TECHNO ECONOMIC FEASIBILITY STUDY ON AGRIVOLTAIC ELECTRICITY GENERATION IN SRI LANKA

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Thesis submitted in partial fulfillment of the requirements for the degree Master of Science

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DECLARATION

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ABSTRACT

A feasibility analysis for generating Photovoltaic Solar Electricity from agricultural areas as a sustainable solution for the increasing power demand in Sri Lanka. PV solar panels will be installed above the existing cultivated areas while maintaining spaces among rows of PV solar panels to provide the required solar radiation for the crops. Shading level is a critical parameter for the crop yield of a plantation and it was analyzed using DSSAT crop simulation software. DSSAT is a widely used software in agricultural researches for simulating crop growth under various environmental conditions. It takes crop models, soil profile data and annual weather data including solar radiation to simulate and predict the yield per hectare for a selected crop. Required Sri Lankan monthly weather data for DSSAT software simulation was obtained from Solar and Wind Energy Resource Assessment (SWERA) databases while Soil profile data were obtained from high resolution (10km grids) soil data file of International Food Policy Research Institute (IFPRI).

Both Mono-crystalline and Poly-crystalline panels were used for the evaluation and the annual energy generation was obtained using RET Screen software which is a widely used Canadian software. RET Screen has inbuilt databases of climate data for selected locations including Sri Lanka. Fixed angle solar arrays with south inclination of 8° and solar tracking with single axis rotation was considered for the evaluation. There were two different mathematical models which were used to obtain the relevant solar shading under the PV array for a given inter row spacing. Shading portions for diffusive solar radiation and direct solar radiation was obtained separately by considering panel tilts and the sun’s location with respect to the considered point under shading. Finally, the percentage of the shading was compared with pre obtained crop yield and shading relationship data to predict the feasible yield and to evaluate the technical and financial feasibility of the agrivoltaic system.

An excel based software tool was developed based on the collected databases and simulations to use as a preliminary decision making tool for selecting a crop, PV solar technology and arrangements for an appropriate area.

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LIST OF ABBREVIATIONS

DSSAT	Decision Support System for Agro technology Transfer
PV	Photovoltaic
SWERA	Solar and Wind Energy Resource Assessment
CEB	Ceylon Electricity Board
DNI	Direct Normal Irradiation
DHI	Diffusive Horizontal Irradiance
GHI	Global Horizontal Irradiation
SLSEA	Sri Lanka Sustainable Energy Authority
PUCSL	Public Utilities Commission of Sri Lanka
LECO	Lanka Electricity Company
TMY	Typical Meteorological Year

CHAPTER 1. INTRODUCTION

1.1. Background

Sri Lanka, while being an upper middle income earning country fulfills its energy needs either directly by primary energy sources such as biomass and petroleum or by secondary sources such as electricity generated using coal, petroleum, hydro power, wind power and biomass. As per the Annual PUCSL report of 2016, Generation mix of Ceylon Electricity Board was 35% of Coal, 31% of Oil, 25% of Hydro and 9% of Renewables. Energy sector experienced a severe dependency on imported energy sources. Reduced rainfall exerted more demand on petroleum imports with severe economic impact on the industry. Under this circumstance, the country had to depend on expensive petroleum based thermal power generation to fulfill the rising energy demand during the last few years. Hence this situation is emphasizing the fact that exploration of indigenous energy sources such as renewable energy derived from solar, wind, biomass, hydro and mini hydro is vital to survive through the crisis as well as to enhance the energy security in the country.

Solar energy is probably the most important renewable energy source available at present. Most of other renewable energy sources are also derived directly or indirectly from the solar energy. There are many advantages of solar energy such as its cleanliness, free availability, accessibility from most of the urbanized geographical locations of the country throughout almost the entire year, capability to operate independently or in conjunction with traditional energy sources and being remarkably renewable. Many applications of solar energy are presently in use for meeting electrical loads in most of the remote regions of Sri Lanka without electricity. Still, good potential exists in the country for significant expansion of the use of solar energy.

At present, there are two commonly used methods for harnessing solar energy which are practiced widely over the world. The first one is the conversion of solar energy into electricity by solar photovoltaic modules and its convenient use according to the end user requirement. The other method is the conversion of solar energy into thermal energy by using solar thermal collectors and it's utilization for thermal energy applications. Photovoltaic systems convert solar radiation into electricity via a variety of methods. The most common approach is using silicon panels, which generate an electric current when solar energy irradiates upon it. Solar thermal systems are used to store heat from the sun which can be used for a variety of purposes. Many different approaches exist for solar thermal energy utilization, including active systems such as solar hot water heaters and also passive systems such as greenhouses which store and utilize solar energy.

A good, quantitative knowledge about distribution and the extent of solar energy resources in Sri Lanka is essential in order to make accurate decisions on the application of solar technologies, and to properly size the systems to be designed to meet the desired loads. So an accurate prediction of incident solar radiation at a given location is of prime importance for any solar energy based application such as sizing modules in photovoltaic and thermal power systems, building design applications, agriculture etc. A study of this nature is important for a tropical country like Sri Lanka, where the annual average solar radiation is about 4.5 to6.5 $kWh/m^2/day$ [1]and solar energy being readily available throughout the year with low seasonal variations. Solar energy harnessing by solar photovoltaic modules is usually done on tilted surfaces fixed angle or solar tracking. Since Sri Lanka is located close to the equator single axis solar tracking is more appropriate to maximize the energy conversion.

Since Sri Lanka's sole electricity service provider CEB has a rapid power demand growth, it is required to generate power from a thermal energy source which introduces many challenges for the environment, energy security and economy. Sri Lanka imports all the required fuels for thermal power generation. Sri Lankan government is trying to change this situation by tending to generate more power from renewable energy sources. Since hydro power generations are all, mostly acquired, they are mainly focusing on PV solar as a future solution to achieve power stability in Sri Lanka.

Under this Vision, The Ministry of Power and Renewable Energy has launched a new community based power generation project titled “Soorya Bala Sangramaya” (Battle for Solar Energy) in collaboration with Sri Lanka Sustainable Energy Authority (SLSEA), Ceylon Electricity Board (CEB) and Lanka Electricity Company (Private) Limited (LECO) to promote the setting up of small solar power plants on the rooftops of households, religious places, hotels, commercial establishments and industries. It is expected to add 200 MW of solar electricity to the national grid by 2020 and 1000 MW by 2025 through this intervention [2].

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As discussed above Sri Lanka has a constant solar radiation all over the year. So it is possible to have a distribution power generation based on PV solar. Since 34% of Sri Lanka’s land is occupied by agricultural areas as per Department of Agriculture, it will be more fruitful if these agricultural lands could be converted to PV solar stations while maintaining the existing crops. In this case PV solar panels should be installed above the crops with self-supporting structures while maintaining enough space between the panels and crop canopy to have working space as well as proper ventilation for the crop. There will be a reduction of solar Radiation for the under grown crops and it should be closely analyzed by considering the shade tolerance of the crop. Some crops have a better performance under the shading and some have a lesser performance. This should be evaluated technically as well as financially.

1.2. Solar Energy Potential in Sri Lanka

Sri Lanka is located within the equatorial belt, a region where a substantial amount of solar energy resources exists throughout the year in adequate quantities for many of the solar energy applications including solar water heating, electricity generation etc. The extent of solar resources in Sri Lanka has been estimated by several parties in the past based on the daily total solar radiation recorded at a number of weather stations throughout the country and also based on the satellite observations. Recently National Renewable Energy Laboratory (NREL) which is a Laboratory of U.S

Department of Energy developed a model called Climatological Solar Radiation (CSR) which can be used to predict monthly and annually the average of the daily total solar radiation. CSR model provides monthly the average of the daily total solar radiation estimates for the seven years period from 1985 to 1991.The results of this study indicate that the distribution of solar resources measured in terms of the annual average of the daily insolation (on tilted surface where the tilt angle equals to the local latitude) varies from 4.5 to 6.0 kWh/m^2/day across the country, with the lowest values occurring in the hill country in the Central Province[3]. The seasonal variation in solar resources in Sri Lanka lies between 4.5 and 6.5 kWh/m^2/day (on a tilted surface where the tilt angle equals to the local latitude) (George et al., 2003). The CSR model predicts that the highest resources are available during the hot dry period between March and April when the transition from the northeast to southwest monsoons occurs.

Most of the solar energy application devices such as photovoltaic modules and flat plate solar thermal collectors are fixed at an angle to the horizontal plane for maximizing the solar energy harnessing process. Furthermore, concentrated type solar collectors are employed to obtain direct normal irradiation (DNI) with the aid of solar tracking systems. Figure 1.1 and 1.2 show the solar resource potential of direct normal irradiation on horizontal plane and the annual average of the daily total irradiance at tilted surface where the tilt angle is equal to the local latitude angle.

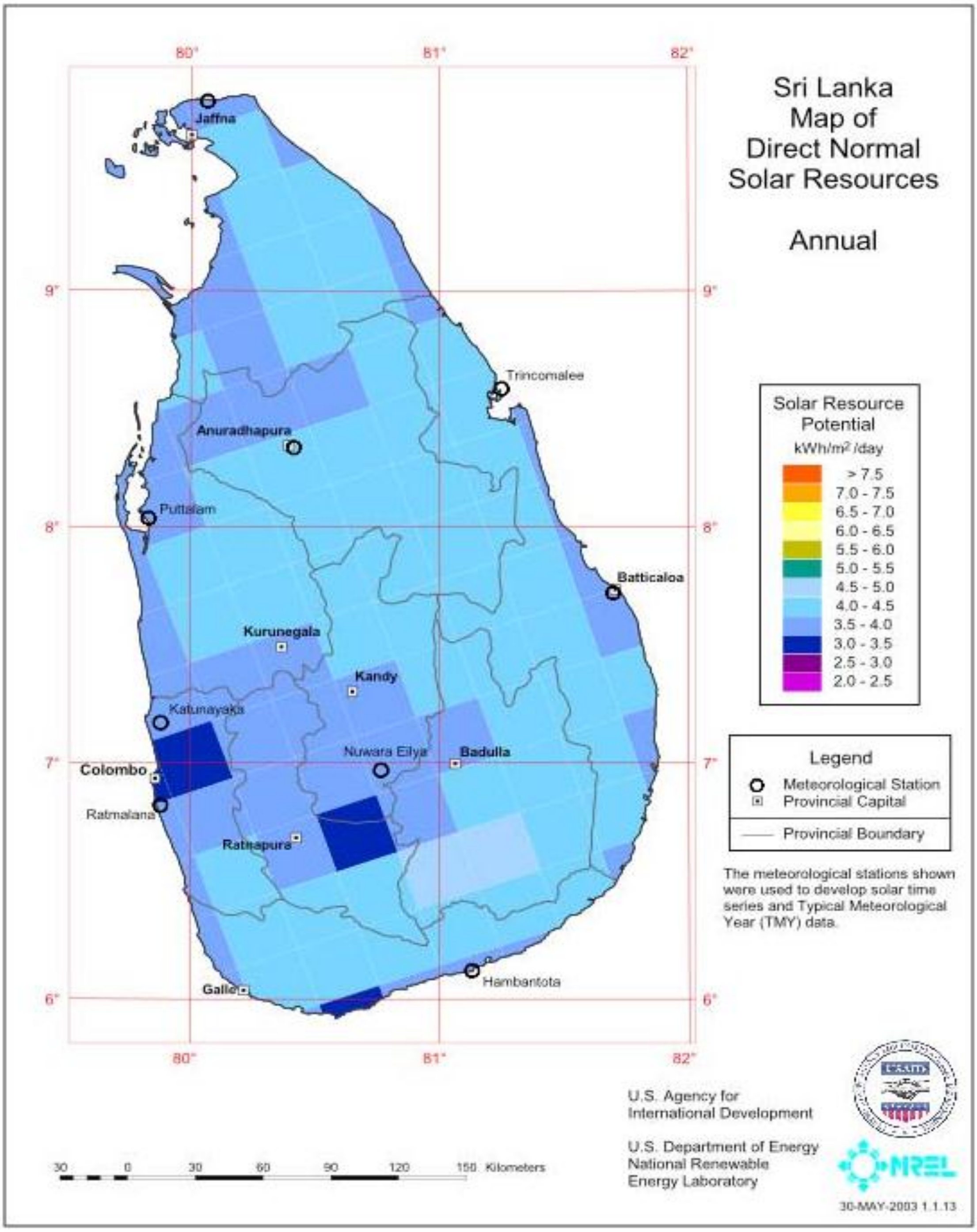


Figure 1.1 : Direct Normal Irradiation (DNI) data for horizontal plane

Source: Solar Resource assessment for Sri Lanka and Maldives by NREL

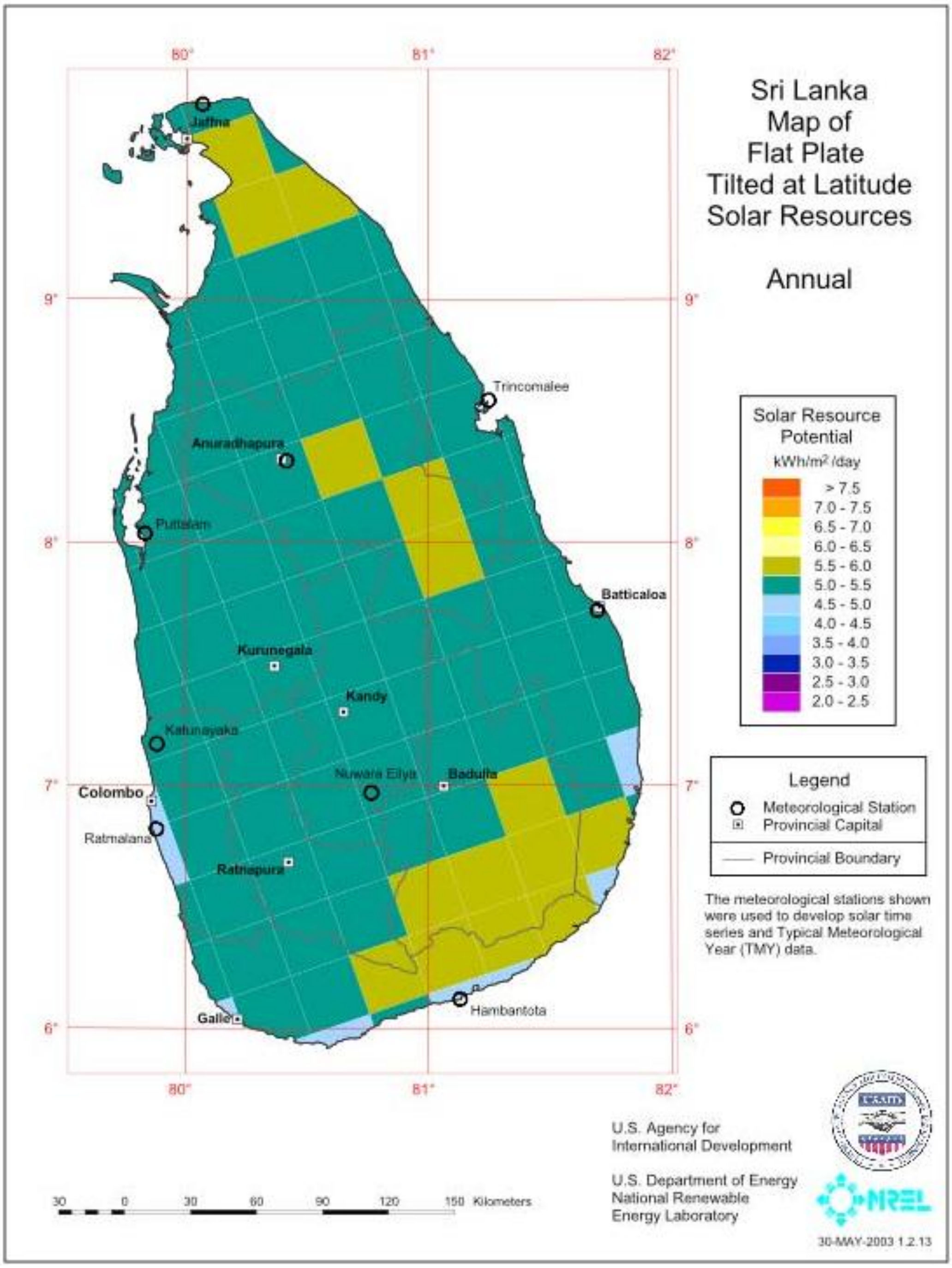


Figure 1.2 : Annual average daily total solar irradiance at surface tilted at latitude angle

Source: Solar Resource assessment for Sri Lanka and Maldives by NREL

The daily solar radiation of 5.0-5.5 kWh/m^2/day (on tilted surface where the tilt angle is equal to the local latitude angle) is possible in most parts of the country. Also it indicates that there exists a substantial solar energy harnessing potential in the dry zone of Sri Lanka

Another solar radiation model developed to estimate the monthly average of daily irradiance data for Colombo, averaged for the 22 years from 1983 to 2005 is available at the Atmospheric Science Data Center web site of National Aeronautics and Space Administration (NASA). This particular solar radiation model is called NASA-SSE model which is totally based on satellite measurements. This model estimates that 6.67 kWh/m^2/day as the maximum irradiance value which was estimated in March while 4.93 kWh/m^2/day as the minimum irradiance value which occurs in November [1]. The estimated annual average global horizontal solar insolation at Colombo is about 5.58 kWh/m^2/day[1].

Table 1.1 : 22 year averaged (1983-2005) monthly average daily global horizontal irradiance at Colombo (kWh/m2/day) derived by NASA-SSE model

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Avg
5.5	6.27	6.67	5.9	5.29	5.3	5.4	5.65	5.65	5.29	4.93	5.16	5.58

Source: NASA Atmospheric Science Data Center

Utilizing solar energy for off grid and grid applications in Colombo, the capital city of Sri Lanka, is economically viable for both in industrial and domestic sectors. Since a large amount of built up area is available in the capital city, an ample number of roof tops are available for solar energy harnessing systems. According to the measured solar radiation data for Colombo for the period from year 2000 to 2003 as illustrated in Figure 1.3, solar energy is available with sufficient intensity for more than six hours in the day time throughout the year. Hence, both solar photovoltaic modules and solar thermal collectors can efficiently operate during the major part of the day time in Colombo.

