000 V	
Rated DC input voltage (V_{dcr})	620V	720V
Rated DC input power (P_{dcr})	102 000W	123 000W
Number of independent MPPT	6	
MPPT input DC voltage range at ($V_{MPPTmin}...V_{MPPTmax}$) at P_{acr}	480...850V	570...850V
Maximum DC input power for each MPPT ($P_{MPPTmax}$)	17500 W [480V≤V_{MPPT}≤850V	20500 W [570V≤V_{MPPT}≤850V
Maximum DC input current for each MPPT (I_{dcmax})	36 A	
Maximum input short circuit current (I_{scmax}) for each MPPT	50 A [1]	
Number of DC input pairs for each MPPT	4	
DC connection type	PV quick fit connector [2]	
Input protection		
Reverse polarity protection	Yes, from limited current source	
Input over voltage protection for each MPPT - replaceable surge arrester	Type II with monitoring only for SX and SX2 versions; Type I+II with monitoring only for SY and SY2 versions	
Photovoltaic array isolation control	as per IEC62109	
DC switch rating for each MPPT	50 A / 1000 V	
Fuse rating (versions with fuses)	15 A / 1000 V [3]	
String current monitoring	SX2, SY2: (24ch) individual string current monitoring; SX, SY: (6ch) input current monitoring per MPPT	
Output side		
AC Grid connection type	Three phase 3W+PE or 4W+PE	
Rated AC power (P_{acr}@cosφ=1)	100 000 W	120 000 W
Maximum AC output power (P_{acmax} @cosφ=1)	100 000 W	120 000 W
Maximum apparent power (S_{max})	100 000 VA	120 000 VA
Rated AC grid voltage ($V_{ac,r}$)	400 V	480 V
AC voltage range	320...480 V [4]	384...576 [4]
Maximum AC output current ($I_{ac,max}$)	145 A	
Rated output frequency (f_r)	50 Hz / 60 Hz	
Output frequency range ($f_{min}...f_{max}$)	45...55 Hz / 55...65 Hz [5]	
Nominal power factor and adjustable range	> 0.995, 0...1 inductive/capacitive with maximum S_{max}	
Total current harmonic distortion	< 3%	
Maximum AC cable	185mm2 Aluminum and copper	
AC connection type	Provided bar for lug connections M10, single core cable glands 4xM40 and M25, multi core cable gland M63 as option	
Output protection		
Anti-islanding protection	According to local standard	
Maximum external AC overcurrent protection	225 A	
Output overvoltage protection - replaceable surge protection device	Type 2 with monitoring	
Operating performance		
Maximum efficiency (η_{max})	98.4%	98.9%
Weighted efficiency (EURO)	98.2%	98.6%
Communication		
Embedded communication interfaces	1x RS485, 2x Ethernet (RJ45), WLAN (IEEE802.11 b/g/n @ 2,4 GHz)	
User interface	4 LEDs, Web User Interface	
Communication protocol	Modbus RTU/TCP (Sunspec compliant)	
Commissioning tool	Web User Interface, Mobile APP/APP for plant level	
Remote monitoring services	Aurora Vision® monitoring portal	
Advanced features	Embedded logging, direct telemetry data transferring to ABB cloud	
Environmental		
Ambient temperature range	-25...+60°C /-13...140°F with derating above 40°C / 104 °F	

For more information please contact your local ABB representative or visit:

www.abb.com/solarinverters
www.abb.com

BCD.00662_EN REV. I 07.06.2018

Appendix D
CanadianSolar 60 kW Inverter datasheet

CanadianSolar

THREE PHASE STRING INVERTER 50-60 KW
CSI-50KTL-GI-HFL CSI-60KTL-GI-H

Canadian Solar's grid-tied, transformer-less string inverters help to accelerate the use of three-phase string architecture for commercial rooftop and small ground-mount applications. An NRTL approved, cost-effective alternative to central inverters, these inverters are modular design building blocks that provide high yield and enable significant BoS cost savings. They provide up to 98.8% conversion efficiency, a wide operating range of 200-800 VDC, and four MPPTs for maximum energy harvest.