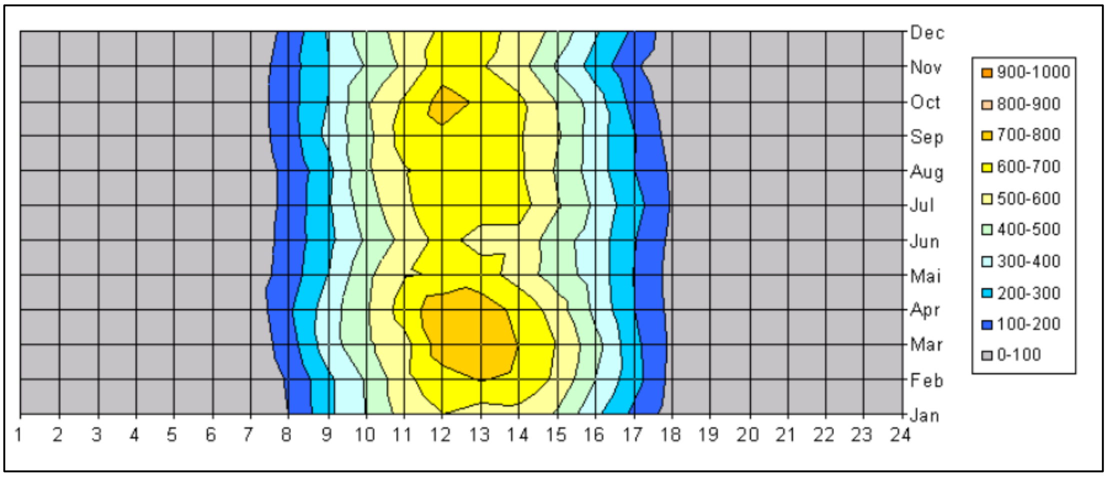


Figure 1.3 : Monthly average hourly global horizontal irradiation (W/m2) in Colombo for the duration from year 2000 to 2003

Source: Solar and Wind Energy Resource Assessment (SWERA) Report

1.3. Present Status of Solar Energy Applications in Sri Lanka

Sri Lanka's first solar power plant (figure 1.5), worth LKR 412million, has been commissioned and operates in Hambantota which adds 500 kW to the national grid[4]. Another solar power plant which costs LKR 1024 million was also installed in Hambanthota, and it contributes 737 kW to the national grid[4]. These pilot solar power projects operating in Hambantota completed a full weather cycle in 2012, and derived annual plant factors of 16.02% and 17.49% for the 500 kW plant and the 737 kW plant respectively [5].

LOLC has installed a 10 MW solar photovoltaic (PV) plant in Hambantota which has been interconnected to the medium-voltage network. The key equity provider (LOLC) and other minority partners have invested Rs.2.6 billion for the project Laugfs has installed 20 MW solar plant at Hambantota which has been commissioned recently. This is the largest power PV solar plant in Sri Lanka. Laugfs has invested about Rs. 5 billion for the project. Figure 1.4 shows the collective generation data of LOLC and Laugfs PV plants for 1st to 5th of March 2017.

Sri Lanka’s Ministry of Power and Renewable Energy and Ceylon Electricity Board (CEB), have called for bids with closing date (26th April 2017) for the construction of 60 PV Solar plants with a capacity of 1 MW each on Build Own & Operate (BOO) basis[6].The projects will be developed under phase II of the solar program ‘Soorya Bala Sangramaya’. CEB is willing to purchase power under a 20-year PPA. CEB has set a price ceiling of LKR 18.37($0.121)per kWh for the tender. The Ministry of Power and Renewable Energy also recently extended a loan scheme for the installation of small solar power plants on residential and commercial buildings.

CEB has also called bids for 10 MW PV solar plant in Polonnaruwa on BOO basis with the closing date of January 3, 2018 for the bids, and[7], 10 MW PV solar plant at Vaunatiu on BOO basis with the closing date of September 13, 2017 for the bids[8].

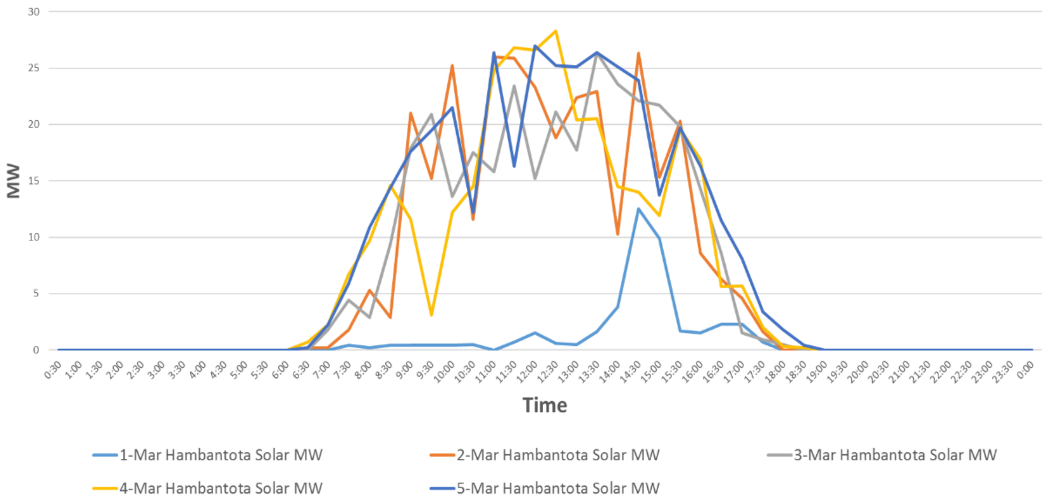


Figure 1.4: Solar Electricity generation of 10 MW LOLC plant and 20MW Laughs plant at Hambantota.

Source: Remote monitoring data, System Control Centre of CEB

Sri Lankan total installed capacity of the rooftop solar PV up to August 2017 is 74MW. Out of that only a 46MW capacity was added during the past one year after the “Battle for Solar” program was launched[9].

Figure 1.5 : Sri Lanka's first solar power plant in Hambantota

Under “SooryaBalaSangramaya” three types of agreements have been introduced [2]for rooftop customers as illustrated below;

Net Metering

The consumer generates electricity using solar panels fixed on their rooftops which are connected to the grid through a net metering system. The consumer has to pay only for the net amount of electricity that was consumed. If the solar electricity production exceeds the electricity consumption of the premises, the balance amount can be carried forward to future use up to 10 years. No fee will be paid for the excess electricity produced. Existing net metering consumers can switch to other schemes if they wish to. However, the accumulated electricity units prior to the signing of new agreements shall not be carried forward.

Net Accounting

If the electricity generation of solar rooftop system is greater than the consumption, the consumer will be paid for the excess according to the table below. If the consumption is greater than the generation, the consumer shall pay for the excess consumption according to the existing electricity tariff structure.

Net Plus

The total electricity generation from the solar rooftop system would be purchased by the utility. The bill for electricity consumption would be paid to the utility as usual.

The utility would pay the solar electricity producers for the excess electricity exported to the grid on the following basis with effect from the date of agreement signed with the utility.

Table 1.2 : CEB tariff plan for Solar

	Period	LKR / kWh
1	First 7 Years	22.00
2	8th to 20th year	15.50

Requirements for System Documentation, Installation, Testing & Commissioning were described under SLS 1522: 2016 Sri Lanka standard code for practice for grid connected photovoltaic power systems.

1.4. Problem Statement

By targeting only, the rooftops of the consumers in Sri Lanka, only 46MW of new rooftop customers have been added under the “Soorya Bala Sangramaya” project. This will not be enough to achieve the required target which is 1000MW by 2025. It has an increased dependency on roof top size, roof design, customer interests and shading of trees. Space limitation for PV Solar generation is the main barrier to introduce large scale solar plants in Sri Lanka in order to achieve renewable energy targets. To overcome this SEA and CEB are planning to install large scale power plants as the second phase of “Soorya Bala Sangramaya” discussed earlier.

According to the large scale PV solar plants installed in Hambantota, 45 acres are required for 10 MW approximately. Finding a bare land large enough for this installation is a severe issue for these projects and because of that many companies do not bid. Although suitable land exists in areas like Polonnaruwa and Vanuatu, most of them are cultivated areas or belong to the forest department. So there is a less probability for a general company to find a suitable land for large scale installation. Even if a suitable land if found, it may not be feasible to spend a high amount.

As a solution for this land limitation, the existing agricultural areas can be used as PV solar generation which will introduce new areas for the project. This is a hybrid system where crops and PV solar coexist in same land which is known as agrivoltaic systems. Since these lands are owned by companies and farmers who are already engaged in agricultural businesses, land cost concerns can be minimized by promoting the owners to convert their lands to hybrid systems. Before introducing agrivoltaic systems, much care should be given to the effects which can cause an issue with the crops grown below and the feasible generation from PV solar. So the agrivoltaic feasibility study should be done by selecting appropriate crops, areas and solar technologies. In this research a techno-economic feasibility study for agrivoltaic technology in Sri Lanka has been conducted which can be used as a pilot project for decision making while selecting agrivoltaic technology for appropriate crops and areas.

1.5. Key Objectives

1. Obtaining the relationship of crop yield under the shading of PV solar panels mounted above the crop canopy.
2. Estimate possible PV solar generations from selected major agricultural areas in Sri Lanka while considering the variation of crop yield.
3. Developing an excel based tool to analyze the techno economic feasibility and to support decision making for deploying agrivoltaic system under given field conditions.

1.6. Other Objectives

1. Study hourly direct and diffusive radiation of various areas in Sri Lanka
2. Study model PV solar arrays using solid angles to determined shading under fixed and single axis solar tracking.
3. Study DSSAT software for simulation of crop growth under shading.
4. Study the ROI of PV solar installation under given conditions.
5. Study Visual Basic macro programing to simplify data analysis in excel.

6. Study the crops which are suitable for agrivoltaic systems based on simulation results.

1.7. Outcomes

1. A mathematical model to predict solar radiation on crops under PV panels.
2. Database for shade performance of selected crops.
3. Database for possible PV solar generation of selected areas
4. Derivation of ROI in years for a PV solar spacing based on defined partial shading coefficient.
5. Estimation of maximum solar resource potential in Sri Lanka based on crops, area and PV solar arrangement.

1.8. Scope of the Study

Under this research the techno-economic feasibility of agrivoltaic electricity generation from agricultural areas while maintaining crop yield is evaluated. Both fixed and single axis solar tracking have been considered for the evaluation.

Colombo, Gampaha, Matara, Hambantota, Baticaloa, Tricomalee, Anuradhapura, Putlam and Jaffna are the interested areas under this research. Areas for the analysis were selected by considering crop distribution as well as land distribution to cover the whole country. The selected crops are Paddy, Corn, Tea, Chili Pepper, Pineapple, Tomato, Bean, Cowpea and Cabbage. Both Mono-Crystalline and Poly-Crystalline PV solar technologies are considered for the analysis.

1.9. Outline of the Study

The first chapter of this study describes the solar energy utilization characteristics in Sri Lanka and the potential for solar energy harnessing, particularly in Colombo. Current status of solar energy generation and its trends are also highlighted. Fundamental theories which describe solar geometry and basic concepts of solar radiation are discussed in Chapter 2. A literature review on correlations developed by various scientists and engineers is included in the same chapter. The research methodology is described in detail in Chapter 3. The results of the study are discussed in Chapter 4 and finally Chapter 5 is dedicated to present the findings and conclusions of this study.

CHAPTER 2. REVIEW OF LITERATURE

2.1. Fundamentals of Solar Radiation

2.1.1. Solar geometry

In order to study about the solar energy received at the earth's surface, a clear understanding on solar geometry is essential. There are some parametric angles defined under solar geometry to make this effort more convenient. Climate zones, seasonal temperature changes and daily temperature changes are largely determined by changes in the amount of energy received by the earth from the sun. The angle at which solar radiation strikes a surface dramatically affects the amount of energy received by the particular surface. Therefore, the amount of energy received at the earth's surface is a function of the angle at which solar radiation strikes the surface.

Solar declination angle (*δ*) illustrated in Figure 2.1 is the angle between a plane perpendicular to incoming solar radiation and the rotational axis of the earth. The earth's axis of rotation is always inclined at an angle of 23.5^0 from the ecliptic axis, normal to the ecliptic plane. The ecliptic plane is the plane of orbit of the earth around the sun. The solar declination angle varies from +23.45°on June 21 when the Earths' axis tilts toward the sun, to -23.45°on December 21 when the Earth's axis tilts away from the sun. The solar declination angle is 0° on equinox dates which are March 21 and September 21.

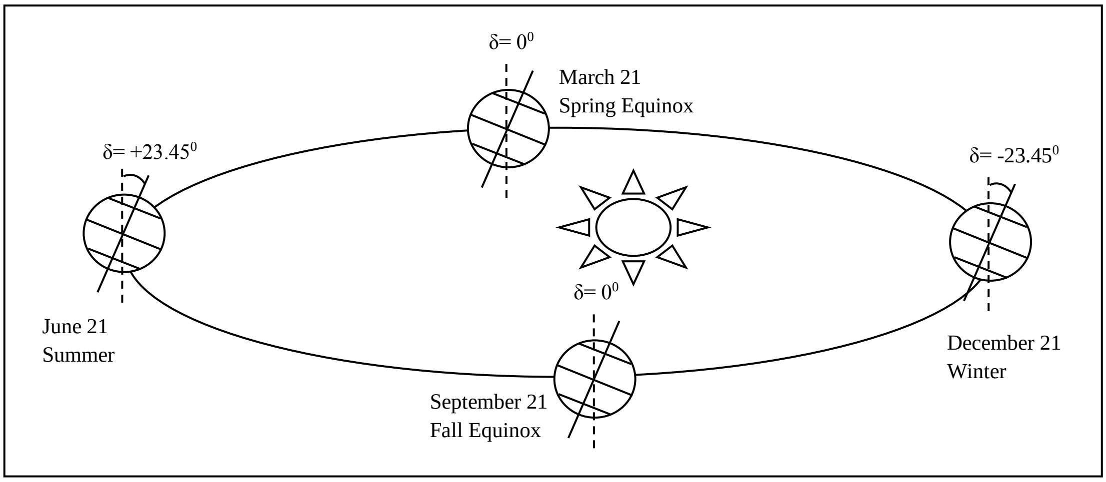


Figure 2.1 : Solar declination angle

Changes in the solar declination angle as the earth revolves around the sun create cyclic changes in solar radiation. These radiation changes contribute to cyclic weather changes that are referred to as seasons. The variation of the solar declination throughout the year is shown in figure 2.2 and the declination angle (δ) in degrees for any day of the year (N) can be calculated approximately by the Equation 2.1.

$$\delta^\circ = 23.45 \sin\left[\frac{360}{365}(284 + N)\right] \tag{2.1}$$

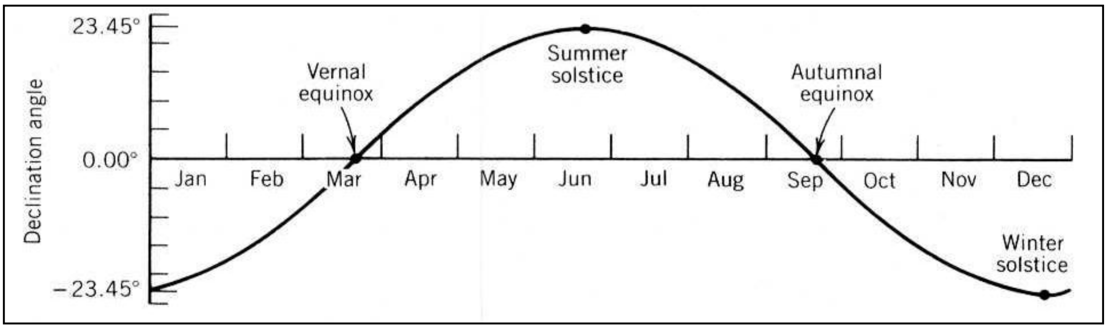


Figure 2.2 : Variation of the solar declination angle throughout the year
Source: www.powerfromthesun.net

Any location of the earth can be described by using the Latitude (ϕ) and the Longitude (L). The Latitude (ϕ) of a location is the angle made by the radial line joining the given location to the center of the earth with its projection on the equatorial plane. This angle indicates how far a particular location from the equatorial plane is. For Sri Lanka the Latitude angle varies between 6^0 to 10^0 on northern pole.

The earth is a sphere that rotates about its rotational axis 15^0per hour relative to the sun. An angle called the hour angle (ω)is defined which is the angle through which the earth has to rotate to bring the meridian plane of any place or location under the sun.

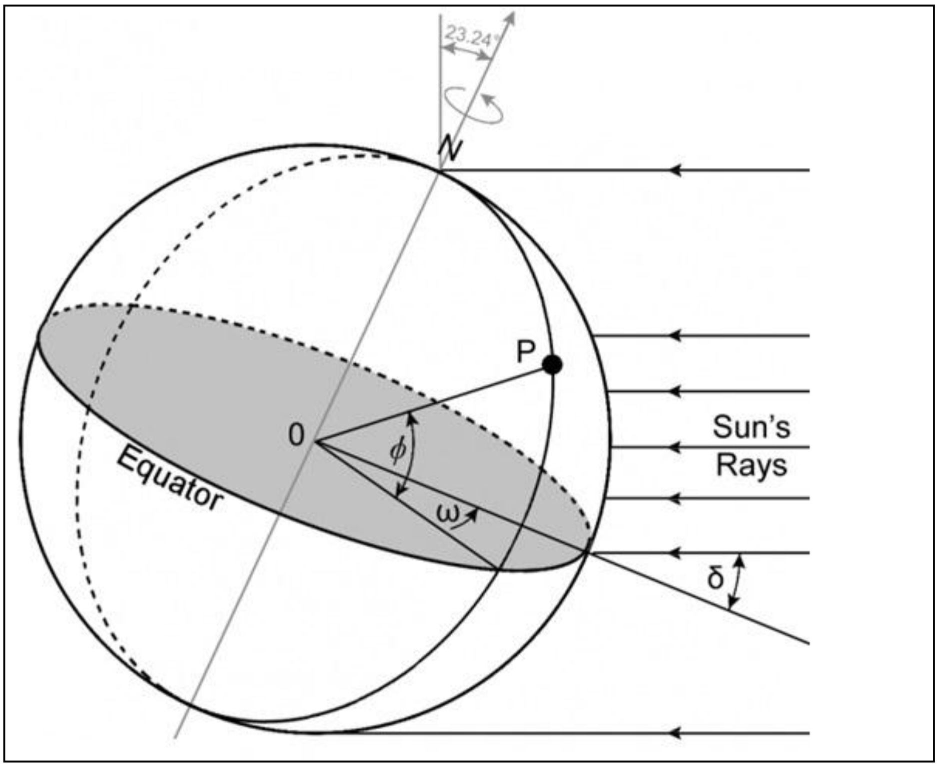


Figure 2.3 : Illustration of the Latitude (ϕ) and Hour angle (ω)

Source: www.itacanet.org

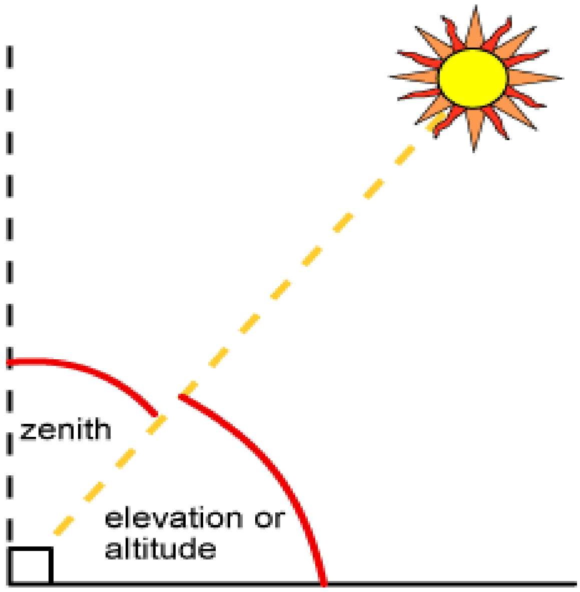


Figure 2.4 : Illustration of the Zenith Angle ($\boldsymbol{\theta_Z}$)

Source: www.pveducation.org

The Zenith Angle (θ_z) is

the angle from the observer's zenith point to the sun's position in the sky which is shown in figure 2.4. According to the Equation 2.2,

The zenith angle can be calculated with the aid of the local latitude, solar declination angle and the hour angle.

$$\cos\theta_Z = \sin\phi\sin\delta + \cos\phi\cos\delta\cos\omega \tag{2.2}$$

2.1.2. Components of Solar Radiation

Solar radiation has been divided in to several components based on the methods of wave propagation.

Direct Radiation:

Direct radiation is received from the sun's rays travelling in a straight line from the sun to the earth. Direction radiation is also termed as beam radiation or direct normal radiation. As direct radiation the sun's rays travelling in a straight line, shadows of the objects which come in the way of the sun's rays are formed. Shadows indicate the presence of direct radiation.

In sunny regions, direct radiation accounts for almost 70% of the total radiation present. Solar tracking is implemented to absorb most of the direct radiation. If a solar tracking system is not installed, valuable direct radiation would go un-captured.

Diffuse Radiation:

Direct radiation has a fixed direction. Diffuse radiation does not have any fixed direction. When the sun rays are scattered by particles present in the atmosphere, these scattered sun's rays account for the diffuse radiation. Shadows of the objects will not form if only diffuse radiation is present.

As pollution increases, the amount of diffuse radiation also increases. In hilly regions too the percentage of diffuse radiation increases. Maximum amount of diffuse radiation is captured by the solar panels when they are kept horizontally. This means, in case of solar panels which are at an angle to track the most of the direct radiation, the amount of diffused radiation captured by the panels will be reduced.

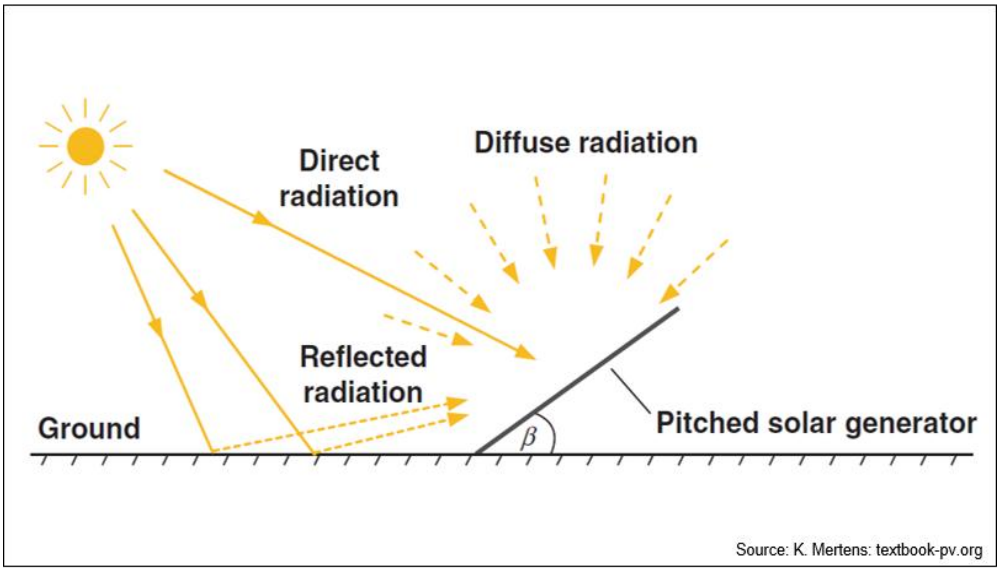
Reflected Radiation:

Reflected radiation is the component of radiation which is reflected from surfaces other than air particles. Radiation reflected from hills, trees, houses, water bodies accounts for reflected radiation. Reflected radiation generally accounts for a small percentage in the global radiation which was not considered for the simulations of this research.

Global Radiation:

Global radiation is the sum of direct, diffuse and reflected radiation. Since reflected radiation is negligible, Global Horizontal Irradiance (GHI) can be expressed as the total radiation on horizontal plane which can be obtained by adding the perpendicular component of Direct Normal Irradiance (DNI) and Diffusive Horizontal Irradiance (DHI) as illustrated in equation 2.3. Figure 2.5 illustrates the components of solar radiation discussed above.

$$\mathrm{GHI} = \mathrm{DNI}\cos\theta_Z + DHI \tag{2.3}$$



Source: K. Mertens: textbook-pv.org

Figure 2.5 : Components of Solar Radiation

Table 2.1 summarizes the above discussed solar angles

Table 2.1 Summary of solar angles

Symbol	Name	Definition	Limits
θ_z	Zenith angle	Angle subtended by a vertical line to the point directly overhead and the line of sight to the sun	$0° \leq \theta_z \leq 90°$
β	Tilt angle	Angle between a plane surface and the horizontal	$0° \leq \beta \leq 180°$
ϕ	Latitude	Angular location relative to the equator (+ north, -south)	$-90° \leq \phi \leq 90°$
δ	Declination	Angular position of the sun at solar noon relative to the plane of equator (+north, -south)	$-23.45° \leq \delta \leq 23.45°$
ω	Hour angle	Angular displacement of the sun east or west of the local meridian (+afternoon, -morning)	

2.2. Relationship between Crop yield and Solar radiation

2.2.1. Photosynthesis of crops

Solar radiation is a key factor for photosynthesis. Hence it directly relates to the yield. Plants use only a portion of the received solar radiation bandwidth for photosynthesis which is called as Photo Activated Radiation (PAR). Bandwidth of PAR is 400nm to 750nm out of 280nm to 3000nm which is the total spectrum of solar radiation. This is about 47% of the total solar radiation energy [10]. Figure 2.6 illustrate PAR over the total bandwidth of solar radiation.

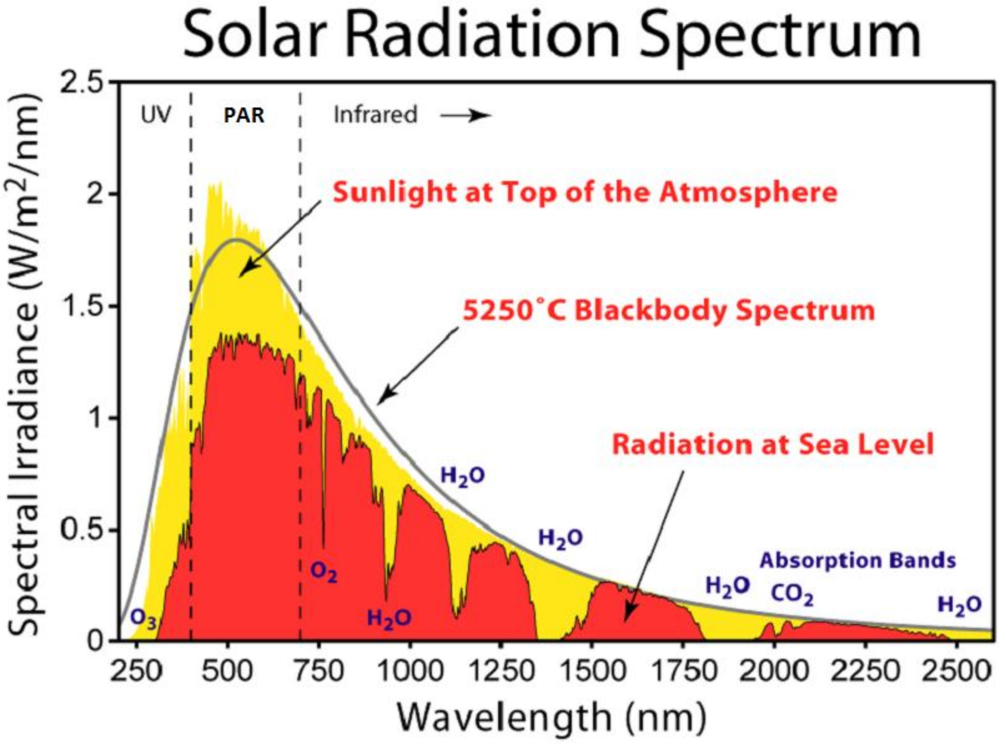


Figure 2.6: PAR of Solar spectrum
Source: Solar Radiation Effect on Crop Production by Carlos Campillo at el

Plant photosynthesis efficiency is defined as the amount of dry matter that can be harvested in grams per 1MJ of received solar energy to the plant. This is often called as Radiation Use Efficiency (RUE) which is a key measurement for analyzing the shade performance of a plant. RUE varies from 1% to 7% depending on plant category and growth phase of the plant [11].

The plant captures the required PAR solar energy from the leaves of its canopy where photosynthesis also takes place. Hence, plant canopy distribution over a considered area is also an important factor of photosynthesis. This is called as Leaf Area Index (LAI) of the plant which is defined as the amount of leaf area (m^2) in a canopy per unit ground area (m^2). LAI varies with plant growth as indicated in figure 2.7.

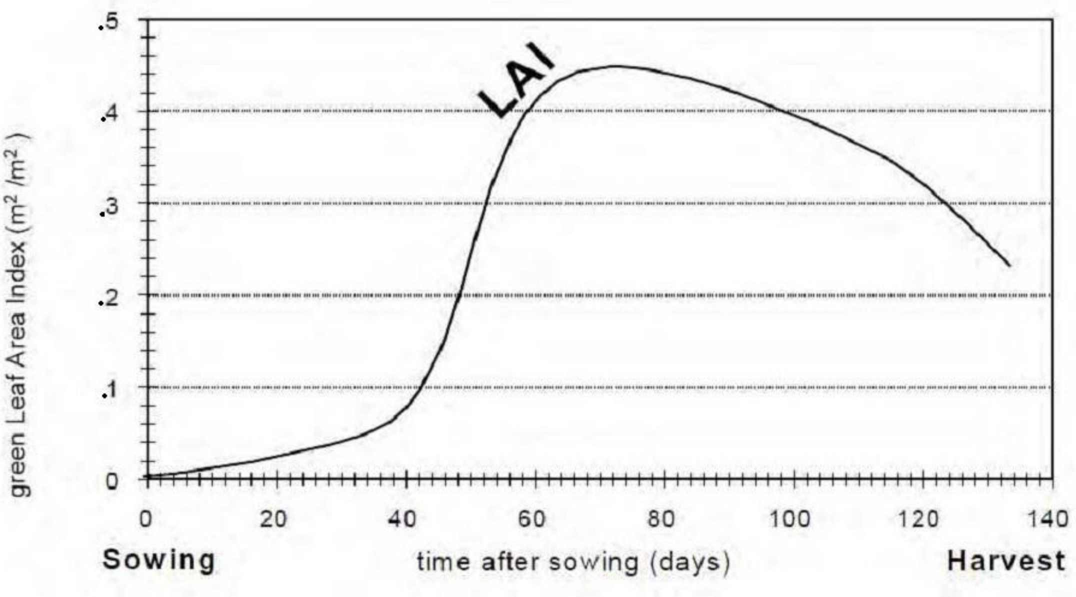


Figure 2.7: Typical LAI variation with plant growth

Source: Solar Radiation Effect on Crop Production by Carlos Campillo at el

2.2.2. DSSAT simulation software

As discussed in the above section plant photosynthesis depends on many factors when evaluating solar radiation effects on the yield. It is not just a single calculation but cumulative calculation over the plant life. To analyze these relationships several software has been designed. Decision Support System for Agrotechnology Transfer (DSSAT) is one such software which has been used by many researches [12],[13]. DSSAT newest version, DSSAT 4.6 consists of crop models for more than 46 crops which is supported by data base management programs for soil, weather, and crop management and experimental data and application programs. The crop simulation models in DSSAT simulate growth and yield as a function of the soil, plant, solar radiation and weather. It has been used for many applications such as crop management as per regional assessments, predict the crop yield and analyzing various effects of the climate change.

DSSAT Crop models are designed based on several crop growth modules such as CROPGRO,CERES, SUBSTOR,AROID and CANEGRO. These modules have been tuned as per the applicable crops based on filed data. Using these pre tuned modules; DSSAT computes daily growth processes as a function of weather, soil, solar radiation and crop management. Figure 2.8 shows the overview of DSSAT software architecture.

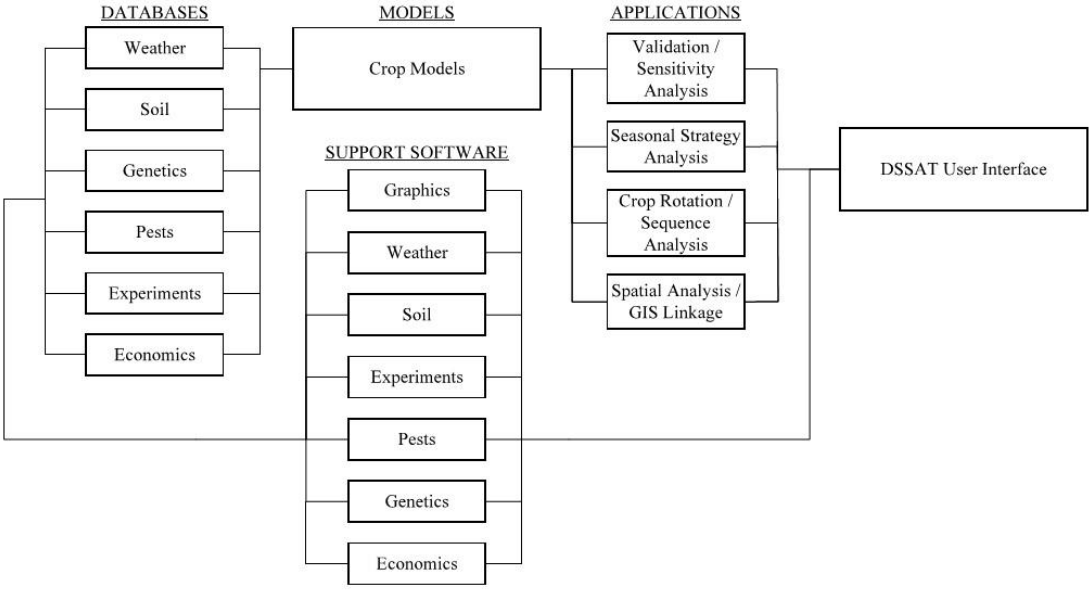


Figure 2.8 : DSSAT architecture

Source: The DSSAT cropping system model by J.W. Jones, G. Hoogenboom

The user needs to edit the required input data as per the simulation requirements. Under this research only the soil files and the weather files needc to be changed as per the selected region. There are inbuilt software applications to generate the required soil and weather data.

Soil data files have been created using the SBuild application which requires soil composition inputs for pre-defined layers with 5cm thickness. Layers are defined based on the depth from the surface.The user needs to provide layer wise percentage compositions of Clay, silt, Stones, Organic Carbon, pH level, Nitrogen content and values for Cation exchange capacity(mol/kg). It is further required to provide the factors mentioned below too for SBuild application.

Albedo:

Albedo is the solar reflection coefficient of the considered soil which is also needed to be given to create the soil data file. The final albedo coefficient will be estimated based on LAI and the given soil albedo[14].

Run off number:

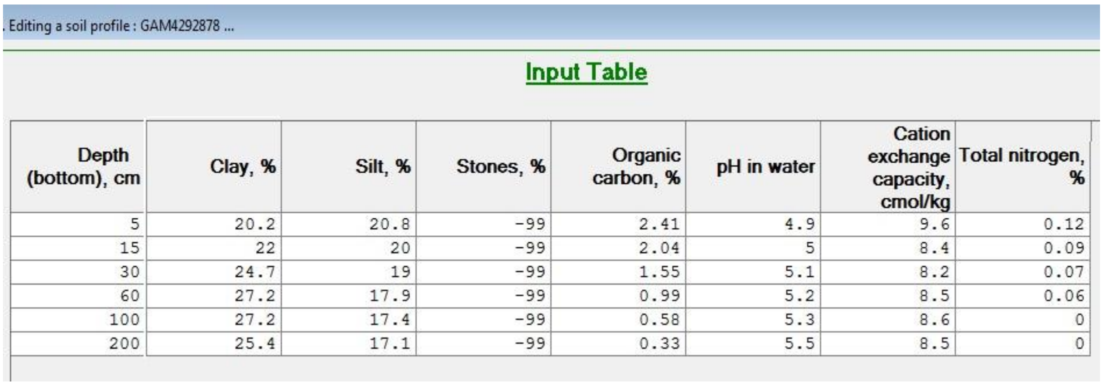
Run off number is another important parameter of soil data inputs which is used to calculate the amount of water that will be stored after precipitation. Soil storage capacity can be calculated using equation 2.1 where S is the storage capacity in mm of soil and CN is the run off curve number [15].

$$S = 254 * (100/CN - 1) \tag{2.4}$$

Drainage rate:

Drainage rate (cm^3/cm^3) refers to the rate of vertical drainage of water after saturation of the current layer. Drainage rate is considered as a constant for all soil layers [12].

SBuild will generate the relevant soil data file after the above inputs. The generated Soil file can be imported by DSSAT for simulation purposes. Figure 2.9 shows user interface of SBuild application.



. Editing a soil profile : GAM4292878 ...

Input Table

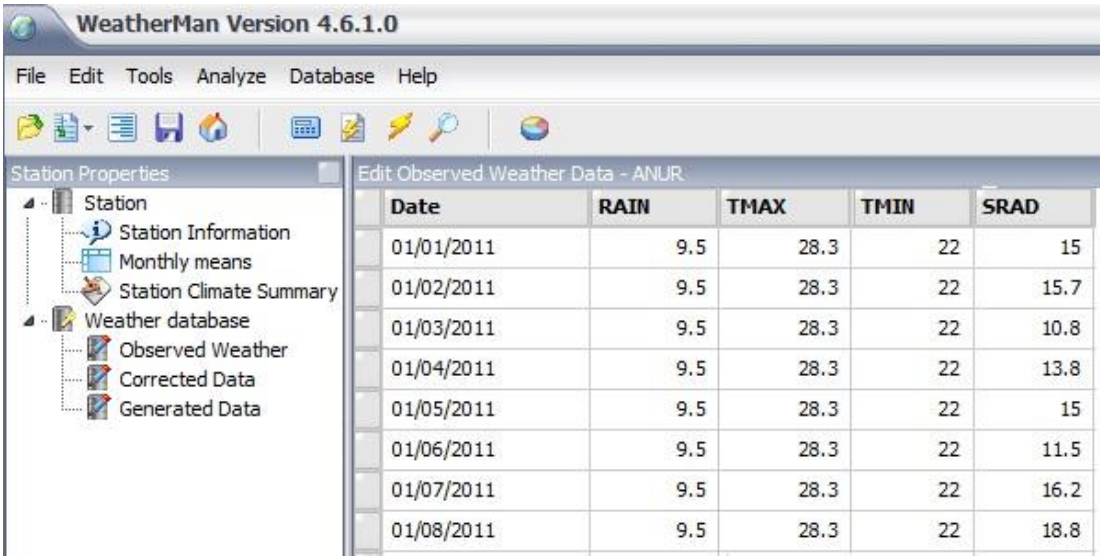
Depth (bottom), cm	Clay, %	Silt, %	Stones, %	Organic carbon, %	pH in water	Cation exchange capacity, cmol/kg	Total nitrogen, %
5	20.2	20.8	-99	2.41	4.9	9.6	0.12
15	22	20	-99	2.04	5	8.4	0.09
30	24.7	19	-99	1.55	5.1	8.2	0.07
60	27.2	17.9	-99	0.99	5.2	8.5	0.06
100	27.2	17.4	-99	0.58	5.3	8.6	0
200	25.4	17.1	-99	0.33	5.5	8.5	0

Figure 2.9 :SBuild soil data application interface

Source: DSSAT 4.6 software

ISRIC has developed a database of soil data with 1km resolution which is specially for DSSAT application [16]. This file system has the same format which is generated using SBuild application. The user can easily import the required Soil Grid file for simulation in DSSAT. Under this research ISRIC Soil Grid file for Sri Lanka was used as soil data input for DSSAT.