10 years Standard warranty, extension up to 15 years

KEY FEATURES

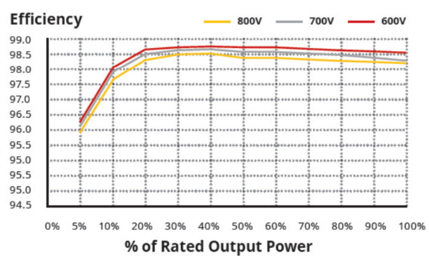
- Maximum efficiency of 99%, Maximum IEC efficiency of 98.5%
- 4 MPPTs to achieve higher system efficiency
- Transformerless design
- High switching frequency and ultra fast MPPT (<5 sec.) for maximum efficiency over a wide load range

HIGH RELIABILITY

- Advanced thermal design and convection cooling
- Built in over-voltage and over-current protection
- DC reverse polarity and AC short circuit protection

EFFICIENCY CURVE

CSI-60KTL-GI-H@480 Vac



*For detailed information, please refer to the Installation Manual.

BROAD ADAPTIBILITY

- IP65 rated for outdoor application
- Utility interactive controls: Active power derating, reactive power control and over frequency derating
- Integrated DC load rated disconnect
- Wide MPPT range for flexible string sizing
- 90 degree installation angle
- Supports up to 8 DC string inputs (2 per MPPT)

CANADIAN SOLAR INC. is committed to providing high quality solar products, solar system solutions and services to customers around the world. As a leading PV project developer and manufacturer of solar modules with over 25 GW deployed around the world since 2001, Canadian Solar Inc. is one of the most bankable solar companies worldwide.

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SYSTEM/TECHNICAL DATA		
MODEL NAME	**CSI-50KTL-GI-HFL**	**CSI-60KTL-GI-H**
DC INPUT		
Max. PV Power	60 kW (16 kW/MPPT)	72 kW (22.5 kW/MPPT)
Max. DC Input Voltage	1100 V_{DC}	
Operating DC Input Voltage Range	200-1000 V_{DC}	
Start-up DC Input Voltage/Power	200 V	
Number of MPP Trackers	4	
MPPT Full Power Voltage Range	568-850 V_{DC}	526-850 V_{DC}
Operating Current (Imp)	88 A (22 A per MPPT)	114 A (28.5 A per MPPT)
Max. Input Current (Isc)	137.2 A (34.3 A per MPPT)	178 A (44.5 A per MPPT)
Number of DC Imputs	8 (2 per MPPT)	12 (3 per MPPT)
DC Disconnection Type	Load rated DC switch	
AC OUTPUT		
Rated AC Output Power	50 kW	60 kW
Max. AC Output Power	55 kW	66 kW
Rated Output Voltage	480/500 V_{AC}	480/500 V_{AC}
Output Voltage Range*	384-576 V_{AC}	
Grid Connection Type	3 Φ/PE	
Nominal AC Output Current @480 Vac	60.2/57.7 A	72.2/69.3 A
Rated Output Frequency	50/60 Hz	
Output Frequency Range*	47-52/57-62 Hz	
Power Factor	1 default (±0.8 adjustable)	
Current THD	< 3 %	
SYSTEM		
Topology	Transformerless	
Max. Efficiency	99 %	
CEC Efficiency	98.5 %	
Night Consumption	< 1 W	
ENVIRONMENT		
Protection Degree	IP65	
Cooling	Natural Convection Cooling	Intelligent Redundant Cooling
Operating Temperature Range	-25 ° C to +60 ° C	
Storage Temperature Range	-40 ° C to +70 ° C	
Operating Humidity	0 - 100 %	
Operating Altitude	4000 m	
Audible Noise	<30 dBA @ 1 m	<60 dBA @ 1 m
DISPLAY AND COMMUNICATION		
Display	LCD + LED	
Communication	Standard: RS485 (Modbus)	
MECHANICAL DATA		
Dimensions (W / H / D)	630 x 700 x 357 mm	
Weight	61 kg	63 kg
Installation Angle	90 degrees from horizontal	
DC Inputs	MC4	
SAFETY		
Safety and EMC Standard	IEC62109-1/-2	
Grid Standard	AS4777, NRS097	
Smart-Grid Features	Voltage-Ride Thru, Frequency-Ride Thru, Soft-Start, Volt-Var, Frequency-Watt, Volt-Watt	

*The "Output Voltage Range" and "Output Frequency Range" may differ according to specific grid standard.