Weatherman application is used to generate the required weather input files for the simulation. This requires the daily averaged solar radiation (MJ/m2/d), daily precipitation (mm), minimum temperature and maximum temperature input to generate weather data files. Typical Metrological Data (TMY) from National Solar Radiation Database (NSRDB) which was developed by National Renewable Energy Laboratory, U.S. can be used to obtain daily solar radiation data for weatherman application[17]. Sri Lankan statistical data of climate can be used to obtain precipitation and the minimum and maximum temperatures for each district in Sri Lanka[18]. After giving these inputs to the weatherman, the user can generate the required weather file for a given area or district. Figure 2.10 illustrates the user interface of weatherman application.



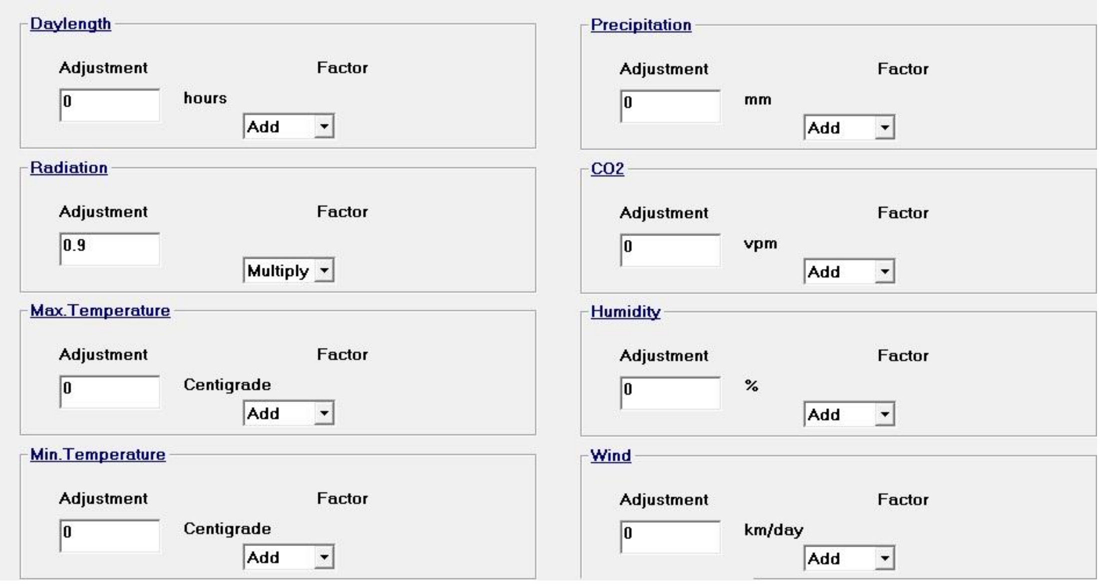
Edit Observed Weather Data - ANUR

Date	RAIN	TMAX	TMIN	SRAD
01/01/2011	9.5	28.3	22	15
01/02/2011	9.5	28.3	22	15.7
01/03/2011	9.5	28.3	22	10.8
01/04/2011	9.5	28.3	22	13.8
01/05/2011	9.5	28.3	22	15
01/06/2011	9.5	28.3	22	11.5
01/07/2011	9.5	28.3	22	16.2
01/08/2011	9.5	28.3	22	18.8

Figure 2.10: Weatherman data application interface

Source: DSSAT 4.6 software

After creating both soil data and weather data files the user can simulate the crop yield variation for solar radiation variation. In DSSAT simulator user can edit factors by adding or multiplying with the percentage changes of concerned variations. Figure 2.11 illustrates the user interface where these adjustments can be done. In this research, only solar radiation adjustments were considered by multiplying with percentage reduction of radiation due to shading of PV arrays.



Daylength
Adjustment 0 hours
Factor Add

Radiation
Adjustment 0.9
Factor Multiply

Max.Temperature
Adjustment 0 Centigrade
Factor Add

Min.Temperature
Adjustment 0 Centigrade
Factor Add

Precipitation
Adjustment 0 mm
Factor Add

CO2
Adjustment 0 vpm
Factor Add

Humidity
Adjustment 0 %
Factor Add

Wind
Adjustment 0 km/day
Factor Add

Figure 2.11: DSSAT crop simulation application interface

Source: DSSAT 4.6 software

As described in the steps above the user can obtain the relationship of the crop yield vs. solar radiation (shading) for a given area.

2.3. PV Solar Technology

Photovoltaic solar cells are electronic devices that convert sunlight directly into electricity. These cells are made with p-type and n-type semiconductor materials which form a p-n junction. When these semiconductors are exposed to sunlight, received energy photons are absorbed by the n-type semiconductor part which is on the top side and releases free electrons. When the potential of these negatively charged electrons becomes higher it will be circulated through an external circuit providing electric current. Figure 2.12 illustrates the arrangement of a simple PV solar cell.

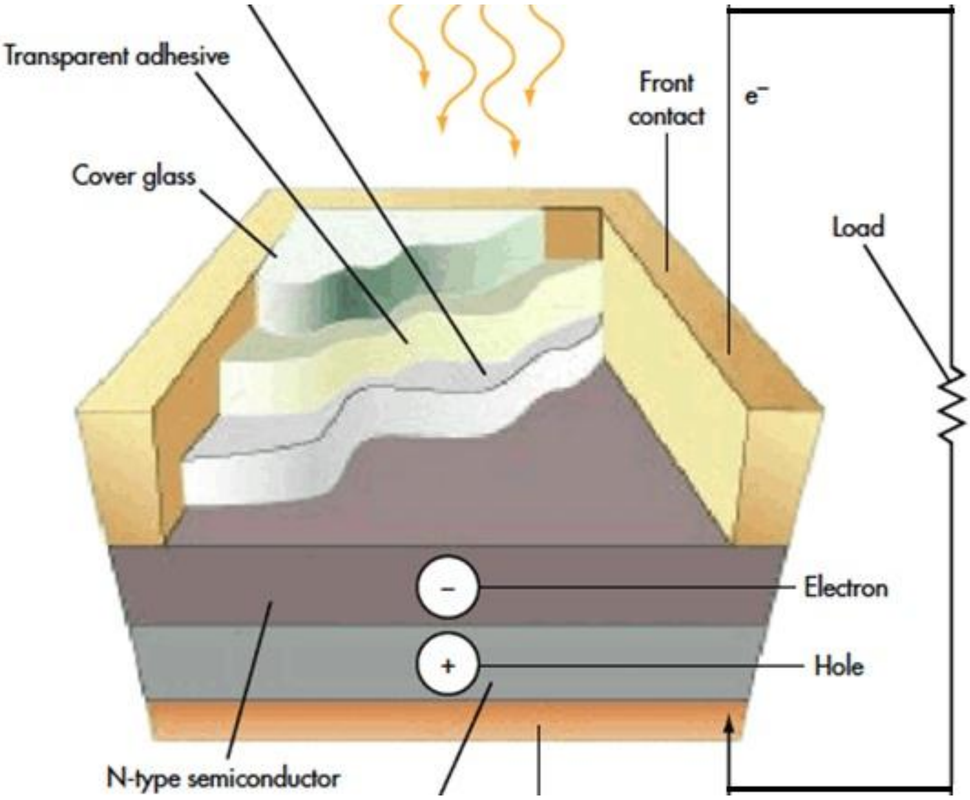


Figure 2.12 : PV solar cell arrangement

Source: Presentation from M. Nageswar Rao, 2105

PV cell technologies are usually classified into three generations, based on the basic materials used to manufacture the cells [19].

1. Crystalline Silicon
2. Thin Film
3. Concentrated photovoltaic (CPV) and Organic Material

Silicon is a semiconductor material which is suitable for PV applications, with an energy band gap of 1.1 eV. Crystalline silicon is the special formation of silicon which is used in the PV industry. There are three main categories of Crystalline silicon based PV solar cells:

1. Mono-crystalline (Mono c-Si).
2. Poly-crystalline (Poly c-Si),or multi-crystalline (mc-Si).
3. Thin film

Annual production shares of three main types of PV modules have been compared under Figure 2.13. It is assumed that the total annual production of PV modules as 57 GWp as per the analysis done by Fraunhofer ISE. According to the figure, most widely used technology is mono-crystalline while least used is thin film. Furthermore, it can be clearly observed that the production of all types rapidly increased from 2000 to 2015.

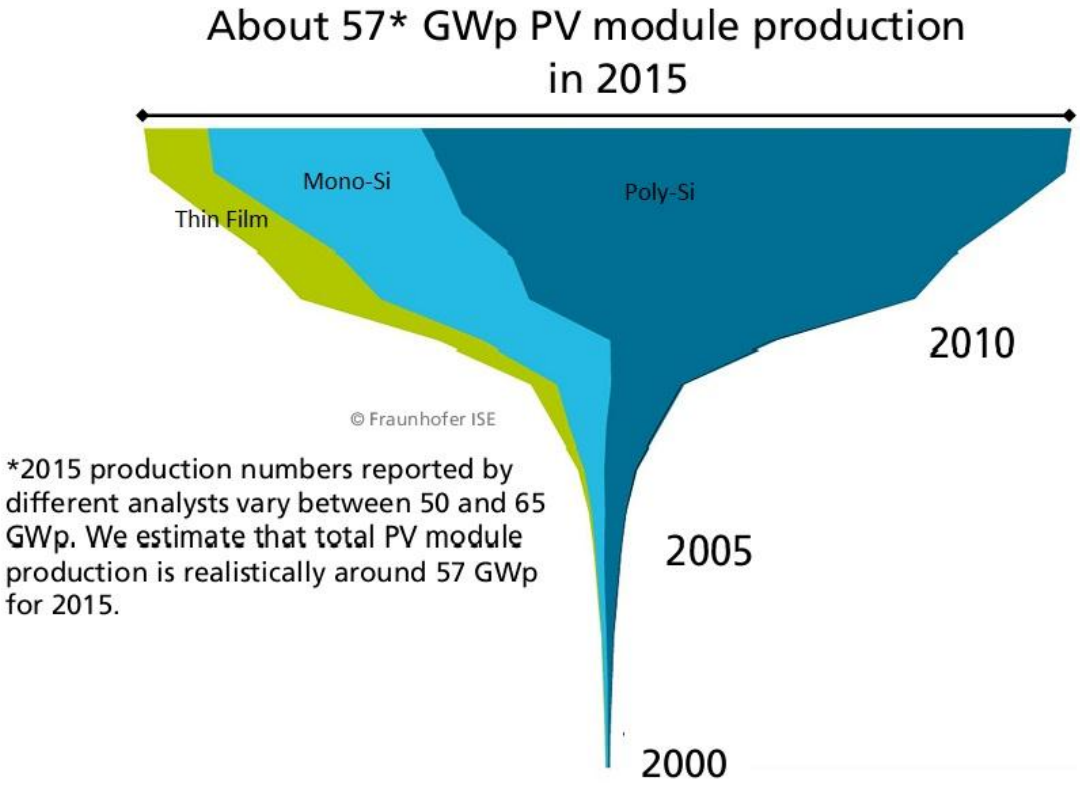


Figure 2.13: PV solar cell arrangement

Source: Photovoltaic Report 2016

Mono-crystalline silicon cells have the highest degree of efficiency of the three most common technologies which is up to 20%. Figure 2.14 illustrates the cell arrangement of Mono -crystalline silicon cells.

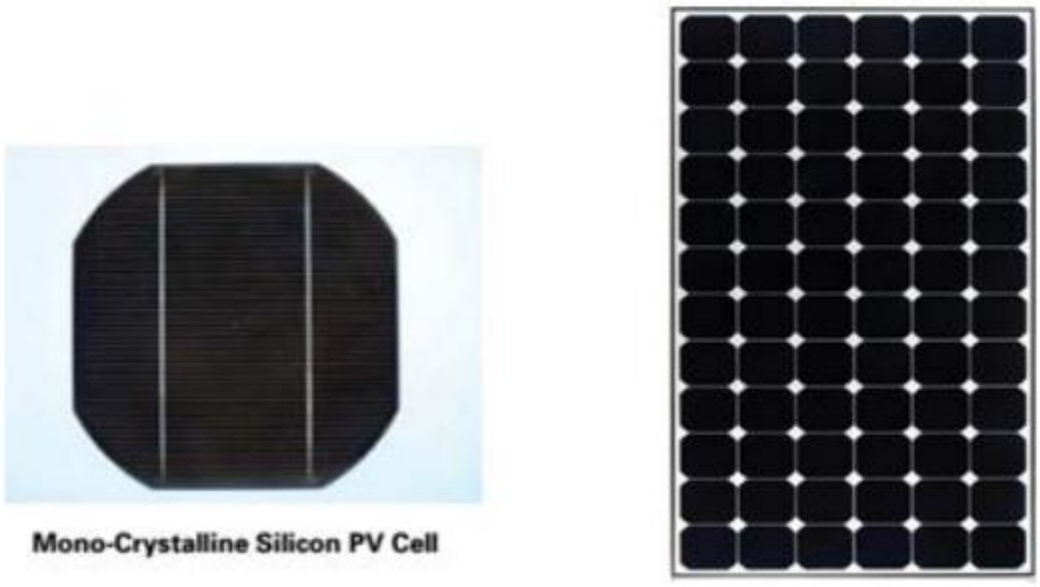
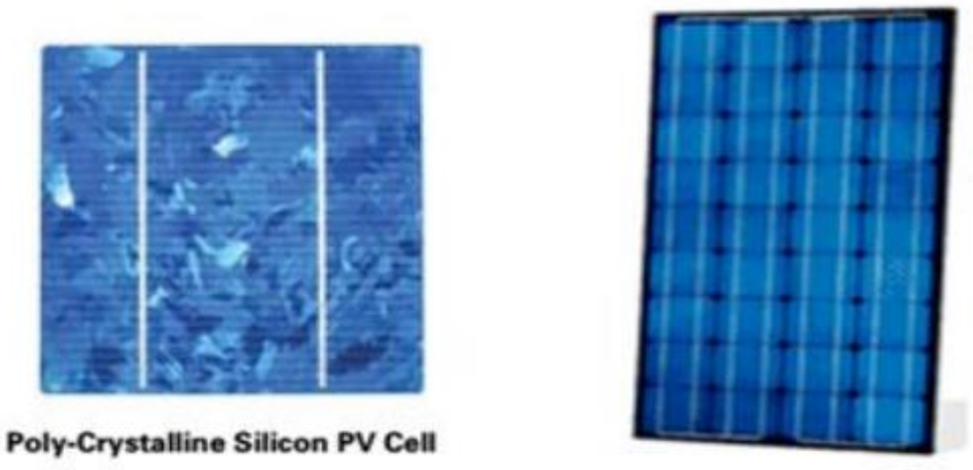


Figure 2.14 : Mono-crystalline PV solar cell arrangement
Source: A Review on Photovoltaic Solar Energy Technology and its Efficiency, Department of Electrical Engineering, University of Alexandria, Egypt

Mono-crystalline photovoltaic cell material manufactured from a single crystal silicon structure with high purity silicon rods (ingots) are extracted from a cast and then sliced in to thin wafers, which are then processed into PV cells by doping with n-type and p-type materials. Expected lifespan of these cells is typically 25 - 30 years.

Poly-crystalline PV cell consists of several smaller groups or grains of crystals, which introduce boundaries between them. Production of these cells is more economical and more efficient compared to mono-crystalline. Poly-crystalline silicon is cast in blocks. So it results in crystal structures with border defects. These defects reduce the degree of efficiency than Mono-crystalline. Figure 2.15 illustrate the cell arrangement of Poly-crystalline silicon cells.



Poly-Crystalline Silicon PV Cell

Figure 2.15 : Poly-crystalline PV solar cell arrangement

Source: A Review on Photovoltaic Solar Energy Technology and its Efficiency, Department of Electrical Engineering, University of Alexandria, Egypt

Thin-film solar cells are comprised of successive thin layers with 1 to 4 μm thickness. These thin solar cells are deposited into a large inexpensive substrate such as glass, polymer, or metal. There are four types of thin-film solar cells that have been commercially developed:

1. Amorphous silicon (A-Si and A-Si/μc-Si)
2. Cadmium -Telluride (CdTe),
3. Copper- Indium- Selenide(CIS)

Thin films can be packaged into flexible and light weight structures which can be easily used as building integrated Photovoltaic (BIPV). Figure 2.16 illustrate a structure of thin film PV cell.

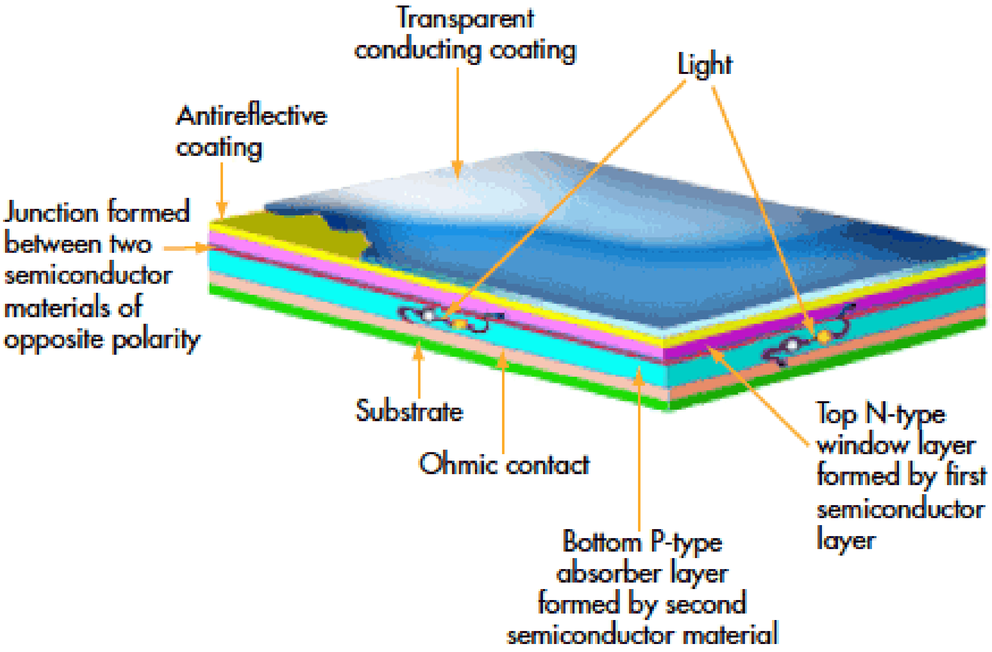


Figure 2.16 : Thin film PV solar cell arrangement

Source: A Review on Photovoltaic Solar Energy Technology and its Efficiency, Department of Electrical Engineering, University of Alexandria, Egypt

Figure 2.17 shows a comparison between the three types of thin film technologies discussed above.

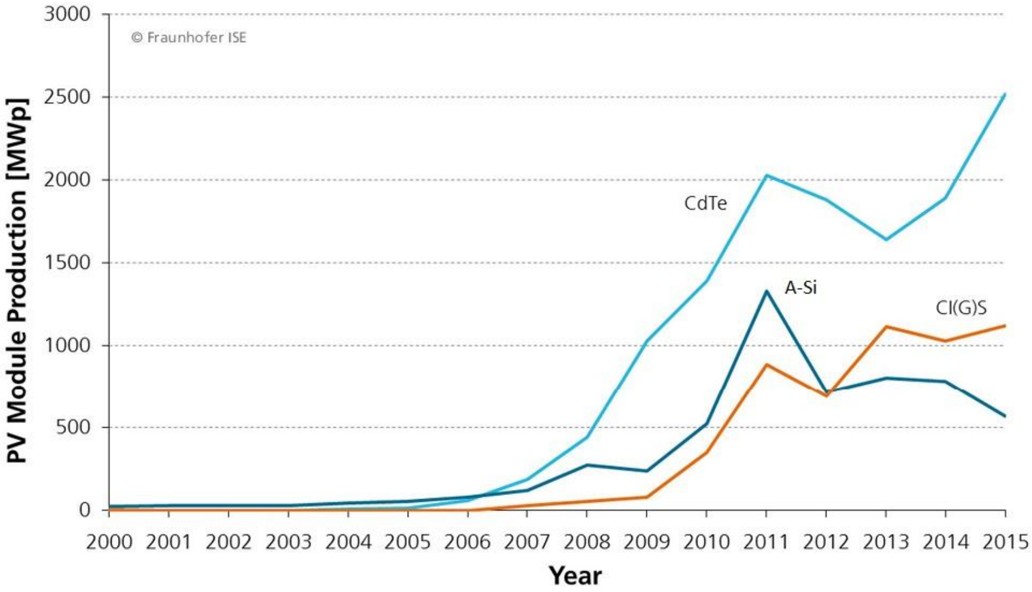


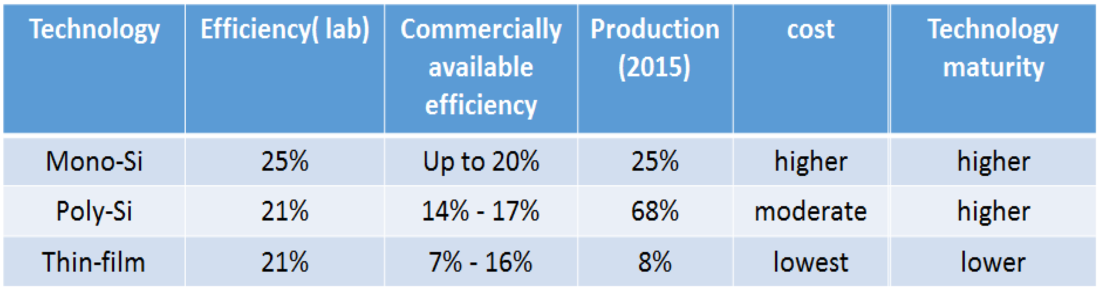
Figure 2.17: Comparison of Thin film PV solar technologies

Source: Photovoltaic Report, 2016

By looking at the figure 2.17 it is clear that Cd-Technology is more popular than other thin film technologies.

There are various efficiencies of PV solar cells ranging from 7% to 20% depending on its technology. As usual when the efficiency increases, the cost of panels also increases. So all three types have their own advantages and disadvantages. Table 2.2 compares the three PV solar technologies based on its efficiency, cost, annual production and technology maturity.

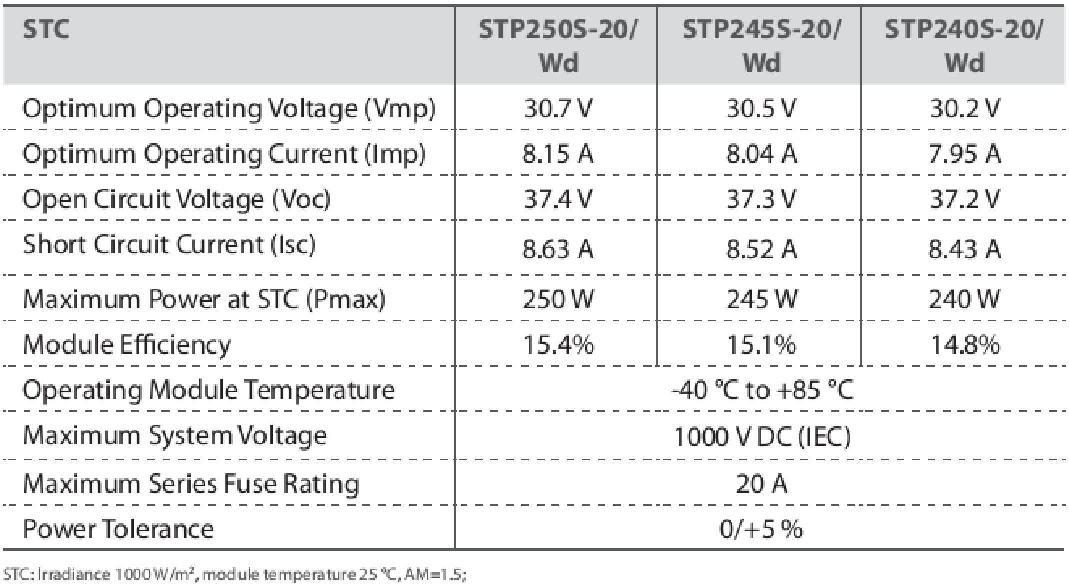
Table 2.2 : Comparison of PV solar technologies



Technology	Efficiency(lab)	Commercially available efficiency	Production (2015)	cost	Technology maturity
Mono-Si	25%	Up to 20%	25%	higher	higher
Poly-Si	21%	14% - 17%	68%	moderate	higher
Thin-film	21%	7% - 16%	8%	lowest	lower

Source: Photovoltaic Report, 2016

General specification of a commercially available PV solar panel is shown in figure 2.18. These ratings are defined under the STC (Standard Test Conditions. Standard test conditions are defined as the solar irradiation of 1000 W/m^2, module temperature of 25˚C and 1.5 of AM (48˚ of azimuth angle)[21].



STC	STP250S-20/ Wd	STP245S-20/ Wd	STP240S-20/ Wd
Optimum Operating Voltage (Vmp)	30.7 V	30.5 V	30.2 V
Optimum Operating Current (Imp)	8.15 A	8.04 A	7.95 A
Open Circuit Voltage (Voc)	37.4 V	37.3 V	37.2 V
Short Circuit Current (Isc)	8.63 A	8.52 A	8.43 A
Maximum Power at STC (Pmax)	250 W	245 W	240 W
Module Efficiency	15.4%	15.1%	14.8%
Operating Module Temperature	-40 °C to +85 °C		
Maximum System Voltage	1000 V DC (IEC)		
Maximum Series Fuse Rating	20 A		
Power Tolerance	0/+5 %		

STC: Irradiance 1000 W/m², module temperature 25 °C, AM=1.5;

Figure 2.18 Comparison of Thin film PV solar technologies

Source: 250 Watt Mono Crystalline Solar Module, 2012

After harnessing solar energy through PV solar panels it should be transmitted to the grid to be used by the consumers. Most of the commercial PV solar panel provide about 38VDC open circuit output. Since the utility supply is 230V AC, inverters are used to convert DC output to AC. There are several inverter topologies based on electrical connections of PV panels. Central inverters arrangement, String inverter arrangement and optimizer arrangement are the main three arrangements used in PV solar installations.

In Central inverter arrangement multiple strings of PV solar panels are connected parallelly before the inverter. MPPT (maximum power point tracker) has been implemented by using DC to DC inverter as show in Figure 2.19. Constant voltage (CV) algorithm is known as the simplest MPPT algorithm. This is based on the observation of I–V characteristics as the ratio of the voltage at the array's Maximum Power Point V_{MPP} to its open-circuit voltage V_{OC} which can be approximated as a constant. In other words, V_{MPP} / V_{OC} has been considered for each case. This ratio is expressed as $\propto$ $(0 < \propto < 1)$, hence V_{MPP} can be expressed as $\propto V_{OC}$. However, there are still some power losses for optimal value of the MPP algorithm depending on temperature and irradiance. In Central inverter systems, where the PV system is composed of L parallel strings with serially connected M modules, where each module consists of N cells in a series, the DC power loss of the system is expressed in equation 2.5.

$$P_{LOSS} = \frac{\sum_{i=1}^{L.M.N} P_{MP,i} - P(\propto VOC)}{\sum_{i=1}^{L.M.N} P_{MP,i}} \qquad (2.5)$$

Where $P_{MP,i}$ is the maximum power of the i^{th} cell and $P(\propto V_{OC})$ is the power obtained by the algorithm that fixes $\propto$ to a certain value $(0.73 \leq \propto \leq 0.8)$. Central inverters are preferred for three phase power generation stations with a capacity of more than 100kW[22].

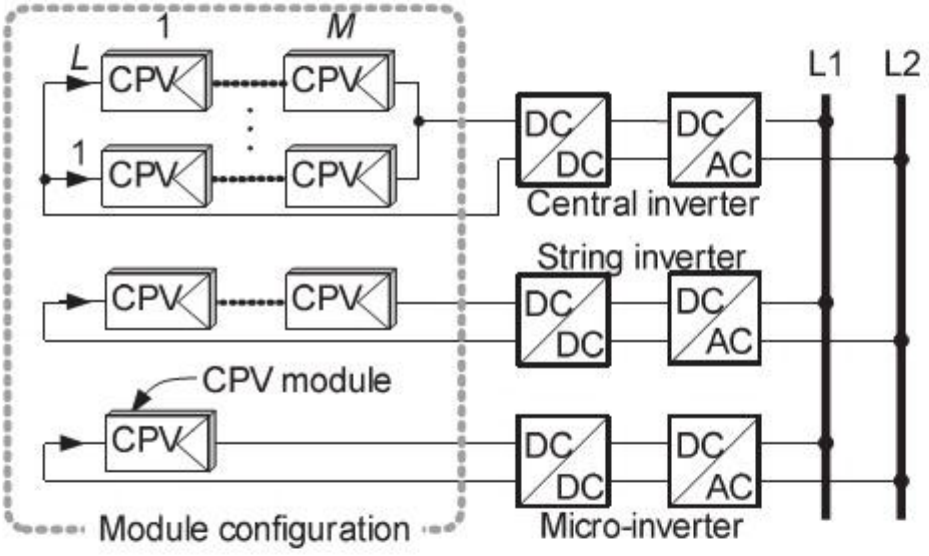


Figure 2.19 : PV solar inverter arrangements

Source: Power conversion in concentrating photovoltaic by YongKim

In the String inverter each string of PV solar panels are connected to its own inverter[23] which is shown in figure 2.19. Since each string is connected to its own inverter they will function independently providing better power harvest than the central conversion. In this arrangement MPP based on CV algorithm are shown in equation 2.6,Where $P_{MP,j}$ is the maximum power of the jth string.

$$P_{LOSS} = \frac{\sum_{i=1}^{L.M.N} P_{MP,i} - \sum_{j=1}^{L} P(\propto V_{OC,j})}{\sum_{i=1}^{L.M.N} P_{MP,i}} \qquad (2.6)$$

In the Micro inverter arrangement dedicated inverters are used for individual PV panel[23] which will provide the highest efficiency than central and string arrangements. Micro-Inverter arrangement is also shown in figure 2.19. With this arrangement all the effects due to shading, panel mismatches and module orientation will be independent from the rest of the system. Further there are more efficient algorithms than CV for obtaining MPP. Perturbed and Observed (P&O) algorithm is the most commonly used in real applications and actively tracks V_{MPP} using iterations[24]. Total DC loss of the Micro Inverter arrangement can be expressed as shown in equation 2.7.

$$P_{LOSS} = \frac{\sum_{i=1}^{L.M.N} P_{MP,i} - \sum_{j=1}^{L.M} P_{MP,j}}{\sum_{i=1}^{L.M.N} P_{MP,i}} \quad (2.7)$$

Generally, these DC losses are encountered for the systems with battery backup systems which is not considered under this research in inverter losses.

2.4. RETScreen Software Simulator

There are several Software created to obtain possible annual PV solar generation of a given location which is a challenging task. HOMER, RETScreen and PvSyst are a few of them. These software will simulate continuous changes in environmental factors such as solar irradiance, incidence angle, panel temperatures, inverter losses and other Miscellaneous losses. Further solar tracking systems and particular technical data based on panel manufacturers will be taken carefully for the calculations. Accurate Solar radiation, temperature database of the selected location will be available. RECScreen is widely used simulation software for predicting possible annual generation based on given location using its inbuilt databases which is used under this research. Figure 2.20 shows a block diagram for PV solar simulation.

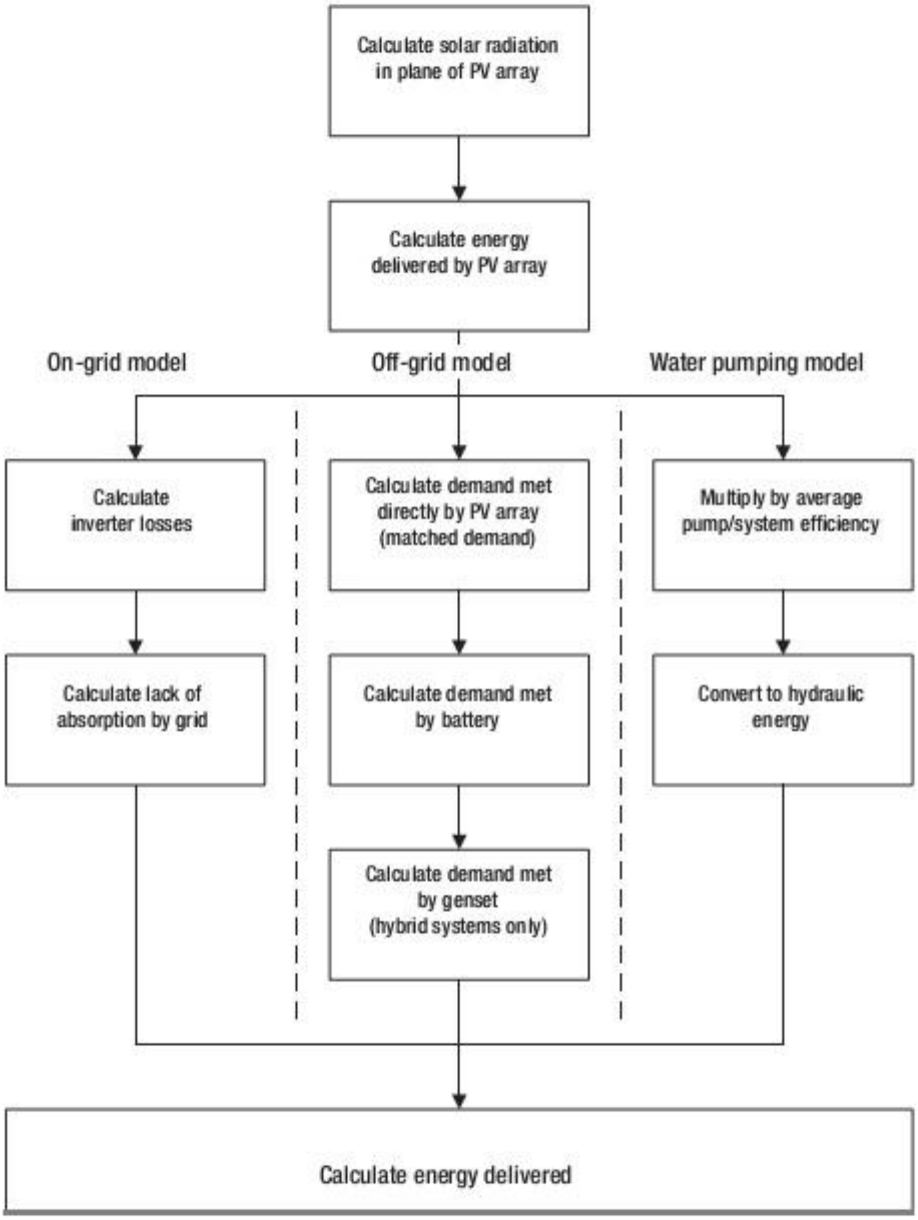


Figure 2.20 :RETScreen PV solar simulation flow chart

Source: RETScreen Textbook, 2004

PV module efficiency is a critical factor for calculating PV solar harnessing. Normally PV panel efficiency is defined under STC conditions as discussed previously. But when solar irradiance is absorbed by PV panels, its temperature rises. Higher temperature results in the reduction of efficiency of the PV solar panel.

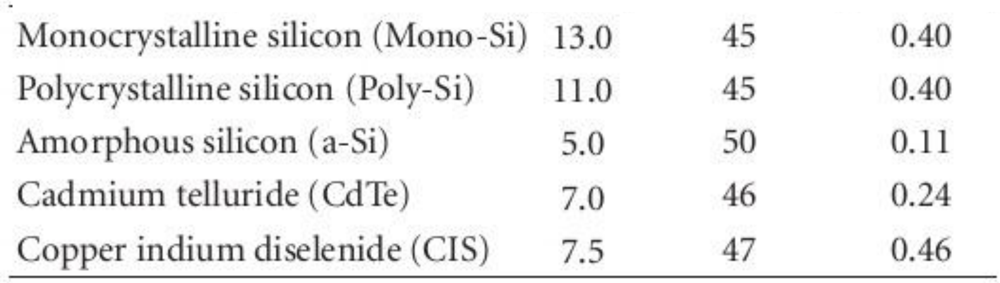
This is defined as PV temperature coefficient, β_p (expressed in %/℃). PV solar panel efficiency at a given temperature η_p has been expressed in terms of PV temperature coefficient and other parameters which is shown in equation 2.8.

$$\eta_P = \eta_r[1 - \beta_P(T_c - T_r)] \tag{2.8}$$

Where

η_r is the PV panel efficiency at STC, T_r is the temperature at STC (25 ℃), T_c is the average monthly temperature. Typical values for β_p are shown in table 2.3.