* The specifications and key features contained in this datasheet may deviate slightly from our actual products due to the on-going innovation and product enhancement. Canadian Solar Inc. reserves the right to make necessary adjustment to the information described herein at any time without further notice.

Caution: For professional use only. The installation and handling of PV equipment requires professional skills and should only be performed by qualified professionals. Please read the safety and installation instructions before using the product.

Appendix E
Results of other site locations

Table E.1 LCOE by €.cent/kWh according to variations of tilt angle and pitch distance for Kampala city

Tilt [°] \ Pitch distance [m]	3	4	5	6
0	2.468	2.383	2.423	2.488
5	**2.172**	2.184	2.221	2.280
10	2.185	2.193	2.217	2.264
15	2.199	2.205	2.226	2.267

Table E.2 by €.cent/kWh according to variations of tilt angle and pitch distance for Cairo city

Tilt [°] \ Pitch distance [m]	4	5	6	7
20	1.918	1.887	**1.885**	1.891
25	1.968	1.899	1.892	1.893
30	2.010	1.928	1.911	1.910
35	2.064	1.970	1.944	1.940

Table E.3 LCOE by €.cent/kWh according to variations of tilt angle and pitch distance for Turin *city*

Tilt [°] \ Pitch distance [m]	5	6	7	8
30	2.564	2.522	**2.501**	2.506
35	2.595	2.538	2.513	2.511
40	2.644	2.577	2.544	2.535
45	2.707	2.629	2.589	2.571

Table E.4 LCOE by €.cent/kWh according to variations of tilt angle and pitch distance for St. Petersburg *city*

Tilt [°] \ Pitch distance [m]	7	8	9	10
30	3.311	3.308	3.309	3.311
35	3.308	3.306	**3.304**	3.314
40	3.394	3.355	3.404	3.332
45	3.404	3.373	3.366	3.354
50	3.473	3.433	3.415	3.410
55	3.557	3.518	3.495	3.485

Table E.5 LCOE by €.cent/kWh according to variations of tilt angle and pitch distance for Tromsø city

Tilt [°] \ Pitch distance [m]	7	8	9	10	11	12
35	3.949	3.932	3.924	3.913	3.917	3.928
40	3.959	3.922	3.914	3.904	**3.903**	3.905
45	4.013	3.958	3.924	3.913	3.908	3.909
50	4.068	4.002	3.961	3.950	3.945	3.937

Table E.6 LCOE by €.cent/kWh according to variations of tilt angle and pitch distance for Songo city

Tilt [°] \ Pitch distance [m]	3	4	5	6
10	1.907	**1.821**	1.825	1.835
15	1.936	1.825	1.823	1.831
20	1.973	1.846	1.836	1.839
25	2.020	1.879	1.861	1.861

Table E.7 LCOE by €.cent/kWh according to variations of tilt angle and pitch distance for Durban city

Tilt [°] \ Pitch distance [m]	3	4	5	6
20	2.185	2.108	2.100	2.105
25	2.217	2.116	**2.095**	2.095
30	2.260	2.137	2.108	2.105
35	2.314	2.177	2.135	2.126

Table E.8 LCOE by €.cent/kWh according to variations of tilt angle and pitch distance for Dunedin city

Tilt [°] \ Pitch distance [m]	5	6	7	8	9
25	2.452	2.422	2.423	2.430	2.439
30	2.471	2.431	2.418	**2.138**	2.429
35	2.498	2.450	2.420	2.419	2.425
40	2.536	2.474	2.445	2.435	2.425
45	2.591	2.520	2.486	2.468	2.469

Table E.9 LCOE by €.cent/kWh according to variations of tilt angle and pitch distance for Rio Grande city

Tilt [°] \ Pitch distance [m]	7	8	9	10	11	12
30	3.289	3.282	**3.279**	3.286	3.290	3.300
35	3.306	3.291	3.289	3.289	3.281	3.290
40	3.350	3.321	3.316	3.315	3.303	3.306
45	3.410	3.369	3.360	3.359	3.340	3.339