Table 2.3 : Typical values for PV temperature coefficient, $\boldsymbol{\beta_p}$



Monocrystalline silicon (Mono-Si)	13.0	45	0.40
Polycrystalline silicon (Poly-Si)	11.0	45	0.40
Amorphous silicon (a-Si)	5.0	50	0.11
Cadmium telluride (CdTe)	7.0	46	0.24
Copper indium diselenide (CIS)	7.5	47	0.46

Source: Economical Feasibility of Utilizing Photovoltaics for Water Pumping in Saudi Arabia by Sahin, Ahmet Z.

Energy harnessing of PV array, E_p can be calculated using equation 2.9 shown below,

$$E_{p} = S\,\eta_P H_T \tag{2.9}$$

Where

S is the area of solar array and H_T is Hourly irradiance on the panel.

To obtain energy before inverter, miscellaneous PV array losses λ_p and other power conditioning losses λ_c has to be reduced. Hence, energy before inverter is given as shown in equation 2.10.

$$E_{A} = E_p(1 - \lambda_p)(1 - \lambda_c) \tag{2.10}$$

Final energy of on grid system, E_{Grid} can be obtained by multiplying E_A with inverter efficiency, η_{inv} as shown in equation 2.11.

$$E_{Grid} = E_A \eta_{inv} \tag{2.11}$$

Modern inverters normally have more than 98% or higher efficiencies[20]. RETScreen software uses the above mentioned equations to obtain the annual solar energy generation of a given location. The software also uses inbuilt NASA database for solar radiation and minimum and maximum average temperatures.

2.5. Agrivoltaic related Commercial Data

After modeling all the required inputs and relationships, it is possible to simulate the crop yield verses PV solar generation. In order to quantify this, an economic analysis should be done. For this purpose, all the financial costs and profits along with crop reduction should be considered and evaluated.

Existing crop purchasing prices and district wise crop population data was obtained from documents published by Hector Kobbekaduwa Agrarian Research and Training Institute. Crop purchasing prices are shown in Table 2.4.

Table 2.4 : Purchasing Prices of crops

Crop	**Purchasing price per kg**
Paddy	50
Corn	65
Cabbage	92
Pineapple	91
Chilly Pepper	240
Tea	100
Tomato	100
Bean	127
Cowpea	140

Source: Food Information Bulletin, Hector Kobbekaduwa Agrarian Research and Training Institute

PV solar installation costs were considered as mentioned in the table below based on local companies who are engaged in solar installations. Table 2.5 illustrates the prices of PV solar panels.

Table 2.5 : Per kW prices (LKR) of solar installations

Solar Panel type	Fixed	Solar Tracking
Mono-Cristaline	149814	160300
Poly-Cristaline	135000	145485

Sources: Reputed local companies

Since the installation is about 4m above the crop canopies to keep necessary working spaces for crop related activities, galvanized steel based structures are required for the PV solar installation. These costs are calculated based on a 40m length row with two 12 panel strings and then per panel installation costs were obtained. As per the calculations per panel installation costs were calculated as 10943.00 LKR which is shown in table 2.6.

Table 2.6 : PV solar Installation cost for 24 panel row

	required quantities for 40m panel raw with 24 panels	Unit rate LKR	Cost for 24 Panels in LKR
Poles with 2'x2'x1' contrite pad, 75x75x5500mm L channels	18m	3375	60750
Length of horizontal beams with 50x50mm L angles	14m	1600	22400
length of cross beams with 50x50 mm L channels	19.8m	1600	31680

nuts and bolts	291	20	5820
DC power cable	60m	2200	132000
Installation Cost	1	10000	10000
Total installation cost for 24 panels			**262650**

Sources: Reputed local companies

CHAPTER 3. RESEARCH METHODOLOGY

3.1. Obtaining the Relationship between Shading level and crop yield

The relationship between the shading level of the PV solar panel arrays and the respective crop yield have to be obtained in order to evaluate the effect of the PV solar installation over crops. To obtain this DSSAT crop simulation software is used. It is required to insert necessary input files of weather data in order to simulate crops growth with a given shading. TMY database for global weather data files have all the required inputs for generating weather data files. Since Typical Metrological Data (TMY) from National Solar Radiation Database (NSRDB) files contain hourly global radiation data, it was converted to obtain daily data in order to create weather files using weatherman software which was described under clause 2.2.2. Required precipitation, minimum and maximum temperatures for each district was obtained in Sri Lanka[18]. After giving these inputs to the weatherman, weather input files for DSSAT was generated. ISRIC Soil Grid file for Sri Lanka was used as soil data input for SBuild application to create input soil data files for DSSAT. Finally shade simulation was carried out for various crops and selected areas. Selected areas for the study depended on the various climate profiles and deferent crop distributions. Hence one location from all the provinces was selected. DSSAT simulation was done for shading levels of 0% to 40% and respective crop yields ware obtained as percentages.

3.2. Obtaining possible PV solar generation

RETScreen software was used to calculate possible solar radiation for all provinces of Sri Lanka. Since the software contains the NASA database for global climate data for all provinces of Sri Lanka, the only requirement was to select the simulation parameters needed. Both mono-crystalline and poly-crystalline panels were simulated under fixed and single axis tracking methods. Selected mono-crystalline and poly-crystalline

Panel details are shown in table 3.1 and 3.2 respectively. Here panels were selected based on the same physical dimensions by considering the same shade levels for a given array.

Table 3.1 : Mono-Crystalline 270W PV solar panel data

Output	270W
Model	Trina solar
Dimension	1650mmx992mm
Panel efficiency	16.40%
Inverter efficiency	96.00%
Area	1.633m^2

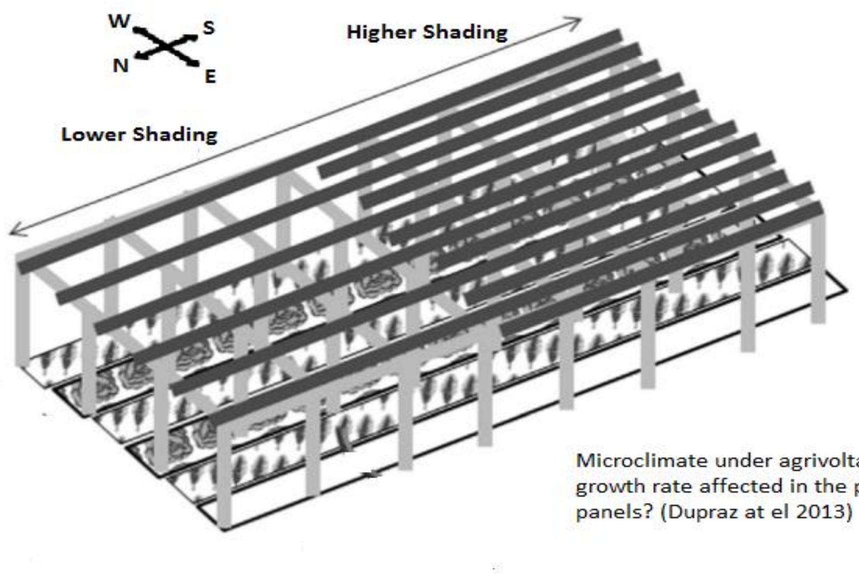
Source: RETScreen Software

Table 3.2 : Poly-Crystalline 250W PV solar panel data

Output	250
Model	trina solar
Dimension	1650mmx992mm
Panel efficiency	15.3%
Inverter efficiency	96.00%
Area	1.633m^2

Source: RETScreen Software

The analysis of PV solar generation was done based on both fixed arrays and single axis solar tracking. For fixed arrays 8° was used which is the average latitude angle of Sri Lanka. Solar panels were faced towards south. For solar tracking, single axis solar tracking was used and panels ware rotating around North-South axis when the sun goes around from East to West. PV solar installation over the crops is shown in figure 3.1.



Microclimate under agrivoltaic systems: Is crop growth rate affected in the partial shade of solar panels? (Dupraz at el 2013)

Figure 3.1: PV solar arrangement over the crop
Source: Is crop growth rate affected in the partial shade of solar panels? byDupraz

RETSreen software was used directly to simulate the above two solar installations and the annual possible generations were obtained. Total inverter loss was assumed as 96% where other miscellaneous losses including DC side losses, Solar panel losses were assumed as 1% which was the default suggestions from the software.

3.3. Obtaining crop shading under PV solar array

There are two different types of solar radiation methods based on its method of propagation. First type is direct solar radiation which directly comes from the sun to the earth’s surface. Second type is diffusive radiation which is uniformly distributed over the sky. Both of these types are described under clause 2.1.2. When the sun rotates direct solar radiation shading factors change with solar angle but diffusive factors do not. So these two have to be calculated separately.

3.3.1. Direct solar shading of a Fixed PV solar installation

Direct solar shading is calculated using trigonometry. Solar Panels were installed to form rows from North to South and “d” is the distance between two adjacent rows which is shown in figure 3.2.

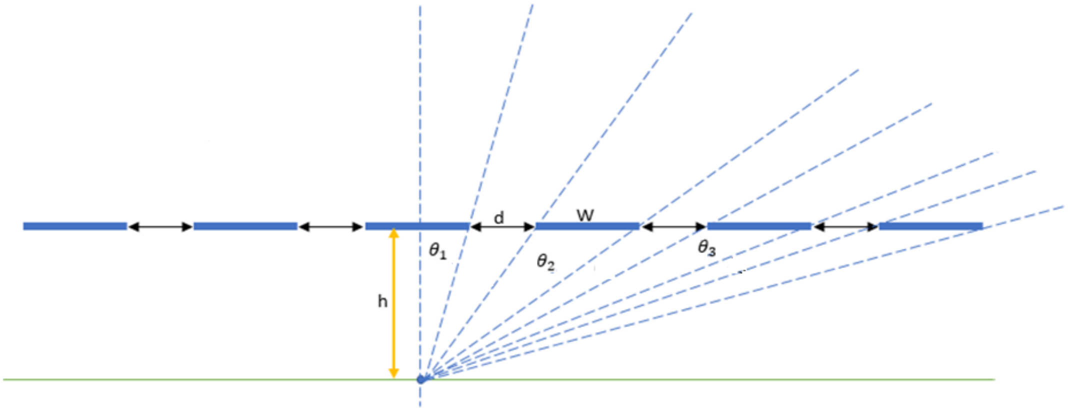


Figure 3.2: Fixed PV solar arrangement over the crop

The solar shading under the center of solar arrangement was calculated based on each row which is “w” in width. Panel installation height was taken as “h” which is the measurement from the top of the crop canopy. While the sun rotates from East to West the center point will be under the shade when the sun is located $\theta_1, \theta_2, \theta_3 \ldots \theta_n$ angular positions, n denotes the number of PV solar rows.

Hours of the day are represented as a multiplication of 15˚ of hour angle ω as shown in table 3.3. Since solar radiation data is available only on an hourly basis which is 15˚ of solar angle, it is required to obtain the angles projected by PV rows to the considered center point as a portion of 15˚ which denotes the direct solar radiation period of the center point under each PV solar row. After obtaining the portions it should be multiplied by the relevant direct normal radiation component, calculated by using DNI $\cos\theta_Z$ to obtain the direct normal radiation losses, on the center where $\cos\theta_Z$is calculated using equation 2.2.

Table 3.3 : Solar angles of relevant hours of the day

Hour of the Day	Solar Angle in degrees
0700	0˚
0800	15˚
0900	30˚
1000	45˚
1100	60˚
1200	75˚
1300	90˚
1400	105˚
1500	120˚
1600	135˚
1700	150˚
1800	165˚
1900	180˚

3.3.2. Direct solar shading of a single axis tracking PV solar installation

Unlike fixed solar arrays, panels are always facing the sun in solar tracking systems. When considering single axis tracking, South-North axis is fixed at 8˚ which is the longitude. Panels rotate around the South-North axis tracking the path of the sun. Since panels are always facing the sun it is assumed that the panel and solar rays are perpendicular to each other when solar rays are directed to the center by straightening out panel edges which is shown in figure 3.3.

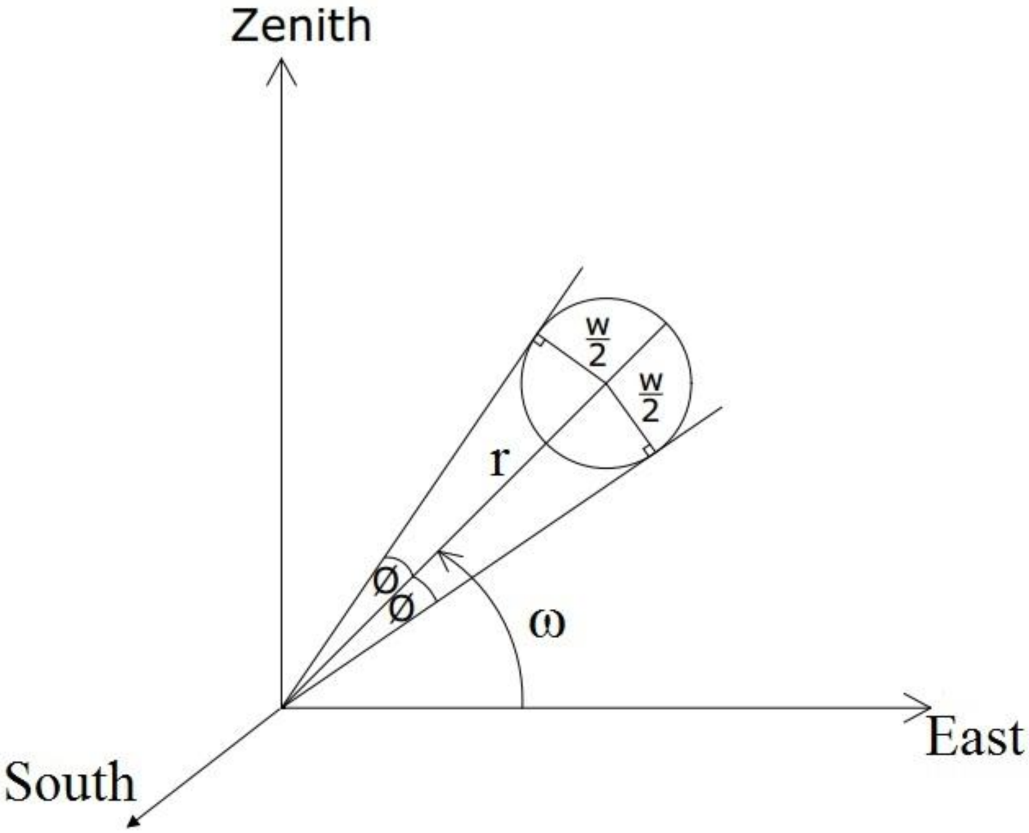


Figure 3.3: Crop shading under PV solar tracking system

Under the solar tracking arrangement, the considered point is under the shading for 2Φ period where Φ is calculated using equation 3.1.

$$Tan\,\emptyset = \frac{W}{2r} \tag{3.1}$$

Same as in fixed PV installation, in this case also it is required to map the relevant solar hour and to multiply by the direct normal radiation of that hour.by following this for all rows, Total direct solar radiation losses due to shading of all PV rows are obtained.

3.3.3. Shading of Diffusive solar radiation

Diffusive radiation is uniformly distributed over the sky. So the ratio between PV array projection over the imagined hemisphere and total semi sphere area is equivalent to the shading portion for a considered hour. Figure 3.4 shows the projection of PV solar array over the imagined hemisphere.

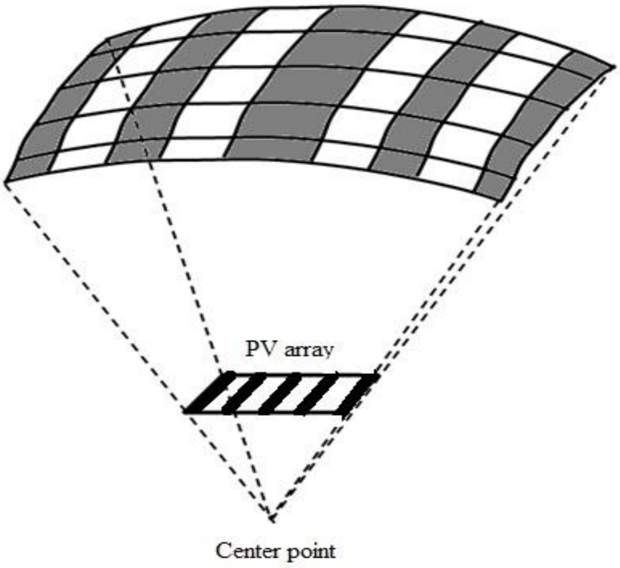


Figure 3.4: Diffusive shading under PV solar installation

To calculate the projected area, solid angle is used. Solid angle is defined as ration of the surface area of a sphere subtended by the lines and the squire of the radius of that sphere [25]. Figure 3.5 illustrate the definition of solid angle. Solid angle is measured using steradians (Ω) which is 2π for semi sphere.

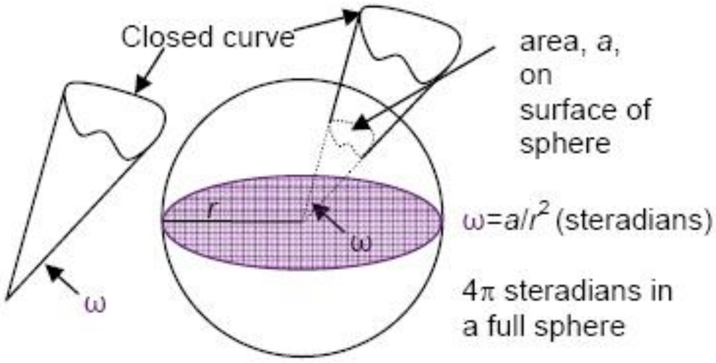


Figure 3.5 : Solid angle

Source: Field Guide to Illumination by Arecchi, A. V.

It is complex to calculate steradian values for each panel with respect to the origin. For fixed panels steradian values are constant, although the solar angle changes. But for single axis tracking the steradian values change with time, so it is needed to calculate with considerable resolution which was taken as 1˚ under this study. Equation 3.2 shows the equation used to calculate steradian under this research. This equation is assumed for planes with at least two symmetrical axis and factor of circularity (f_c) is greater than 0.5 [26].

$$\Omega \cong 2\pi\left[1-\frac{1}{\sqrt{1+\frac{A\cos\theta}{\pi r^2}}}\right] \tag{3.2}$$

Where,

A is panel area, r is the distance from origin to panel center of panel θ is angle between normal to the panel and the line joining origin to the center of the panel.

factor of circularity (f_c) is defined as per equation 3.3.

$$f_c = \frac{4\pi wl}{(2w+2l)^2} \tag{3.3}$$

Where,

W is the width of panel and l is the length.

For PV solar panel with dimensions of 1650mmx992mm,

$$f_c = \frac{4*\pi*992*1650}{(2*992+2*1650)^2} = 0.736$$

Since $f_c > 0.5$ equation 3.2 is used to calculate the solid angle of the PV panel with respect to origin.

Equation 3.4 which is the definition of dot product is used to find $\cos\theta$.

$$\cos\theta = \frac{n.r}{|n||r|} \tag{3.4}$$

Where,

n is the unit normal vector of the panel and r is the position vector of panel center with respect to the origin. Figure 3.5 illustrates above describe vectors which is used for the calculations.

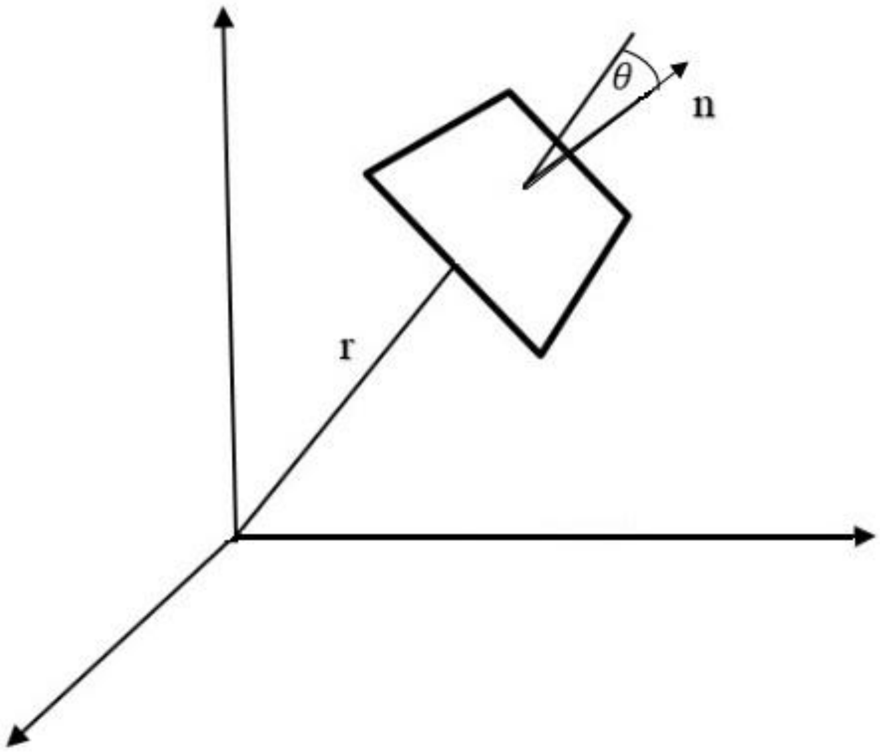


Figure 3.6: Solid angle calculations

Source: Field Guide to Illumination by Arecchi, A. V.

For fixed angle solar panels, n is defined below in equation 3.4. r is the position vector of the panel center with respect to the considered point which is obtained by simple Cartesian coordinated as shown in equation 3.5.

$$n = \sin\phi \, i + 0 \, j + \cos\phi \, k \tag{3.4}$$

Where, ϕ is the panel tilt which is 8° facing south.

$$r = x_{p,0} \, i + y_{p,0} \, j + z_{p,0} \, k \tag{3.5}$$

The total of steradian value Ω_{total} of each panel is obtained by equation 3.6. which is a constant value since panels tilts are fixed over the time.Ω_p is calculated by using equation 3.2

$$\Omega_{total} = \sum_{p=1}^{n} \Omega_p \tag{3.6}$$

Fractional coverage of PV arrays was obtained by dividing Ω_{total} by 2π which is the steradian value of a semi sphere of the sky. Diffusive shading is calculated by multiplying fractional sky coverage with the respective hourly diffusive radiation values obtained from TMY database. Total solar radiation shade on the point which is under the PV array was obtained using equation 3.7.

$$DHI_{shade.h} = DHI_h \times \frac{\Omega_{total}}{2\pi} \tag{3.7}$$

Where,

$DHI_{shade.h}$ is the dissuasive shading at hourh,

DHI_h is the global diffusive radiation at hour h,

Received diffusive solar radiation to the considered point is obtained using equation 3.8. which is the difference between the shaded DHI and global DHI of a particular hour.

$$DHI_{recieved.h} = DHI_h - DHI_{shade.h} \tag{3.8}$$

For solar tracking PV panels, normal vector n is defined in equation 3.9 below and position vector of panel center r is same as shown in equation 3.5.

$$n = \sin\phi\ i + \cos\phi\cos\omega\ j + \ \cos\phi\sin\omega\ k \qquad (3.9)$$

Where, ϕ is the panel tilt which is 8° facing south and ω is the hour angle ranges from 0° to 180°. To get a higher accuracy solid angles are calculated for every 1° change in ω and the hourly average is taken as shown in equation 3.10.

$$\Omega_{p,h} = \frac{\sum_{p=1}^{n}\sum_{\omega=1}^{14}\Omega_{\omega,p}}{15} \qquad (3.10)$$

Where,

p is the panel number and ω is the hour angle of considered hour.

Diffusive shading is calculated by multiplying hourly average steradian values obtained using equation 3.9 with the respective hourly diffusive radiation values obtained from TMY database. Total solar radiation shade on the point which is under the PV array is obtained using equation 3.11.

$$DHI_{shade.h} = DHI_h \times \frac{\sum_{p=1}^{n}\Omega_{p,h}}{2\pi} \qquad (3.11)$$

Where,

$DHI_{shade.h}$ is the dissuasive shading at hour h,

DHI_h is the global diffusive radiation at hour h,

Received diffusive solar radiation is calculated by using same equation 3.8 which is used for fixed PV solar arrays.

After obtaining solar radiation, of both direct and diffusive radiations under the PV arrays which was received hourly, the total solar radiation received is obtained by adding calculated direct and diffusive components together as shown in equation 3.12

$$GHI_{under\ array} = DHI_{under\ array} + DNI_{under\ array} \tag{3.12}$$

It is required to obtain the portion of received solar radiation in order to insert the DSSAT simulation to get crop yield under the different row spaces. It is obtained dividing $GHI_{under\ array}$ by Global Horizontal Radiation (GHI). Hence solar shading under the PV array is obtained as shown in equation 3.13.

$$Solar\ Shading\ level = 1 - \frac{GHI_{under\ array}}{GHI} \tag{3.12}$$

3.4. Techno-Economic feasibility

After considering crop yields and solar energy harnessing of the installations for particular case, its techno economic feasibility should be evaluated. This is done by using Simple Net Present Value (NPV) calculations and Internal Rate Of Return (IRR) calculations. Remaining initial cost at a considered year is obtained using equation 3.13.

$$C_i = I_{pv,i} - L_{Crop,i} - M_i - C_{i-1} \tag{3.13}$$

Where,

$I_{pv,i}$ is the income of PV installation of the year *i*,

$L_{Crop,i}$ is the reduction of the income because of solar shading of year *i*,

$M_i$is the maintenance cost of year *i*,

C_{i-1} is the remaining initial cost value of the last year.

Sample cases were selected for feasibility analysis under selected crop and selected areas. Since solar harnessing as well as the crop yield may vary with environmental factors, contingency analysis was done for each case to study the feasibility further.

CHAPTER 4. SIMULATION RESULTS

4.1. Relationship of crop yield verses solar shading level

Relationship of solar shading level and crop yield was obtained from DSSAT simulations. Although simulation results vary with the area under consideration, percentage changes are almost the same for the same crop. So only the percentage variation of crop yield verses percentage shading was considered. Simulation was done for eight selected crops which were shown in figure 4.1.

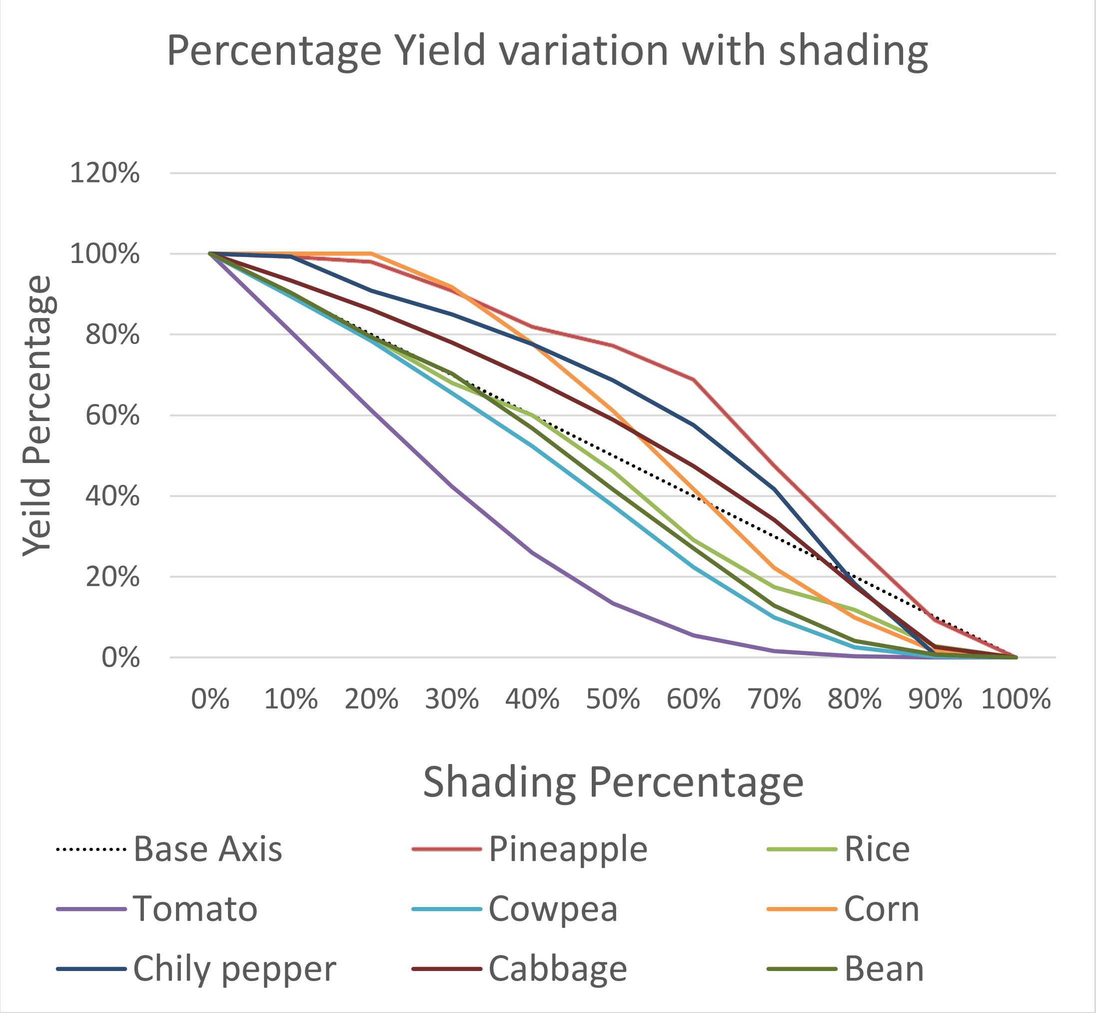


Figure 4.1: Shading verses Crop yield relationship

As per the graph, some crops have certain shade tolerance capabilities. When the shading increased, the yield was decreased lightly until 30%- 40% for some crops like pineapple and corn. Paddy, Bean and Cowpea shows inverse proportionally decreasing yield when shading increase. But for crops like chili pepper the yield rapidly dropped when shading increases. To obtain actual yield of a particular province these yield coefficients were multiplied by actual yield without shading.

Yield relationship based on shading level for tea is shown in graph 4.2 which was obtained based on researches done by the Tea Research Institute.

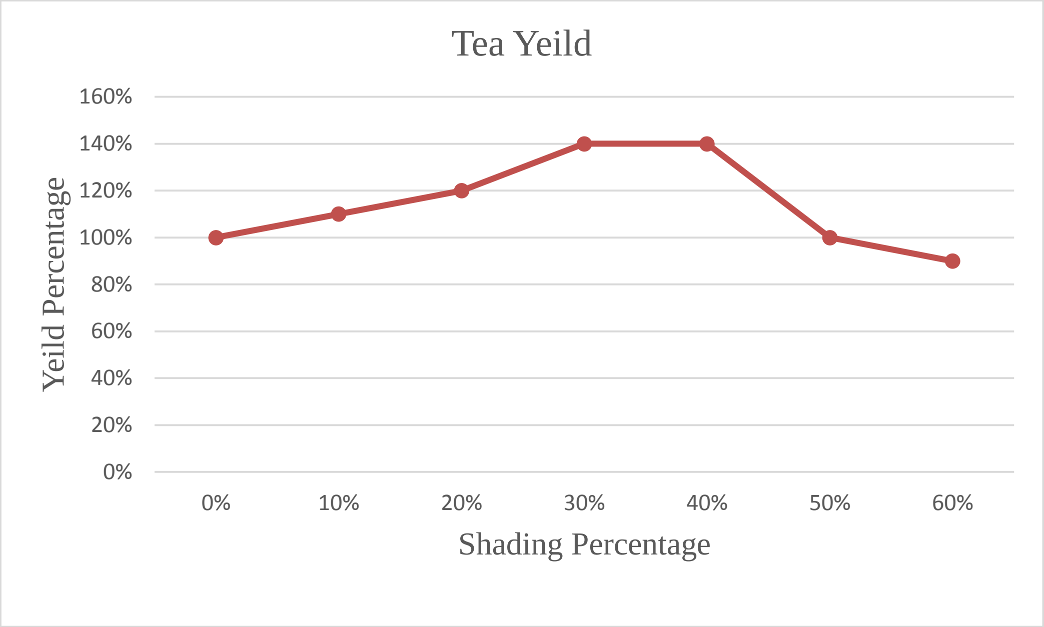


Figure 4.2: Shading verses Crop yield relationship of tea

Source: Role of shade trees in tea by Gamage

4.2. Possible solar generations

Possible solar generation under fixed and single axis tracking systems were obtained by using rescreen simulation software. Both the Mono-Si and Poly-Si PV panels were used for simulations. 270W Mono-Si panels and 250W Poly-Si panels were used panel types and the dimensions 1650mmx992mm for all cases. Table 4.1 shows the simulation results for possible annual generation data per square meter under each province.

Table 4.1 : Possible per square meter annual solar generations of selected areas

AREA	Fixed solar annual generation (kWh)		Single Axis solar annual generation (kWh)	
	Mono-Si	Poly-Si	Mono-Si	Poly-Si
COLOMBO	260	242	316	294
GAMPAHA	294	273	369	345
HAMBANTOTA	288	268	360	335
ANURADHAPURA	265	246	326	304
NUWARAELIYA	262	244	321	299
JAFFNA	273	255	340	315
TRINCOMALEE	276	258	343	319
PUTTALAM	301	280	383	356
BATTICALOA	301	280	383	335
MATARA	287	267	359	335

Above mentioned data in table 4.1 is used for feasible energy generations of Provinces. Here it is assumed that the generations of provinces are same as the selected area of the province.

4.3. Solar Shading under the PV array

As described under chapter 3 solar shading was modeled based on geometrical parameters and VB macros in excel were used to calculate the shading levels under the given PV panel row spacing. A 64mx64m area was selected for shading simulations which is approximately one acre. Since the solar shading depends only on panel spacing and solar tracking method, percentage shading simulation results does not vary with location provinces. Obtained results are shown in the figure 4.3.

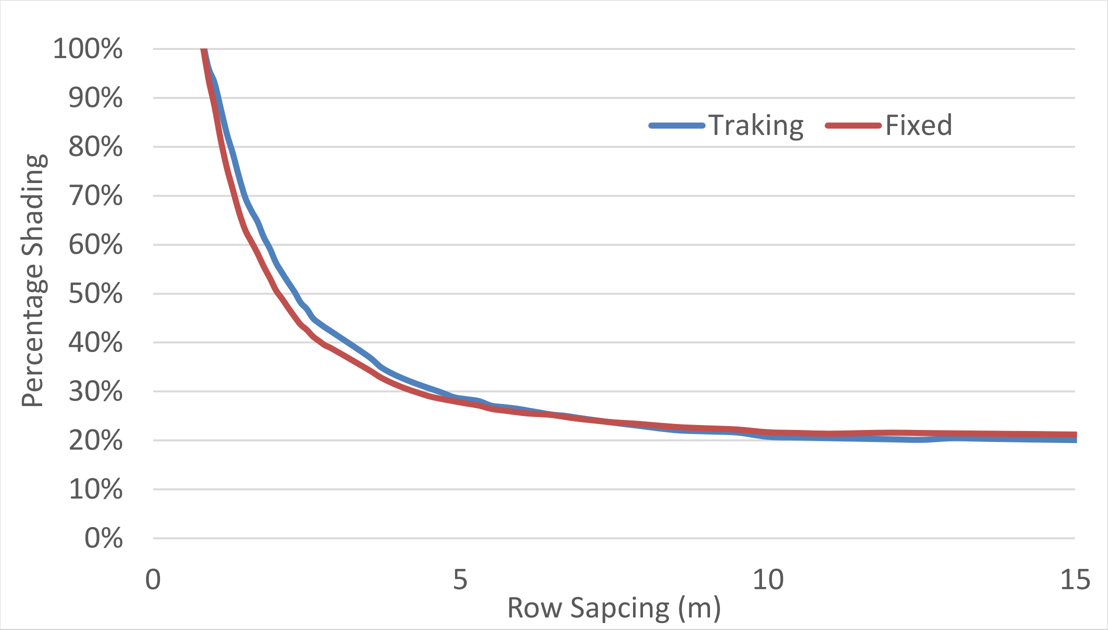


Figure 4.3: Percentage Crop Shading directly under panels Verses Row Spacing

Shading under the PV arrays are always more than 20% as per the simulation. Here it is clear that shading of single axis tracking gives more shade when panel spacing is less than 5m. At 30% shading, the panel spacing of fixed PV solar installation is 4.3m where single axis it is 4.7m. Under this simulation the center point of the PV array was taken as the origin where the shading was evaluated. Hence shading of all the other points are obviously less than this.

Shading level at the middle point of two rows was also obtained which shows the least shade level for a particular arrangement. Here also the same 64mx64m PV arrays was considered and the results are shown table 4.4 below.

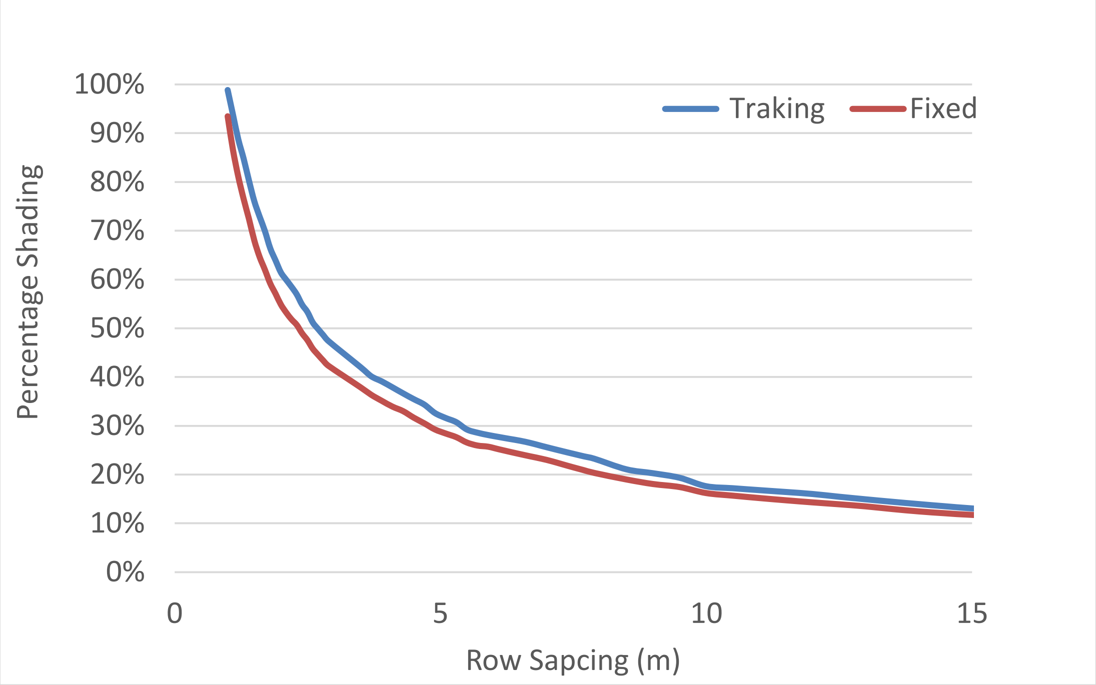


Figure 4.4: Percentage Crop Shading between middle of adjacent rows Verses Row Spacing

Comparing figure 4.3 and 4.4 it was clear that the shading level directly under the panel is more than the middle point of the of two panel rows. For crop yield calculations the average shading was not used because it may result in a very low yield of the crops directly under the PV panels. So shading relationship obtained under figure 4.3 was used to calculate the relevant crop yield. But total yield result is will be always greater than this as described above.

4.4. Case study

Since it's more complicated to evaluate the feasibility for each and every case, some sample simulations were conducted and the results were used for evaluating the feasibility. Here feasibility was considered for paddy, tea and pineapple by considering its distribution and areas of growing so that there will be more generation opportunities. Here a 40mx40m area is considered and results were obtained based on 25% and 35% shading levels for each case. Annual maintenance costs were used as 20 USD which is 3100 LKR per 1kW([27]. Annual cost incremental factors, inflation costs were used as shown in table 4.2.

Table 4.2 : Annual factors used for PV solar evaluations

Description	Factor
Annual increase of Crop income	5%
Inflation cost of Maintenance	5%
Annual reduction of PV income	1%
Finance Discount factor	12%

Net profit margins were calculated using equation 4.4. Net profit was taken as the total profit after compensating all the expenses and PV installation costs and revenue was used as total expenses and incomes for a 20 year period.

$$Net\ Profit = \frac{net\ profit}{total\ revenue} \tag{4.1}$$

Case I: simulation for paddy

This simulation is done in the Hambantota area where there is a higher solar generation feasibility as well as availability of large paddy fields. Considered 64mx64m area and simulations were done for fixed axis and single axis, Mono-Si and Poly-Si cases with 25% and 35% shading levels.

Table 4.3 : Agrivoltaic feasibility evaluation for Paddy, Anuradapura

PV technology	Solar Tracking	Percentage Shading	Annual Generation (MWh)	Pay Back in Years	IRR	Profit margin	Crop reduction percentage
Mono-Si	Fixed	25%	131.9	19.3	12%	0%	29.06%
		35%	230.9	18.8	12%	1%	41.09%
	Single Axis	25%	162.3	11.2	16%	78%	29.06%
		35%	263.8	11.1	16%	81%	39.78%
Poly-Si	Fixed	25%	122.5	15.2	13%	14%	29.06%
		35%	214.4	14.9	14%	16%	41.09%
	Single Axis	25%	151.4	9.8	18%	123%	29.06%
		35%	246.0	9.8	18%	127%	39.78%

As per the simulated data it can be clearly seen that IRR for Poly-Crystalline PV panels with single axis tracking systems are more relevant for Poly-Crystalline PV panels. It also has a higher net profit margin and a least payback period compared to other installations. Since paddy production is widely effected at 35% shading it is more convenient to go forward with 25% shading scheme with payback period of 9.8 years. Since agricultural costs are not considered here, it is assumed that those costs are covered by crop yield itself. So in higher shading levels the losses of agricultural cost also will be considered for simulations.

From the above simulations it is clear that fixed axis PV solar installations are not suitable for agrivoltaic systems because of its higher payback period and lower net profit margins.

Case II: Simulation for Pineapple

Pineapple was used as the second simulation by considering its shade loving behaviors as per shading simulation results shown in table 4.1. Gampaha was selected as the area for simulation, since pineapple is highly available there. Same as for paddy the simulations were done for a 64mx64m area with 25% and 35% shading levels. Financial parameters were same as in table 4.1. Simulation results are shown in table 4.4 below.

Table 4.4 : Agrivoltaic feasibility evaluation for Pineapple, Gampaha

PV technology	Solar Tracking	Percentage Shading	Annual Generation (MWh)	Pay Back in Years	IRR	Profit margin	Crop reduction percentage
Mono-Si	Fixed	25%	132.2	17.9	12%	2%	6.29%
		35%	231.4	18.2	12%	2%	13.58%
	Single Axis	25%	159.0	11.5	16%	73%	5.57%
		35%	258.4	11.6	16%	68%	14.46%
Poly-Si	Fixed	25%	121.6	14.9	14%	17%	6.29%
		35%	212.8	15.0	13%	15%	13.58%
	Single Axis	25%	149.0	9.9	17%	123%	5.57%
		35%	242.1	10.0	17%	116%	14.46%

By considering the simulation results it is clear that Poly-Crystalline PV solar panels with single axis tracking system is more suitable for agrivoltaic systems. 35%

installation is selected as the best because of the higher generation, IRR and least payback period.

Case III: Simulation for Tea

Tea is a shade loving tree with better shade performances as per TRI. Feasibility study under case III was done for tea plantations in NuwaraEliya by considering higher tea density. Simulation parameters were kept the same as case I and II and simulations were done for 25% and 35% shading levels. Simulation results are shown in table 4.5 below.

Table 4.5 : Agrivoltaic feasibility evaluation for Tea, Galle

PV technology	Solar Tracking	Percentage Shading	Annual Generation (MWh)	Pay Back in Years	IRR	Profit margin	Crop reduction percentage
Mono-Si	Fixed	25%	132.2	16.2	13%	10%	-30.00%
		35%	231.4	16.4	13%	9%	-40.00%
	Single Axis	25%	154.3	8.9	19%	194%	-32.00%
		35%	286.5	8.9	19%	188%	-40.00%
Poly-Si	Fixed	25%	127.7	12.0	15%	62%	-30.00%
		35%	223.4	12.1	15%	59%	-40.00%
	Single Axis	25%	143.6	8.0	21%	261%	-32.00%
		35%	266.8	8.0	21%	252%	-40.00%

It was clear that the single axis tracking PV solar installation with Poly Crystalline technology gives the best results for tea as per the simulation results. By considering higher crop improvements and Annual energy generation, 35% shading level was selected for tea plantations for agrivoltaic installations since there is not a significant difference of other factors in single axis Poly-Crystalline installations.

Case IV: Simulation for Maize

Simulation results of maize is shown in table 4.6. As per the simulation results single axis poly-crystalline installation gives best results at 25% shading level.

Table 4.6 : Agrivoltaic feasibility evaluation for Maize, Hambantota

PV technology	Solar Tracking	Percentage Shading	Annual Generation (MWh)	Pay Back in Years	IRR	Profit margin	Crop reduction percentage
Mono-Si	Fixed	25%	125.3	13.3	14%	36%	22.34%
		35%	250.6	13.2	14%	37%	33.29%
	Single Axis	25%	156.7	8.9	19%	181%	22.34%
		35%	291.0	8.9	19%	183%	33.29%
Poly-Si	Fixed	25%	116.8	11.3	16%	75%	22.34%
		35%	233.5	11.3	16%	77%	33.29%
	Single Axis	25%	145.8	8.0	21%	239%	22.34%
		35%	270.7	8.0	21%	242%	33.29%

Case V: Simulation for Tomato

Tomato was selected for the fifth simulation which has the worst crop yield with shading according to the shading performance analysis. Obtained results are shown in Table 4.7.

Table 4.7 : Agrivoltaic feasibility evaluation for Tomato, NuwaraEliya

PV technology	Solar Tracking	Percentage Shading	Annual Generation (MWh)	Pay Back in Years	IRR	Profit margin	Crop reduction percentage
Mono-Si	Fixed	25%	130.4	20.0	3%	0%	48.23%
		35%	228.2	20.0	5%	0%	65.86%
	Single Axis	25%	159.6	20.0	8%	0%	48.23%
		35%	259.4	20.0	10%	0%	67.50%
Poly-Si	Fixed	25%	121.6	20.0	3%	0%	48.23%
		35%	212.8	20.0	6%	0%	65.86%
	Single Axis	25%	148.7	20.0	9%	0%	48.23%
		35%	241.6	20.0	10%	0%	67.50%

Here it was noticed that Poly-Crystalline with single axis still gives the best outputs among the others. However, Tomato is not feasible for agrivoltaic because of its lower profit margins and higher yield reduction.

Since all the installations gave its best outputs at single axis tracking poly-crystalline PV installations, simulations were done only for the balance crops. Results are shown in table 4.8. Here only Bean and Cabbage were considered based on crop distribution.

Table 4.8 : Agrivoltaic feasibility evaluation for Cabbage and Bean, NuwaraEliya

Crop	District	Poly-Si Installtion type	Percentage Shading	Annual Generation (MWh)	Pay Back in Years	IRR	Profit margin	Crop reduction percentage
Bean	NuwaraEliya	Single Axis	25%	148.7	9.8	18%	133%	25.18%
			35%	241.6	9.8	18%	133%	37.85%
Cabbage	NuwaraEliya	Single Axis	25%	148.7	9.8	18%	133%	17.94%
			35%	241.6	9.8	18%	133%	27.42%

As per the simulation results IRR and Profit margins and payback is same for all the cases. By considering crop reductions installation with 25% shading will be selected as the most suitable for both cabbage and bean.

4.5. Province vise energy production

According to the simulations done for tea, paddy, maize, pineapple, cabbage, bean and tomato Agrivoltaic systems are feasible for them under Poly-Crystalline single axis tracking installations. For paddy, maize, cabbage and bean shading level will be 25% and it will be 35% for tea and pineapple while tomato was not further considered since it is not feasible. Province vise energy production capability of these crops were obtained assuming 10% of cultivated land of each crop is used for agrivoltaic. This assumption was based on the availability of flat lands and to minimize the impact of annual food production. It is assumed that nearby district simulation results for the districts which do not have weather database published under TMY. When selecting the cultivated area, largest value from Yala and Maha were selected assuming the field is not cultivated in the other season. Table 4.9 illustrates possible generation in GWh for selected crops.

Table 4.9 : Possible agrivoltaic annual electricity generation in GWh

District	Paddy			Tea			Pineapple			Cabbage			Maize			Bean		
	Cultivated Area (Acres)	Possible Installation capacity (MW)	Possible annual generation (GWh)	Cultivated Area (Acres)	Possible Installation capacity (MW)	Possible generation (GWh)	Cultivated Area (Acres)	Possible Installation capacity (MW)	Possible generation (GWh)	Cultivated Area (Acres)	Possible Installation capacity (MW)	Possible generation (GWh)	Cultivated Area (Acres)	Possible Installation capacity (MW)	Possible generation (GWh)	Cultivated Area (Acres)	Possible Installation capacity (MW)	Possible generation (GWh)
Colombo	8,912	68	131	2,025	25	48	368	5	9	-	-	-	-	-	-	-	-	-
Gampaha	28,405	216	423	1,294	16	31	3,182	39	77	-	-	-	-	-	-	-	-	-
Kalutara	33,345	253	497	31,510	389	750	351	4	8	-	-	-	-	-	-	-	-	-
Galle	37,759	251	542	66,999	827	1,787	746	9	20	-	-	-	-	-	-	-	-	-
Matara	41,789	278	600	58,786	726	1,568	291	4	8	-	-	-	-	-	-	-	-	-
Hambantota	71,912	478	1,048	1,983	24	54	235	3	6	-	-	-	403	3	6	-	-	-
Badulla	59,737	397	871	68,174	842	1,846	215	3	6	1,467	10	21	6,958	46	101	4,192	28	61
Monaragala	96,330	641	1,404	-	-	-	672	8	18	-	-	-	5,318	35	78	-	-	-
Ratnapura	35,815	238	514	105,565	1,304	2,555	593	7	14	-	-	-	447	3	6	-	-	-
Kegalle	21,526	143	309	28,487	352	690	457	6	11	-	-	-	-	-	-	-	-	-
Kurunegala	206,677	1,374	3,129	-	-	-	3,404	42	82	-	-	-	351	2	5	-	-	-
Puttalam	56,785	378	1,005	-	-	-	1,064	13	31	-	-	-	-	-	-	-	-	-
Kandy	39,488	263	567	52,569	649	1,272	-	-	-	509	3	7	1,914	13	27	1,662	11	24
Matale	52,759	351	758	8,129	100	197	-	-	-	346	2	5	837	6	12	731	5	11
Nuwara Eliya	16,808	112	250	107,168	1,324	2,589	-	-	-	2,013	13	30	543	4	8	2,025	13	30
Anuradhapura	237,821	1,582	3,600	-	-	-	-	-	-	-	-	-	1,015	7	15	-	-	-
Polonnaruwa	85,833	571	1,299	-	-	-	-	-	-	-	-	-	272	2	4	-	-	-
Jaffna	28,306	215	444	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Kilinochchi	56,808	432	891	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Mannar	51,413	391	910	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Vavuniya	48,931	372	768	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Mullativu	42,155	281	585	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Trincomalee	104,348	695	1,449	-	-	-	-	-	-	-	-	-	287	2	4	-	-	-
Batticaloa	159,530	1,061	2,325	-	-	-	-	-	-	-	-	-	855	6	12	-	-	-
Ampara	187,463	1,247	2,733	-	-	-	-	-	-	-	-	-	531	4	8	-	-	-
Sub Total	**1,810,655**	**12,286**	**27,053**	**532,690**	**6,579**	**13,387**	**11,577**	**143**	**291**	**4,335**	**29**	**64**	**19,730**	**131**	**288**	**8,610**	**57**	**126**
Total possible installation capacity in MW																		**19,225**
Total possible Electricity generation in GWh																		**41,208**

CHAPTER 5. Conclusions and Recommendations

Under this chapter, results obtained in Chapter 4 based on techno economic feasibility analysis of selected PV array installations were discussed and the outcomes were concluded.

5.1. Conclusions

Seven cases were analyzed in Chapter 4 based on crop shading performance results and PV solar generation feasibilities while changing other parameters like PV technologies, installation methods. Two shading levels were considered which are 25% and 35%. Shading levels below 20% was not feasible because of the higher row spacing. Seven different crops were selected for simulations and only six of them were feasible. Districts for each case simulations were selected based on highest crop density of crops. Results of the analysis showed that mono crystalline PV modules are not feasible for agrivoltaic under both fixed and single axis tracking methods. They gave less IRR values and profit margins. Poly crystalline installations were feasible for agrivoltaic with single axis tracking installations. Fixed axis installations of poly crystalline was not feasible for agrivoltaic as per the simulation results. Fixed PV installations generate higher electricity income to cover capital installation costs within a minimum time although solar tracking installations absorb higher solar energy and generating more shading.

Panel spacing will be increased in solar tracking installations to get the same percentage of shading compared to fixed installations. Although the effect of more panel spacing limits the plant capacity, energy generations are always higher than that of fixed arrangements. Furthermore, the structural costs of PV solar installations were also reduced. Although structural cost is reduced because of the lesser panels, there is an additional cost about 8% of structural cost for solar tracking installations. Still, the cumulative summation of installation costs will be recovered because of the higher energy generations of single axis tracking installations.

In crops with poor shading performances, the yield losses were high in 35% of the cases although the installation was still economically feasible. All simulation cases with both 25% and 35% poly crystalline single axis installations have similar IRR and profit margins. But the annual generation was higher in the case of 35% installation as the plant capacity is higher. With this result it can be clearly seen that the crop yield losses are not significant in the economic analysis of crops with poor shading performances. The main reason for this result is that solar radiation usage efficiency is less in all the crops, compared to solar energy generation efficiency of PV cells. Normally plants have a radiation usage efficiency which varies from 3% to 8% while commercial PV cells have 14% - 17%. Since food yield is also a critical factor for a country, the increased reduction of the crop yield will not be accepted. Hence it is proposed to use 25% of shading for paddy, maize, beans and cabbage which have poor shade performance. Since pineapple and tea have better shading performances, they give better results at 35% of shading level.

Pineapple has a better shading performance than those of the crops discussed above. The percentage of Pineapple yield reduction was 7% at 25% shading and 14 % at 35% percent shading. Both the cases are technically feasible same as the previous cases. Since pineapple has a very low crop yield loss, 35% shading is proposed for pineapple based agrivoltaic.

Observations conducted about the case study on tea were different than those of all other crops. Tea yield increased when shading was applied. At 25% shading level it gave 30% increase of yield and at 35% shading levels tea gave 40% increase of yield. So simulation results for tea agrivoltaic were given a win-win situation. It gives solar income as well as an increased income from crop yield. Tea will be treated as the best plantation for agrivoltaic installations of Sri Lanka.

After analyzing individual performance of crops, total possible generations were obtained considering the whole country. Here only 10% of cultivated area were selected for calculating agrivoltaic energy generation. As per the calculations, total possible energy generation was 41,208 GWh which is more that annual electricity generation of Sri Lanka was 14,300 GWh in 2016 as per PUCSL. By comparing agrivoltaic generation with annual electricity demand, it was observed that power growth issues of Sri Lanka solved with the support of agrivoltaic. As a straight forward start for agrivoltaic Sri Lanka shall focus on tea with feasible annual generation of 13,387 GWh which is also more than annual demand of the country.

5.2. Problems and Limitations

Higher structural costs are a key figure when discussing about the problems of agrivoltaic installations. It requires permanent steel structures with 5m high above the ground with concreate foundations. Since panels are mounted 5m above the ground, cost will be higher. With the PV shelter the plants will not be exposed to direct raining so that dust particles may contaminate and reduce the photosynthesis efficient. Specially for tea, dust contamination may be a problem for the product quality because tea is not washed under processing.

Simulated result may be not applicable for hilly areas with higher solar shading. Installation at sloped lands may not be feasible because of lower solar radiations and inter panel shading which shall be modeled separately. For large scale plants step up transformers and power transmission line cost shall also be considered for economic feasibility which may reduce the payback and IRR.

Structural costs may vary with the climatic situations like higher wind levels. Panel performance may be changed with environmental impacts like birds and dust. Since TMY calculations are based on simulation results, there may be slight deviations from the actual field data.

5.3. Recommendation

This study is based on averaged values published under each responsible division of Sri Lanka and simulation results of widely used application software. So this analysis can only be used in pre-feasibility stage. Crop yield variation with panel shading shall be obtained with actual field experimental at detailed design stage and optimized design shall be done accordingly.

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